RESEARCH REPORT

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Seismic qualification of complex equipment by combined analysis and testing

Authors: Vilho Jussila, Ludovic Fülöp

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Seismic qualification of complex equipment by combined analysis and testing	
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Author(s) Vilho Jussila, Ludovic Fülöp	Pages 33
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Summary

This report is deliverable for 2014 of Subproject 3 in the project SESA "Seismic Safety of Nuclear Power Plants – Targets for Research and Education", part of the SAFIR 2014 program on nuclear safety.

In 2014, in Subproject 3, the review task for an emergency diesel generator day-tank has been carried out and reported.

The day-tank has been one configuration supplied by Wärtsilä, and loads were provided by TVO according to a realistic scenario for placement of the day-tank. The aim was to carry out modeling of the day-tank, starting with simple models and ending with very sophisticated liquid interaction models, in order to understand the limitations of the analysis methods usually used in the qualification process. The use in testing for results from the modelling are indicated further, and testing options for certain components of the day-tank are discussed.

Confidentiality	Public

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Written by	Reviewed by	Accepted by
Ludovic Fülöp Principal Scientist	Ilkka Hakola, Principal Scientist	Eila Lehmus, Head of Research Area

VTT's contact address

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Preface

The decisions to increase the number of nuclear power plants (NPP) in Finland, and especially the positioning of one NPP in the northern part of the country, called for reassessing the potential effect of earthquakes on plant safety requirements.

As a response to this need, the project SESA - ***Seismic Safety of Nuclear Power Plants – Targets for Research and Education*** was included in the Finnish Research Program on Nuclear Power Plant Safety, SAFIR 2014, under the umbrella of Reference Group 7 - Construction safety. SESA is in its first year of financing in 2011, and it has 3 Subprojects:

- Subproject 1. Earthquake hazard assessment,
- Subproject 2. Structural assessment,
- Subproject 3. Equipment qualification procedures,

This report is a deliverable of Subproject 3 for the year 2014.

The work in SESA has been supervised by the Reference Group 7 and the Ad-Hoc group specifically named for the SESA project.

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Juha Rinta-Seppälä	FENNOVOIMA
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Heli Koukkari	VTT
Eila Lehmus	VTT

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Oli Okko	STUK
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Pentti Varpasuo	FORTUM
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Pekka Heikkinen	Uni. of Helsinki
Jouni Saari	ÅF-Consult
Björn Lund	Uppsala University

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Authors

Contents

1 Introduction

While seismic design of buildings is a field interesting from a broad engineering perspective, qualification of components is a more specialised area. Seismic qualification is more fragmented field compared to design of structures. The aim of the work in 2013-2014 was to develop a good practice example qualification for a complex equipment typology commonly agreed in the project: This equipment was fixed during the year 2013 to be a fuel day-tank supplying an emergency diesel generator (EDG).

2 Goal

The aim of this document is to present the/a procedure for seismic qualification of a day-tank. The work was planned to explore modelling techniques not usually used for such qualification by consultants in order to understand the limitations of the traditional modelling techniques. We also analysed simplified models, in order to increase the reliability of the results and compare the different techniques.

The qualification of the day-tank has to be conducted by combined modelling plus testing. The model outputs for future testing are given, and proposed testing methods are indicatively described.

3 Qualification scenario

The day-tank to be modelled is based on the portfolio usually supplied with Wärsilä emergency diesel generator (EDG) sets (Figure 1). The scenario for deploying this day-tank was provided by TVO, with a realistic use scenario in the OL plant.

3.1 Configuration of the day-tank

VTT received the 3D geometry file of the day-tank in a meeting with Wärtsilä, 05.11.2013. The generic drawing of the day-tank is given in VTT-00652-14 [17]. It is important to state that the configuration is a generic tank, representing the standard project type not nuclear purpose specific configuration. If needed, several improvements can be implemented to this configuration to improve its seismic performance.

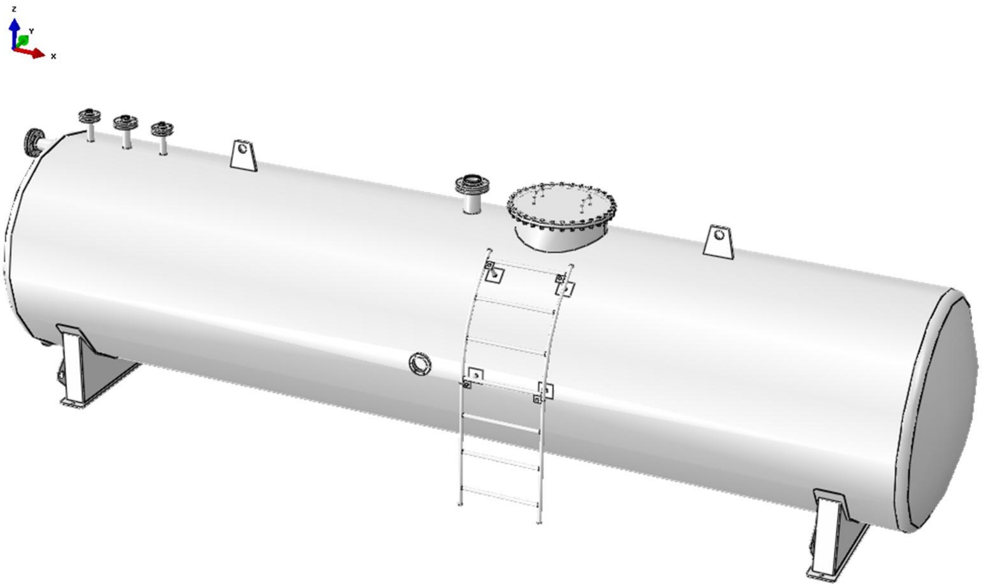


Figure 1. 3D render image of the analyzed day-tank

The list of components has been drafted with the purpose of qualifying the EDG and its auxiliaries in normal operating conditions [1]. The component list states the role of each component and the consequence of failure and is supplemented by assessment/classification on “Probability of Occurrence (PoO)”, “Probability of Detection (PoD)” and “Severity (S)” in case the component fails. The aggregation of the PoO, PoD and S classifies the component from the point of view of consequences in case of its failure.

For the specific requirements of seismic review “Severity (S)” has the highest priority in classification [2]. Component review emphasizes “…meeting the performance requirements during and/or following the seismic event…” (e.g. [4], [5], [6]). For the few seconds seismic event probability of failure occurrence on the multi-annual basis is not relevant. Probability of detection of the failure is also not useful, since repairing the component may not be an option in the conditions immediately following an earthquake.

Besides general checks concerning the anchoring and integrity of the reservoir, the components from Table 1 of the day tank are suggested for seismic review. It must be emphasized here, that the list serves only as example. Such list must be compiled by a multi-disciplinary team with detailed understanding of the roles of components.

Table 1. Components suggested for seismic review and failure modes for daytank sub-system of the EDG

2.	**Fuel oil day tank sub-system**					
2.2	Drainage of fuel oil day tank					SR
2.2.1	Drain valve	flow control of drain from tank	Valve total failure	Fuel from day tank flows to day tank basin.	Engine stops soon due fuel oil drain from day tank.	SR
2.2.2			pipe failure before valve	Fuel from day tank flows to day tank basin.	Engine stops soon due fuel oil drain from day tank.	SR
2.3	Fuel oil day tank controls					SR
2.3.3	Low level sensor/switch	low level indication, possible transfer	Jam of float sensor. Other	No correct level signal. Problem to start	Possible risk that low level not noted. Limited time to operate	SR

		pump start signal. Alarm for low level of day tank	defect.	automatically transfer pump.	engine	
2.3.4	Low low level sensor/switch	Low Low level switch	Jam of float sensor. Other defect.	No correct level signal. If Low level switch have been passed	If low level switch is passed and Low low do not work only limited time before engine stops.	SR
2.4	Fuel outlet					
2.4.1 a	Outlet connection	fuel outlet	leak of connection due to damage or failure	some leakage to tank basin.	some limited operation time due to loss of fuel.	SR
			total failure	day tank fuel flows to tank basin	very limited time to operate the Engine	SR
2.4.1 a	Outlet pipe	fuel flow outlet tank	leak of pipe due to damage or failure	some leakage out.	some limited operation time due to loss of fuel. Risk of fire increases	SR
			total failure	loss of pressure in pipe. Cavitation in feed pump	very limited time to operate the Engine	SR
2.4.2	Outlet valve	Fuel flow outlet control	leak of pipe due to damage or failure	some leakage out.	some limited operation time due to loss of fuel. Risk of fire increases	SR
			total failure	loss of pressure in pipe. Cavitation in feed pump	very limited time to operate the Engine	SR

3.2 Qualification approached by modeling and testing

The scope of qualification guides like e.g. IEEE 344 is to give guidance on how to qualify equipment. In the framework of OL only shakings by a SSE (Safe Shutdown Earthquake) shaking is required. Preliminary OBE (Operation Basis Earthquake) shaking is not used in Finland.

We acknowledge the requirements stated in IEEE 344 (§4.1) that earthquakes create at ground level:

- simultaneous shaking in all 3 directions of space
- the components of the shaking are statistically independent
- the strong motion part is 10-15s
- the significant frequency content is 1-33Hz

But, duration, independence and frequency content arriving to a component may be affected/changed by the filtering effect of its support, and we need to asses these possibilities in light of having only floor spectra as input as input. For the FE modeling, the seismic environment for a component will be specified as time history (shaking).

"Component qualifies" means that the component is able to perform its safety function during and/or immediately after the SSE events. Qualification is to be demonstrated by analysis and testing.

- In the first stage a FE model will be analyzed, focusing the assessment on integrity of the reservoir and the anchorages (mechanical assessment). The accelerations and displacement will be recorded to the location of the tree components to be qualified (see 3.1).
- Proposals will be sketched concerning the procedure leading to the qualification of the 3 components;

In the first stage a FE model will be built and subjected to shaking at the supports. Stresses, strains and forces are monitored in the tank's shell and other components of the system to ensure mechanical resistance. In the second stage, accelerations and displacement are collected from the connecting locations of the 3 components: 2.2 drainage of fuel oil day tank, 2.3 fuel oil day tank controls and 2.4 fuel outlet (Table 1), and a modeling or testing plan is presented for these components. Aging mechanisms have to be identified, and taken into account before the “seismic scenario” is applied.

3.3 Loads

According to the information supplied by TVO, the day-tank could potentially be located on the +6.5m floor level of a building (see. VTT-00652-14 [17] for details). Based on the floor spectra for the reservoir location (Figure 2), three independent accelerograms have been generated and used as input for the quantification process. In a real design case the use of at least three sets of such records is suggested.

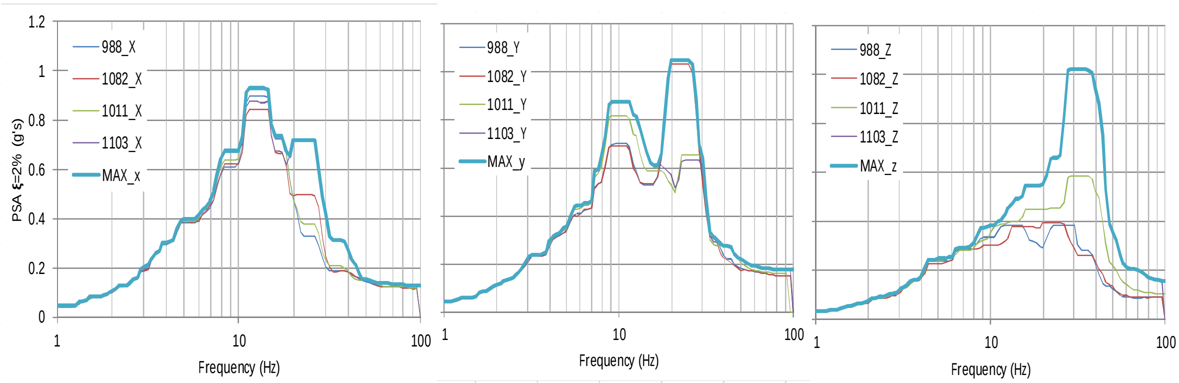
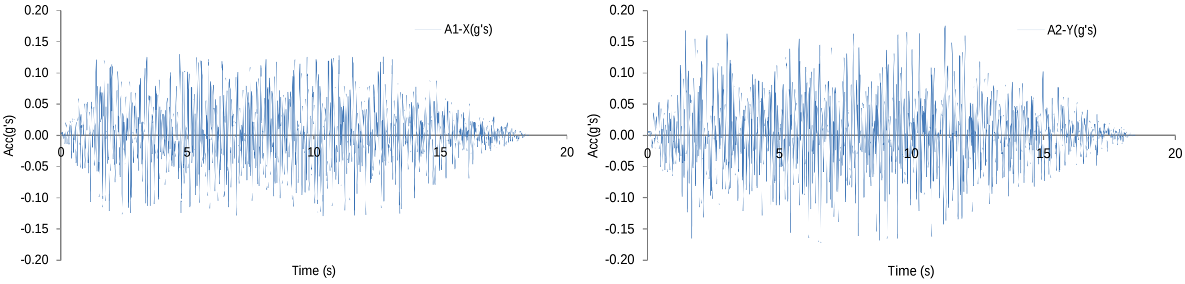
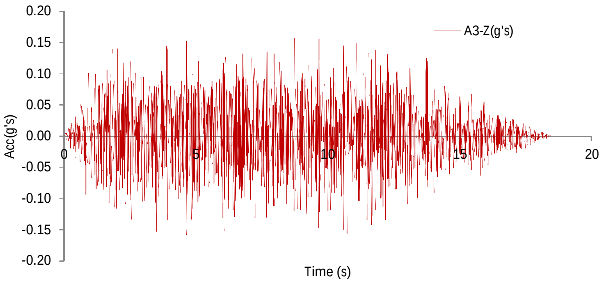


Figure 2. Envelope (MAX) spectra in the three loading directions of the day-tank base (X-longitudinal, Y-transversal and Z-vertical)

It was decided to use overall envelope spectra for each of the shaking directions. In the X and Y direction this choice is fully justifiable. However, in the vertical direction it is known that important variation of floor acceleration can exist even within the area of a few floor spans [7]. The floor spectra were supplied for locations directly on top of walls or columns. If the day-tank reservoir would be located closer to mid-span of floors, the floor amplification should be clearly accounted. A deeper study of the vertical direction effects may be warranted even if only certain supports of the day-tank are away from vertical load bearing elements.

The three statistically independent accelerograms, generated from the spectra using the in-house ArtACC software tool are given in Figure 3. These signals were generated with $T_{plateau}$=10s, for a damping ratio of ξ=2% and with a sampling frequency of 200Hz. Independence of the signals was checked by calculating the correlation factor between them (<0.3) allowing for random time-shift of the signals.





	g's	mm/s^2
Ax	0.129	1270
Ay	0.175	1721
Az	0.158	1546

Figure 3. X, Y and Z acceleration signals acting simultaneously at the base of the reservoir

The peak accelerations (PFA) for the three signals are given in Figure 3. It can be noted that the Y horizontal direction has the largest PFA, with X horizontal direction load being only ~74%, and even the vertical direction (Z) being loaded less (~90%).

4 Modelling

4.1 Complex shell based FE model

The size of the day-tank makes it unfeasible for qualification by testing. Hence a complex FE model has been developed to assess the performance of the large parts of the day-tank, including the anchoring, legs, reservoir and diesel liquid.

A classical, shell based finite element (FE) model, where an element describes deformation under a load was used.

All ladders and the fuel inlet and outlet pipes etc. were removed in order to simplify the FE model. The body and the legs of the day tank were modelled (Figure 19). The material of the day tank was isotropic elastic-plastic S355 steel (Table 3). In the second stage, the reservoir was filled with diesel fuel at 15°C. The fuel material model was defined with three material cards in Abaqus: Mie-Grunesein equation of state (EOS), density and viscosity (Table 3). Mie-Grunesein equation of state requires three parameters. They are speed of sound of the fuel, a linear Hugoniot slope coefficient and Gruneisen's gamma at the reference state. All other parameters except the speed of sound were set to zero because diesel fuel was assumed incompressible. Interactions between walls and fuel were modelled with general contact.

Table 2 Mesh properties

Part	Element type	Number of elements	Number of nodes
Diesel Coupled Euler-Lagrangian (CEL)	Eulerian element EC3D8R (Linear hexahedral element with reduced integration)	13200	14941
Diesel Smoothed Particle Hydrodynamics (SPH)	Lagrangian element C3D4 (Linear tetrahedral elements)	78149	14792 Remark: this number of particles
Container and legs	Lagrangian shell element S4R (Linear quadrilateral elements)	2522+ 180=2702	2524+212=2736

Table 3 Material properties

Part	Material property	Value
Diesel	Dynamic viscosity in 15 Celsius	$1.65 \cdot 10^{-9}$ Ns/mm^2
	Density in 15 Celsius	$8.25 \cdot 10^{-10}$ tons/mm^3
	Speed of sound	$1.25 \cdot 10^{6}$ mm/s
Container and legs: steel S355	Density	$8.00 \cdot 10^{-9}$ tons/mm^3
	Elastic modulus	$2.10 \cdot 10^{5}$ N/mm^2
	Yield stress	355 MPa

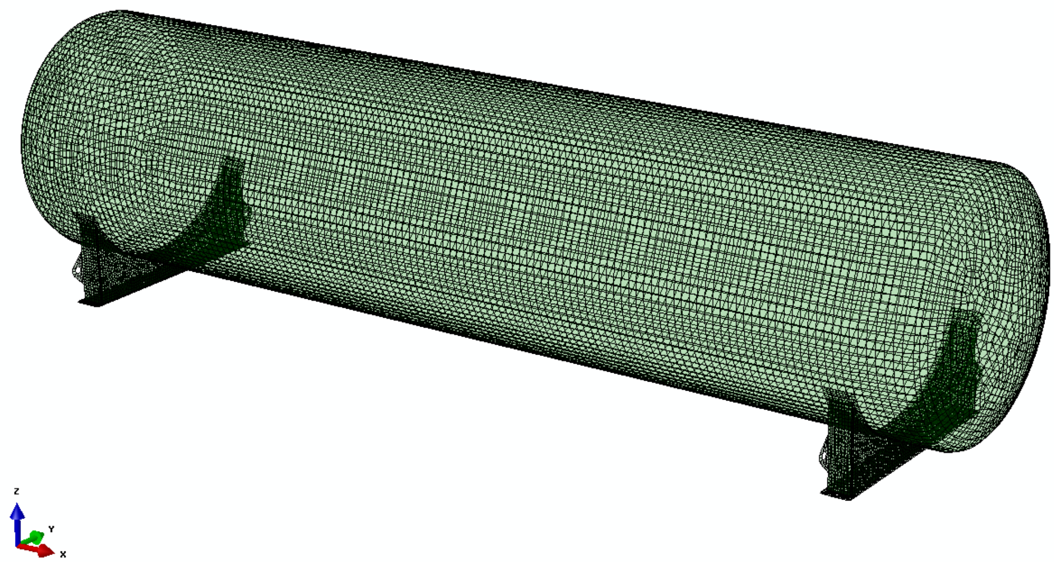


Figure 4. Shell-based model of the day-tank

4.1.1 Gravity results

The weight of the reservoir has been evaluated to be 15.8kN (1.61 tons) without liquid. The liquid in the reservoir, when filled to 90% of the height, has a further weight of 111.7kN (11.39 tons).

4.1.2 Frequency analysis of the empty and full reservoir

In the first step, the vibration analysis of the empty reservoir was carried out. The empty reservoir has a mass of about 1.6 tons, 15.8kN total base reaction force. As a first attempt to understand the structure 50 modes were calculated. Because the total mass factor in the Y and Z direction was 68% and 71%, both values less than 90% (see EN 1998-1 and ASCE 4-98[8]), it was decided to extend the calculation to up to 100 modes. However, due to the prevalence of local modes as frequency increases, even with this limit only 96%, 69% and 76% mass factor was achieved in the X, Y and Z directions. This practically means that 100 modes would not be enough for estimating base shear forces for the empty reservoir, in the Y and Z directions.

Table 4. Frequencies and mass total factors with first 100 modes calculated

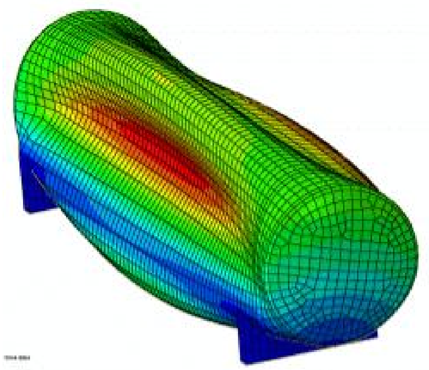
			tons	N
		Total	1.61	15788
		X(tons)	Y(tons)	Z(tons)
f_{min}(Hz)	f_{max}(Hz)	1.56	1.12	1.22
18.7351	233.571	97%	69%	76%

The most significant modes for the global deformation of the reservoir, and for calculating base forces, are Mode 1 and 3 for the Y direction, Mode 7 for the X direction and Mode 25 for the Z direction (Table 5).

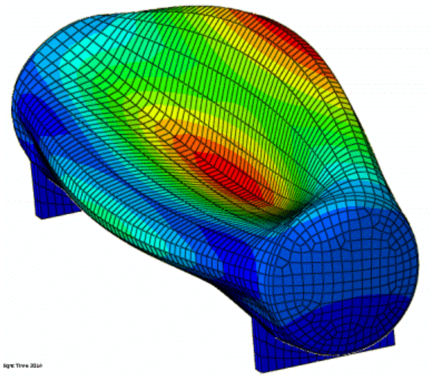
Table 5. Significant modes when the reservoir is empty

	f(Hz)	EM_x	EM_y	EM_z	X(%)	Y(%)	Z(%)
1	18.7351	0.0	0.6	0.0		38%	
2	24.6863	0.0	0.0	0.0			
3	26.3401	0.0	0.2	0.0		10%	
4	31.2856	0.0	0.0	0.1			7%
5	32.7885	0.0	0.0	0.0			
6	36.0612	0.0	0.0	0.1			4%
7	42.0468	1.5	0.0	0.0	96%		
8	47.4668	0.0	0.1	0.0		8%	
9	49.676	0.0	0.0	0.0			
10	49.6956	0.0	0.0	0.0			
11	50.5019	0.0	0.0	0.0			
12	50.7226	0.0	0.0	0.0			
13	58.4552	0.0	0.0	0.0			
14	60.625	0.0	0.0	0.0			
15	71.678	0.0	0.0	0.1			3%
16	72.2763	0.0	0.0	0.0			
17	72.3595	0.0	0.0	0.0			
18	75.9921	0.0	0.0	0.0			
19	76.4855	0.0	0.0	0.0			
20	77.4627	0.0	0.0	0.0			
21	77.7955	0.0	0.0	0.0			
22	77.9234	0.0	0.0	0.0			
23	87.8292	0.0	0.0	0.2			9%
24	89.0576	0.0	0.0	0.0			
25	90.5825	0.0	0.0	0.5			30%
26	98.0273	0.0	0.0	0.0			

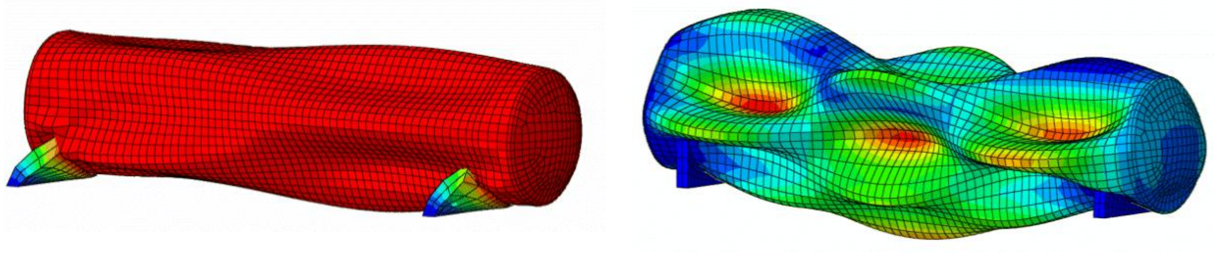
The frequencies corresponding to these modes are ~18Hz-26Hz, ~42Hz and ~90Hz, and mode shapes are presented in Figure 5. It can be noticed that a global bending deformation is visible in Modes 1 and 3 (Y direction). Mode 7 is the clear and only significant mode in the X direction, with a participation of over 96% of the mass. So, the reservoir is most flexible in Y direction (bending mode at ~18Hz), followed by X direction (bending of legs ~42Hz), and is stiffest in the vertical direction with frequency of ~90Hz being the most significant.



Mode 1 (18Hz)



Mode 3 (26Hz)



Mode 7 (42Hz) Mode 25 (90Hz)

Figure 5. Mode shapes of significant modes (empty reservoir)

In the second step the diesel fuel was modelled in a simplified way. The total estimated liquid mass of 9.78tons was divided to elements of the container wall proportionally to their own mass. Hence, larger elements in the container wall received larger contribution of liquid equivalent mass (as it is in reality).

The disadvantages of this modeling can be discussed in light of the two physical effects expected when the liquid is filling the container. On effect is obviously, (1) the substantial increase of the system mass, but (2) the inertial of the fluid is also expected to stabilize the reservoir walls, hence making the response less prone to local modes. The first effect will result in reducing modal frequencies compared to the empty reservoir case, while the second is expected to increase stiffness, so increase the modal frequencies. The two effects are canceling each other to a certain extent. While the first effect is realized when modeling the liquid as masses the second is not. So this model may result in lower frequencies compared to reality.

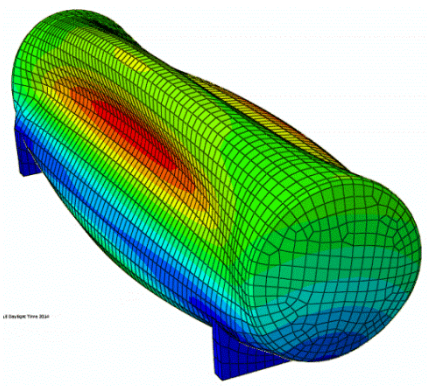
Similar calculation of the first 100 vibration modes results in frequencies and mass factors as summarized in Table 6. The significant modes are given in Table 7 and shapes in Figure 6.

Table 6. Frequencies and mass total factors with first 100 modes calculated

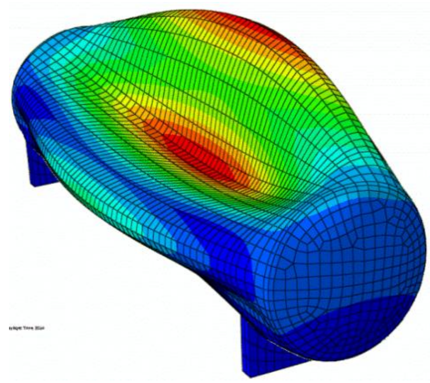
			tons	N
		Total	11.3894	111730
		X(tons)	Y(tons)	Z(tons)
f_{min}(Hz)	f_{max}(Hz)	11.34	8.36	9.13
6.80638	85.2358	100%	73%	80%

Table 7. Significant modes when the reservoir is full

		Effective mass - trans (tons)					
	f(Hz)	EM_x	EM_y	EM_z	X(%)	Y(%)	Z(%)
1	6.80638	0.0	4.6	0.0		40%	
2	8.92682	0.0	0.0	0.0			
3	9.52849	0.0	1.2	0.0		10%	
4	11.4355	0.0	0.0	0.8			7%
5	11.9549	0.0	0.0	0.0			
6	13.1453	0.0	0.0	0.5			5%
7	15.4782	11.2	0.0	0.0	98%		
8	17.2923	0.0	0.9	0.0		8%	
9	18.1309	0.0	0.0	0.0			
10	18.1376	0.0	0.0	0.0			
11	18.3191	0.0	0.0	0.0			
12	18.4033	0.1	0.0	0.0			
13	21.3386	0.0	0.0	0.0			
14	22.1015	0.0	0.1	0.0			
15	26.129	0.0	0.0	0.4			4%
16	26.3881	0.0	0.0	0.0			
17	26.4244	0.0	0.0	0.1			
18	27.7047	0.0	0.0	0.0			
19	27.7928	0.0	0.0	0.1			
20	28.1796	0.0	0.0	0.0			
21	28.3932	0.0	0.0	0.0			
22	28.4316	0.0	0.0	0.0			
23	32.0233	0.0	0.0	1.2			11%
24	32.4859	0.0	0.1	0.0			
25	33.0557	0.0	0.0	3.6			32%



Mode 1 (7Hz)



Mode 3 (9Hz)

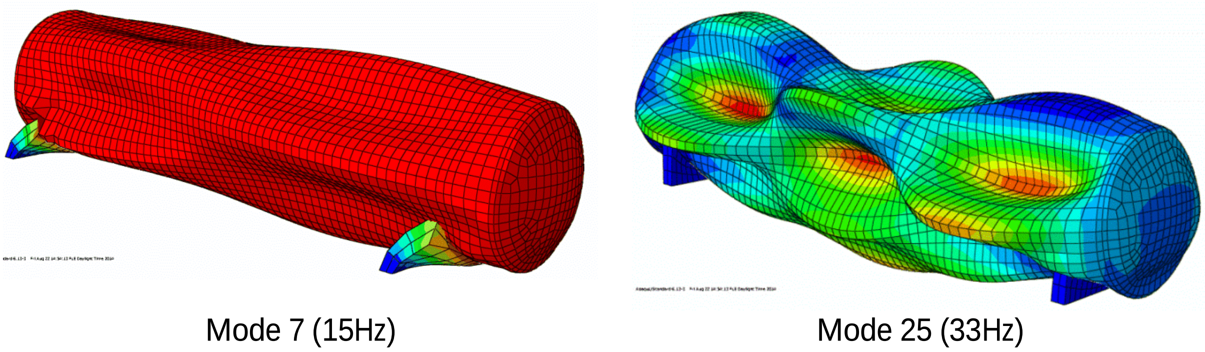


Figure 6. Mode shapes of significant modes (full reservoir)

4.2 Simplified model

A two-degree of freedom model has been developed to provide simplified results for the vibration response of the day-tank. The model was based on considerations of EN 1998-4[21], but also several other design recommendations [18], [19], [20].

Since methods dedicated to horizontal cylindrical tanks are rare, and *EN 1998-4, Annex A, ChapterA5-Horizontal cylindrical tanks on-ground* accepts the simplification of the cylindrical tank as an equivalent rectangular one. The equivalency is achieved so that the liquid depth is preserved and the width of the rectangular tank is so that the liquid quantity is preserved. This leads to the configuration presented in Figure 7, in the transversal and longitudinal directions.

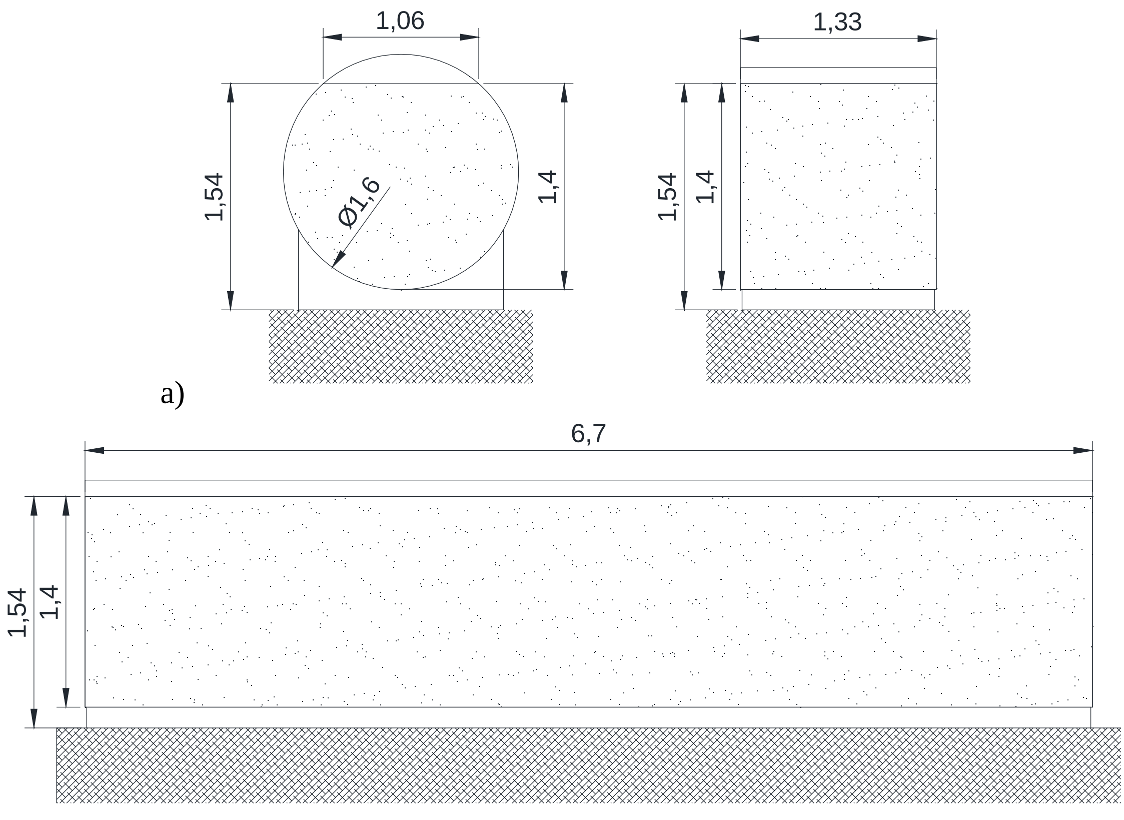


Figure 7. Dimensions of the circular and rectangular equivalent tank (to EN1998-4. A5)

The liquid mass can be divided into impulsive (m_1) and convective (m_{c1}) components. In the transversal direction, having a ration H/R=1.4/(0.5*1.33)=2.11>1.6 (EN1998-4, A5), the tank could be considered completely filled and only impulsive mass used. For the purpose of this study we still distinguish the sloshing/convective component. As it will be seen later, this component is very small. In the longitudinal direction H/R=1.4/(0.5*6.7)=0.41.

EN1998-4, Chapter A6 provides indications how to calculate the impulsive and convective components of the mass. The m_i/m and m_c/m ratios can be determined form the graphs from Figure 8

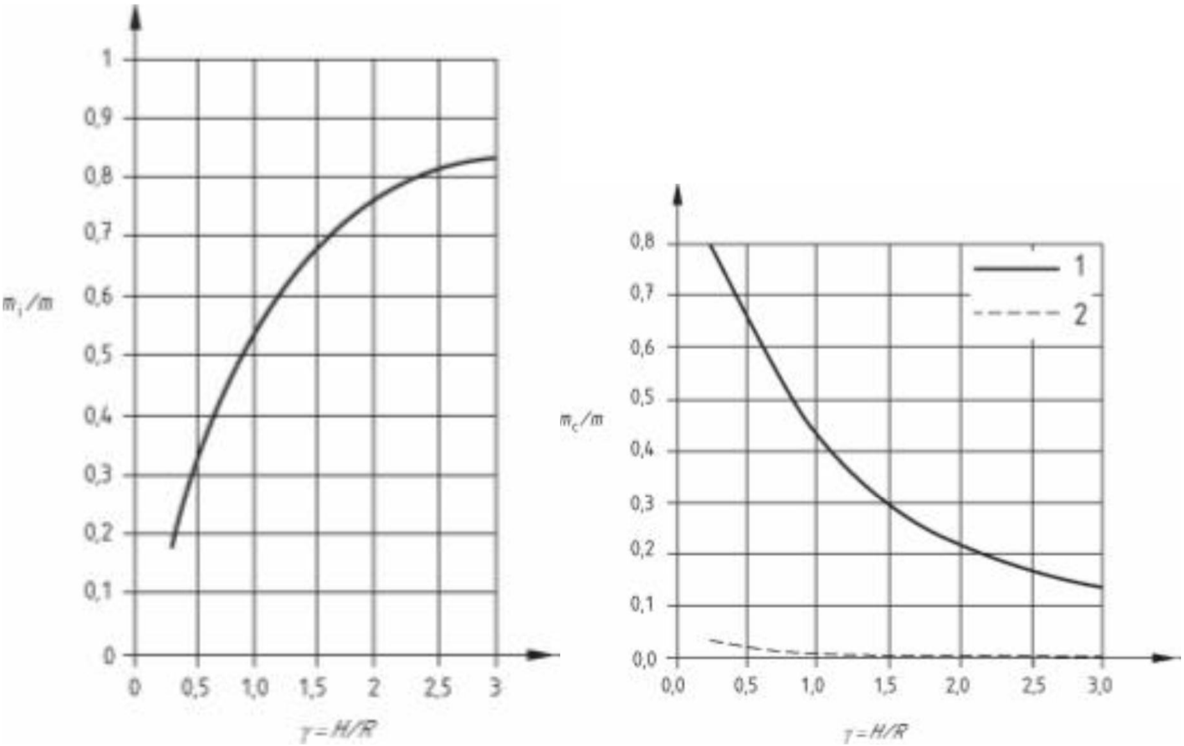


Figure 8. Ratios of impulsive and convective mass as function of H/R ratio in circular tanks. H – is liquid height, R – radius of the tank. In case of rectangular tanks the formulas are adapted by considering R=L/2, where L is the half-width of the tank in the direction of the seismic action (see EN1998-4, Eq. A.44)

Likewise, conventional height ratios where the impulsive (h_i/H) and convective masses (h_c/H)are applied can be found form similar charts (Figure 9).

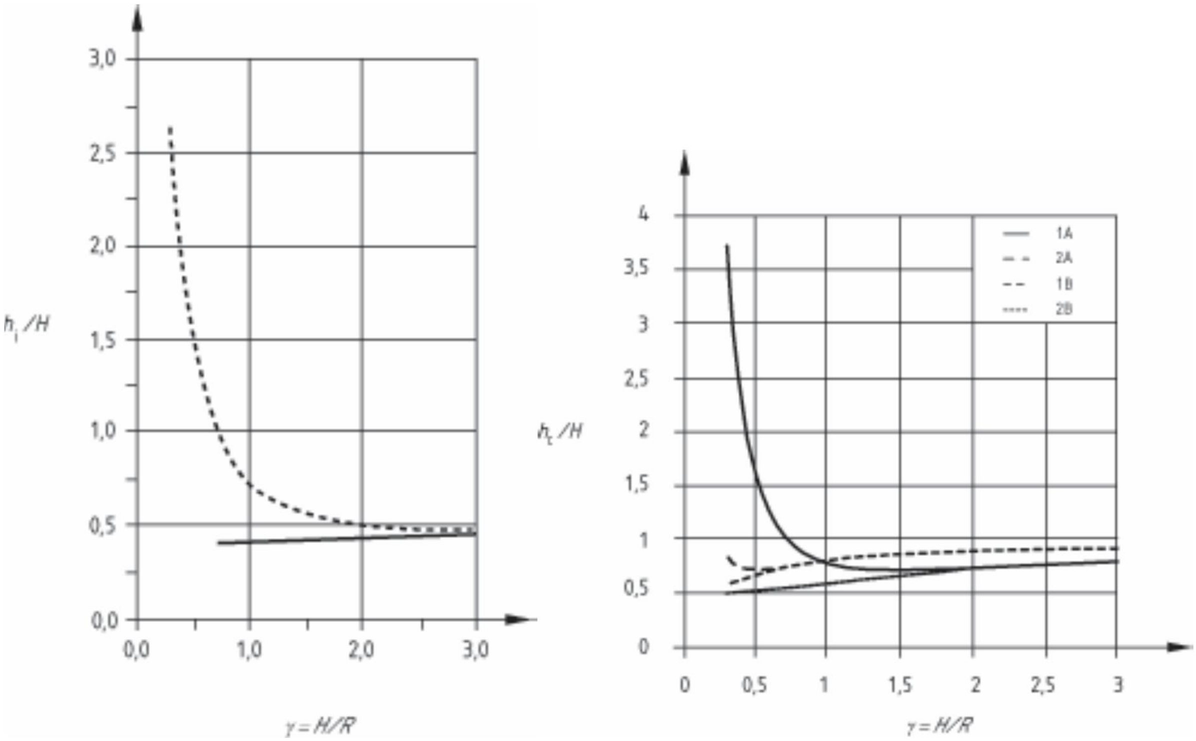


Figure 9. Ratios of impulsive and convective mass-heights for H/R ratios of circular tanks. H – is liquid height, R – radius of the tank. In case of rectangular tanks the formulas are adapted by considering R=L/2, where L is the half-width of the tank in the direction of the seismic action (see EN1998-4, Eq. A.44)

EN 1998-4, Chapter A6 also provides a methodology to calculate the stiffness of the spring connecting the convective mass to the walls of the tank (K_c). This stiffness together with the convective mass itself (m_c) defined the frequency of the first sloshing mode. The impulsive mass is connected rigidly. It is also suggested that the mass of the tank (Δm) needs to be cumulated with the impulsive mass.

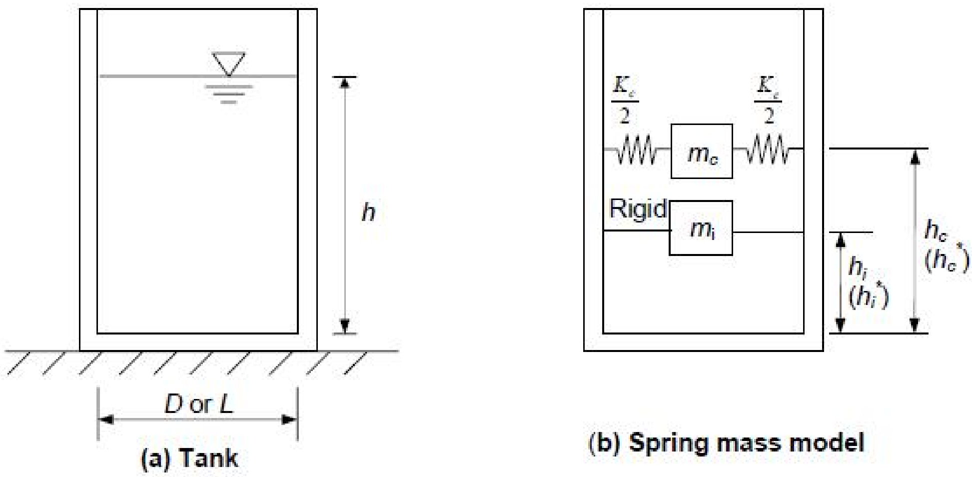


Figure 10. Schematic representation of the two-degree of freedom (2-DOF) modeling of the liquid filled tank

The parameters of the 2-DOF model have been calculated using EN1998-4 [21] and IITK's guidelines for seismic design of liquid storage tanks [20] as alternatives. The outcome of the estimates in transversal and longitudinal direction are given in Figure 11. It can be observed that the resulting estimated are very close to each other, but for the modeling the EN1998-4 estimates will be used.

a)

EN 1998-4		
Longitudinal direction		
L	6.7	m
D	1.6	m
H_liquid	1.4	m
m_liquid	11.39	t
g	9.81	m/s2
γ=H/R	0.41791	
mi	2.84	t
hi	0.56	m
mc1	8.55	t
hc1	0.75	m
λ1	1.841	
ωc1	1.87	rot/s
Tc1	3.37	s
Kc	29.81	kN/m

b)

EN 1998-4		
Transversal direction		
L	1.33	m
H_liquid	1.4	m
m_liquid	11.39	t
g	9.81	m/s2
γ=H/R	2.11	
mi	8.80	t
hi	0.63	m
mc	2.59	t
hc	1.06	m
λ1	1.841	
ωc1	5.21	rot/s
Tc1	1.21	s
Kc	70.19	kN/m

c)

IITK Guidelines		
Longitudinal direction		
L	6.7	m
D	1.6	m
H_liquid	1.4	m
m_liquid	11.39	t
g	9.81	m/s2
h/L	0.21	
mi	2.75	t
hi	0.53	m
mc	8.33	t
hc	0.72	m
Kc	22.25	kN/m

d)

IITK Guidelines		
Transversal direction		
L	1.33	m
H_liquid	1.4	m
m_liquid	11.39	t
g	9.81	m/s2
h/L	1.05	
mi	9.37	t
hi	0.41	m
mc	2.85	t
hc	1.01	m
Kc	66.14	kN/m

Figure 11. 2-DOF parameters of the liquid tank according to the EN1998-4 (a, b) and IITK's guide (c, d)

To the values presented in Figure 11, we added the mass of the tank (1.61 tons) and estimated separately the flexibility of the tank walls. In order to estimate this flexibility we used the 3D FEM model of the tank. Uniform load was applied to the walls in the direction of the applied loads (transversal and horizontal). The deformation was read at the vertical center-line of the tank wall, at the height of the impulsive mass (h_i). The stiffness was calculated as ration between the force and the displacement. This procedure is in line with the method of taking into account the flexibility of tanks (EN1998-4, Section A.4.2). Stiffness values are given in Figure 12.

a)

Bending stiffness (longitudinal loads)		
Hi	0.70	m
Deflection	0.002317	m
Force	296	kN
K	127751	kN/m

b)

Bending stiffness (transverse loads)		
Hi	0.77	m
Deflection	0.0518	m
Force	1302	kN
K	25135	kN/m

Figure 12. Stiffness related to the tank deformation

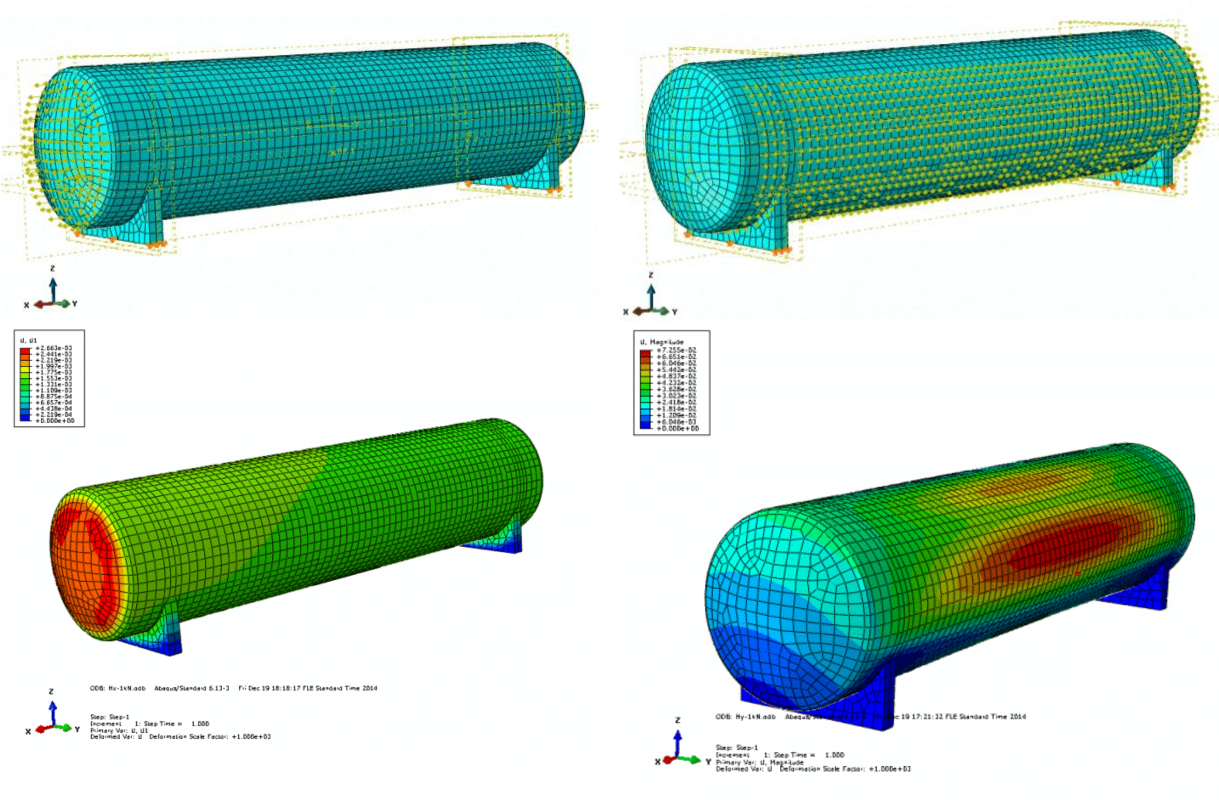
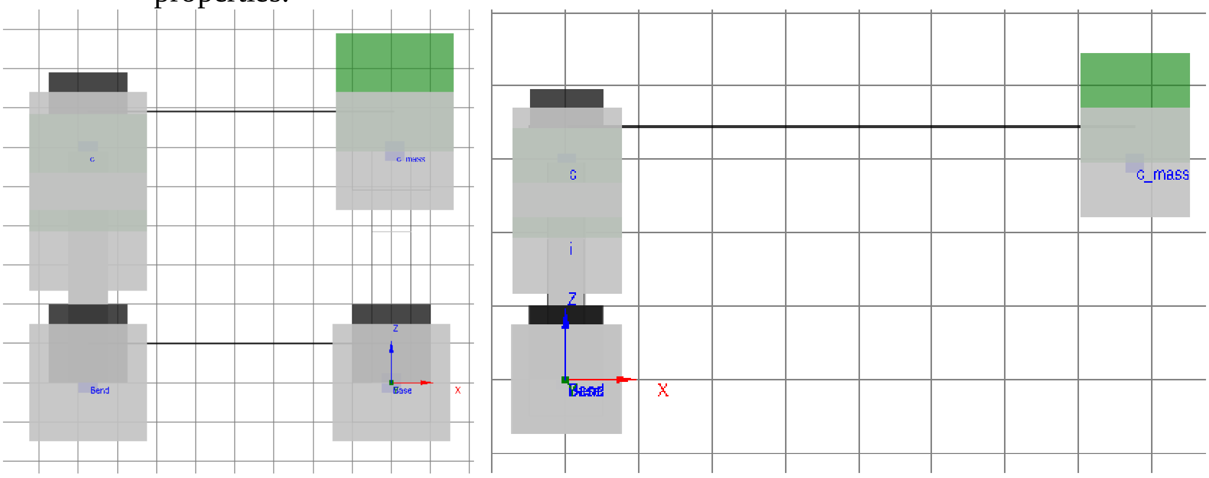
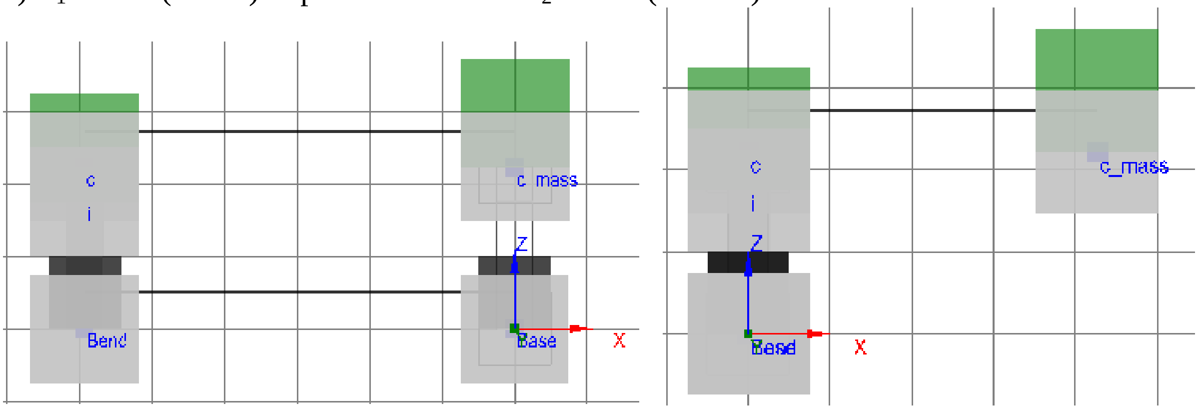


Figure 13. Loading scheme used for determining stiffness and deformed shapes of the tank under transversal and longitudinal loads

Using the above values of mass and stiffness, two 2-DOF models have been developed for the modeling of the day-tank's earthquake response. One describes the day-tank in the transverse, the other in the longitudinal direction. The modes of vibration of the two modes are given in Figure 14 and Figure 15 for mass properties.



a) T_1=0.13s (7.8Hz) impulsive T_2=1.21s (0.82Hz) convective



b) T_1=0.04s (27Hz) impulsive T_2=4.03s (0.25Hz) convective

Figure 14. Modes of vibration for the transversal/Y (a) and longitudinal/X (b) directions

a)

Mode	T(s)	f(Hz)	[Ux]
1	0.13	7.83	79.62%
2	1.21	0.83	20.38%
			100.00%

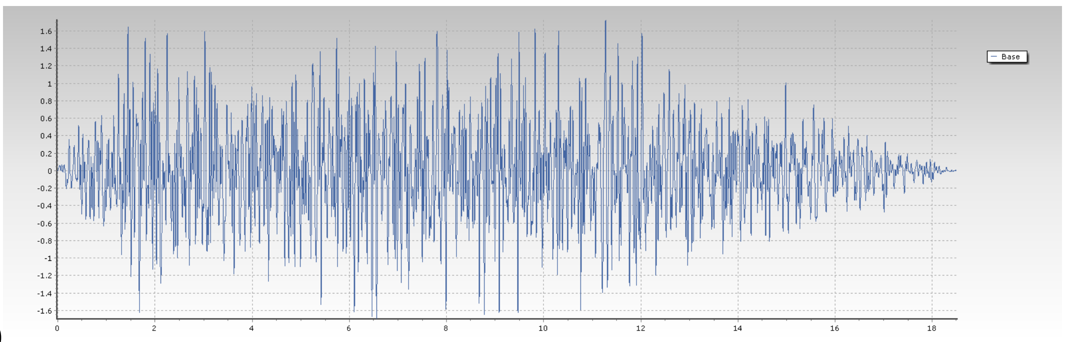
b)

Mode	Period	f(Hz)	[Ux]
1	0.04	26.97	34.22%
2	4.03	0.25	65.78%
			100.00%

Figure 15. Mass participation for the transversal/Y (a) and longitudinal/X (b) directions

The damping values considered for the convective mode was taken 0.5% of the critical. The damping in the impulsive mode was taken as 2% of the critical for steel tanks. In case of concrete tank this value could go up to 5% of the critical [20].

With the two models we can carry out decoupled time-history analysis of the day-tank in the two horizontal directions (X and Y). For the purpose, the accelerograms presented in Figure 3 were used as input. The modeling was carried out in SeimoStruct [22].


a)

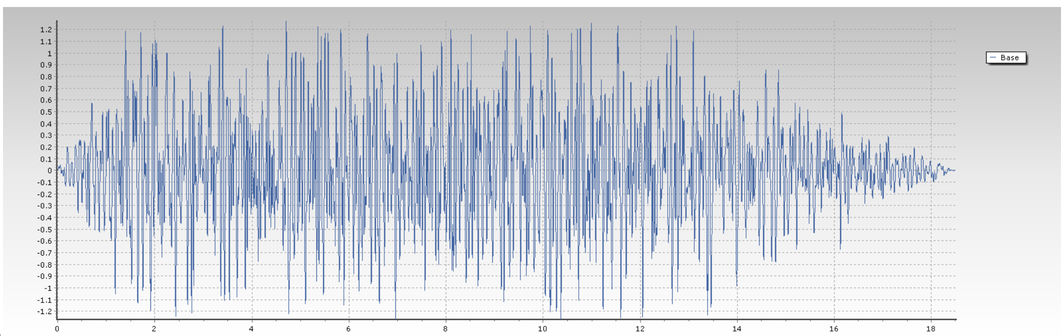
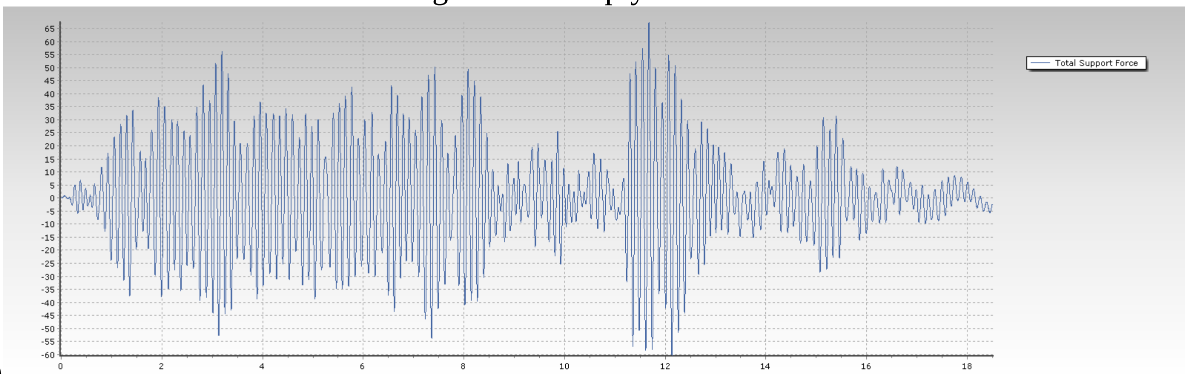
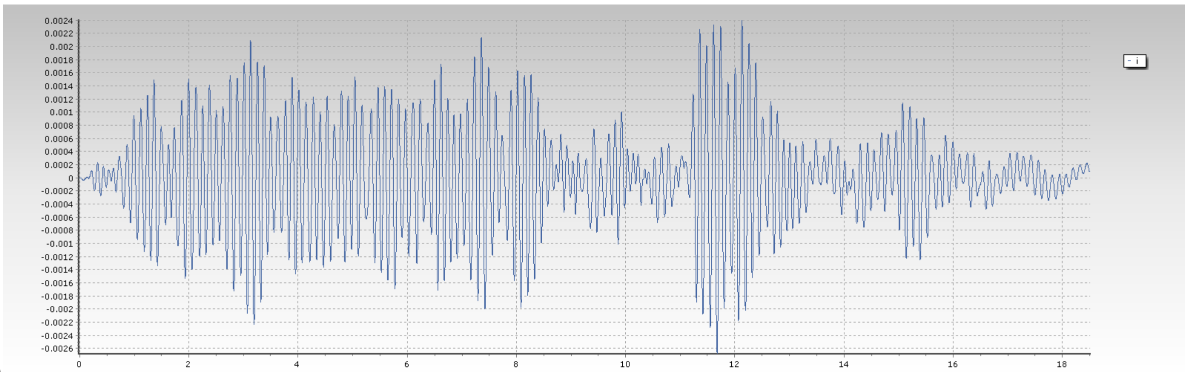

b)

Figure 16. Acceleration signals collected at the base of the 2-DOF models in order to confirm the correctness of the base loading (a) transversal/Y and (b) longitudinal/X directions. Y direction ACC~1.7m/s^2 and X direction ACC~1.3m/s^2.

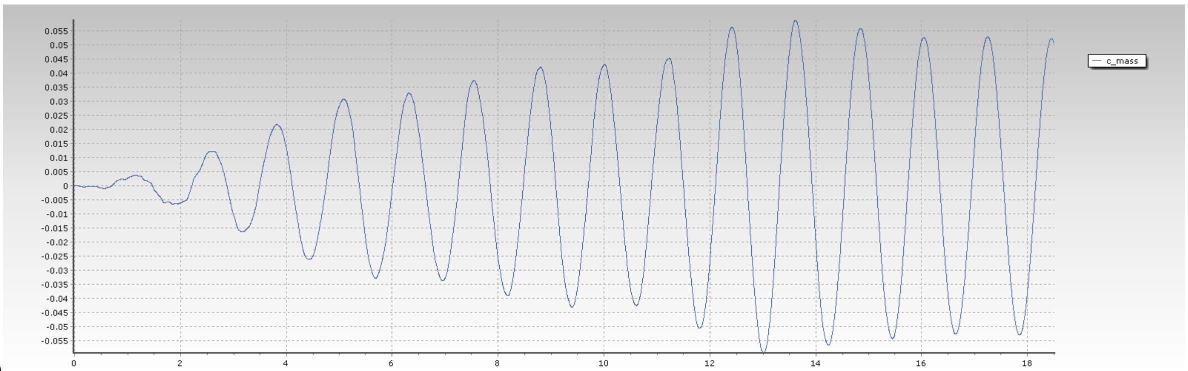
The reported outputs from the two models are the base forces, the relative to base displacements of the impulsive and convective mass, and the accelerations of the impulsive mass. It should be remembered that impulsive mass moves together with the structure of the tank, hence impulsive mass motion generated stresses in the tank. However, the convective mass describes sloshing motion of the liquid, so movement in sloshing does not imply deformation of the tank walls.



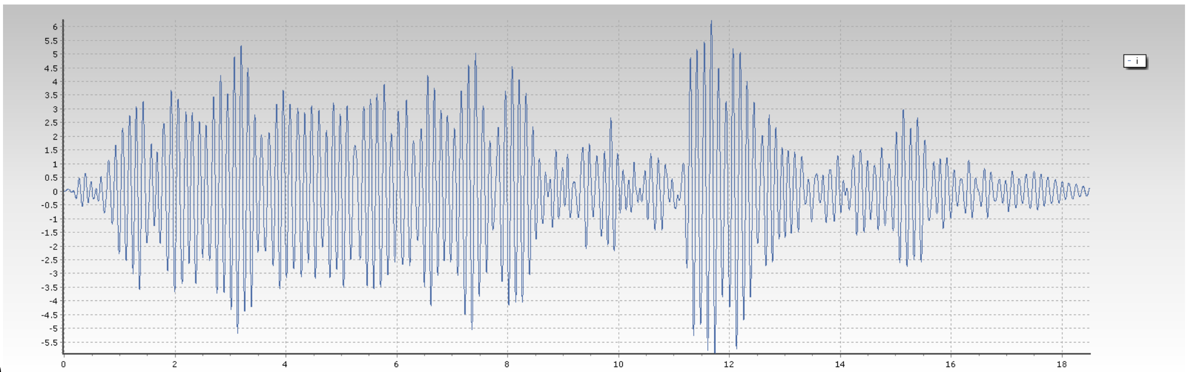
a)



b)

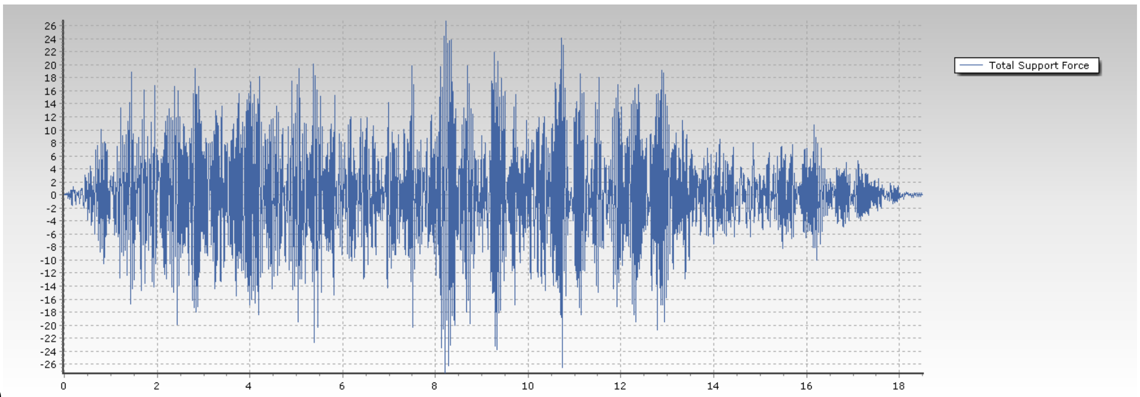


c)

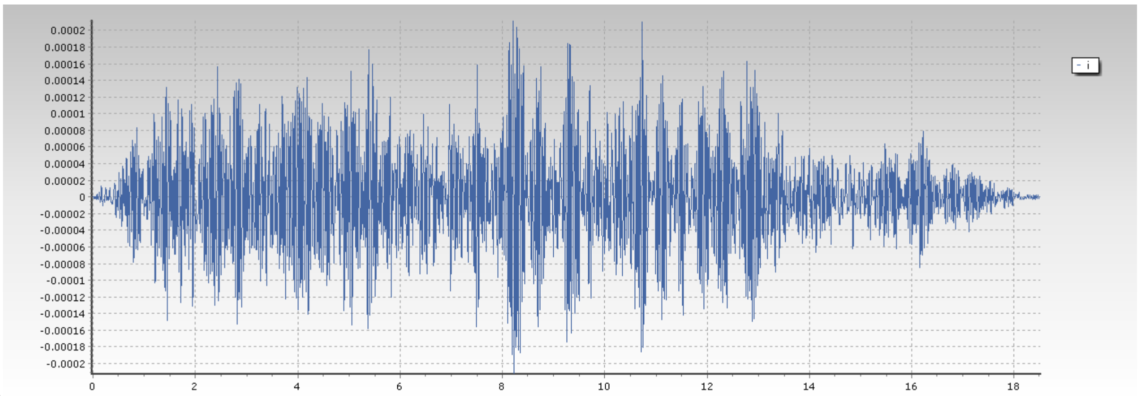


d)

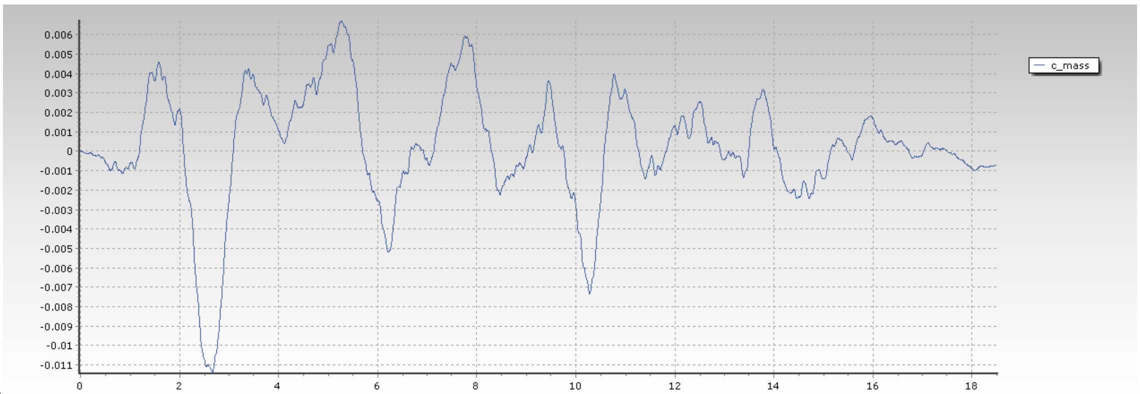
Figure 17. Transverse direction output. (a) base force with peak of about 65kN; (b) impulsive mass movement of ~26mm; (c) sloshing of the liquid with a very low damping and (d) accelerations of the impulsive mass of ~6m/s^2. Hence, 6/1.7=3.53 amplification of the accelerations from the base of the day-tank.



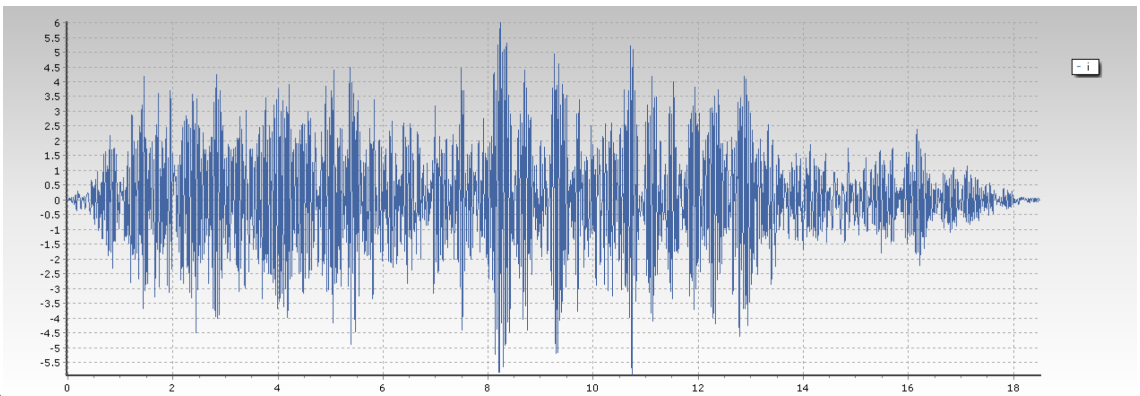
a)



b)



c)



d)

Figure 18. Longitudinal direction output. (a) base force with peak of ~31kN; (b) impulsive mass movement of ~0.25mm; (c) sloshing of the liquid and (d) accelerations of the impulsive

mass of ~7m/s^2. Hence, 6/1.27=4.72 amplification of the accelerations from the base of the tank.

4.3 FE models for liquid interaction

Two modelling techniques were used to model the liquid-solid interaction of the tank. First, coupled Lagrangian and Eulerian modelling technique was employed. General deformation plots resulted reasonable, but we were unable to stabilize the energy balance of the model in the later stages of the modelling. The second modelling technique was based on Smoothed Particle Hydrodynamics and resulted in more stable models.

4.3.1 Coupled Lagrangian and Eulerian model

Coupled Lagrangian and Eulerian modelling techniques were employed in the simulation of the fuel sloshing in the day tank, due to a seismic excitation. Lagrangian domain is a classical finite element (FE) method where an element mesh describes deformation under a load. In Eulerian method the mesh is un-deformable but a single element could be occupied by a material. If fraction of the material occupancy in the element is 1.0 then this element full of material. In contrast, 0.0 fraction of the material occupancy implies void in the element.

As a first step, all ladders and the fuel inlet and outlet etc. were removed in order to simplify the FE model. The body and the legs of the day tank were modelled with shell elements (Figure 19). The material of the day tank was isotropic steel.

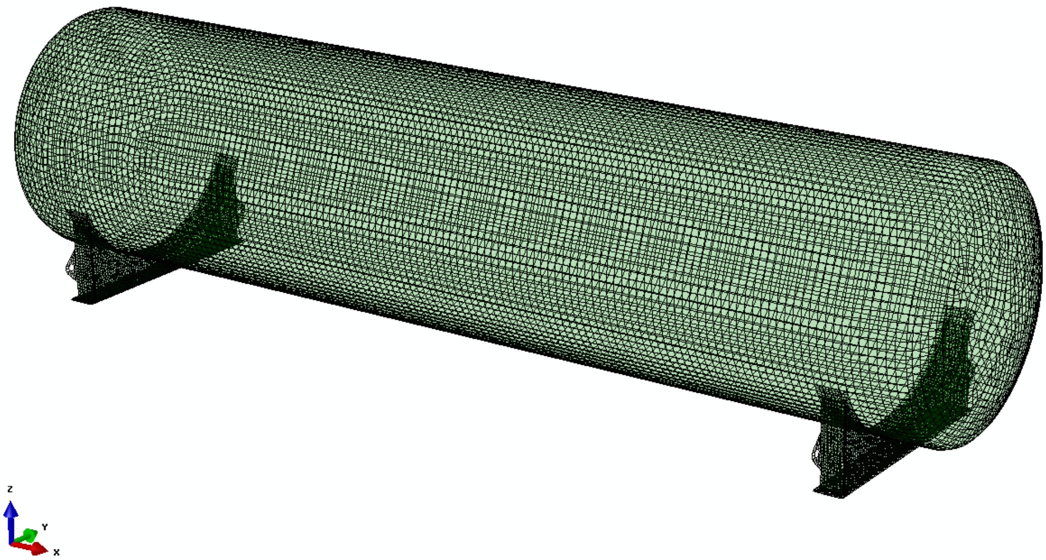


Figure 19. Lagrangian part of the day tank model

In the second stage, the Lagrangian model was embedded into Eulerian model (Figure 20). The diesel fuel was modelled with Eulerian domain. Rough contact was used between fuel and tank wall with option for no slipping. The fuel was modeled with 8 node linear brick element.

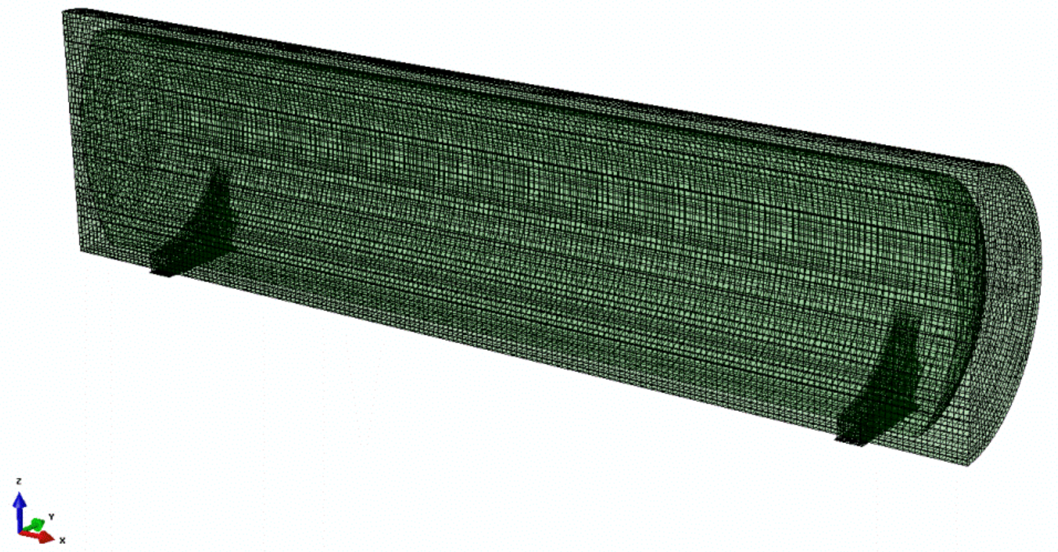
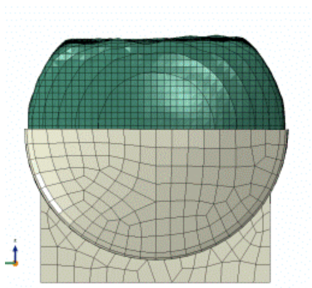
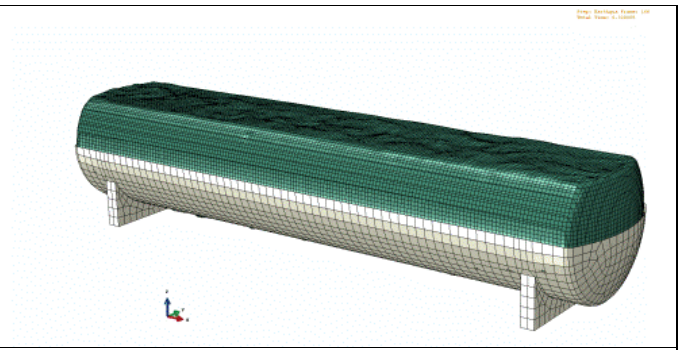
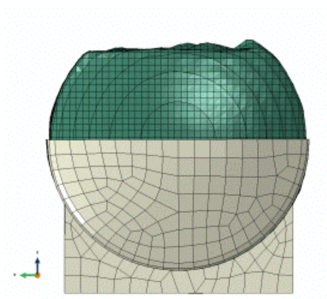
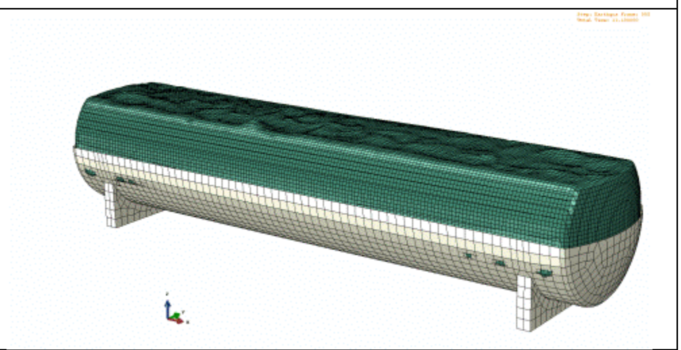


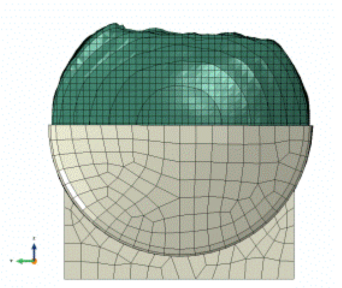
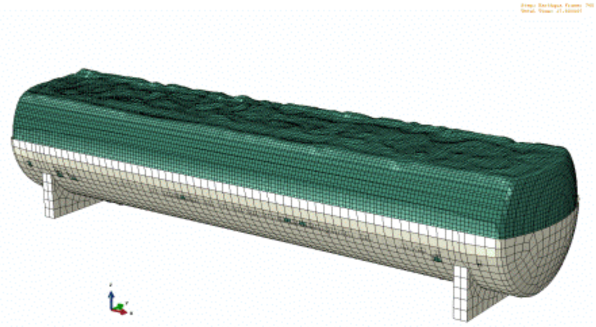
Figure 20. Lagrangian day tank model embedded in the Eulerian domain

The simulation was divided in two steps. In the first step gravity was applied in 3 second time span, and in the second step the earthquake acceleration signal was applied in 20s time span.

In Step 1 the liquid (diesel fuel) is materialized and gravity is applied in a 3 seconds timeframe. As the reservoir is filled 90%, and as consequence of the sudden appearance of gravitational forces the diesel drops to the bottom of the reservoir in the 3 seconds. The open surface of the liquid is formed, and as consequence of the raining” of droplets, some waving can be observed.

Table 8. Sloshing of the diesel in the tank at different time steps of the seismic action

	
Time: 3.32 s	Time: 3.32 s
	
Time: 10.10 s	Time: 10.10 s

	
Time: 14.80 s	Time: 14.80 s

The seismic shaking is generating an increasing sloshing in the tank up until t=14.8s (Table 8). The sloshing is stronger in the transversal (Y) direction of the tank. This can be explained by the larger flexibility of the tank in this direction. But, a distinct longitudinal component of the sloshing is also present.

Primary data extraction revealed problems with the energy balance of the model (Figure 21). Repeated attempt of stabilizing the model failed because of the complex geometry caused leakage of the fuel at the end of the tank. The model has two type of external kinetic energy source: 1) gravity and 2) seismic acceleration. In Figure 21 a sudden impulse in the kinetic energy is clearly visible. The plausible explanation for these impulses is not sloshing or wall pressure due to movement of the fuel inside the tank. The feasible explanation could be that at the occurrence of impulse in the kinetic energy plot the material is leaking out. This would lead emerge of void inside the tank causing sudden release of the potential energy stored into springs which are used to model the contact between fuel and tank walls. As a consequence the remaining fuel inside the tank would be under an artificial impulsive loading.

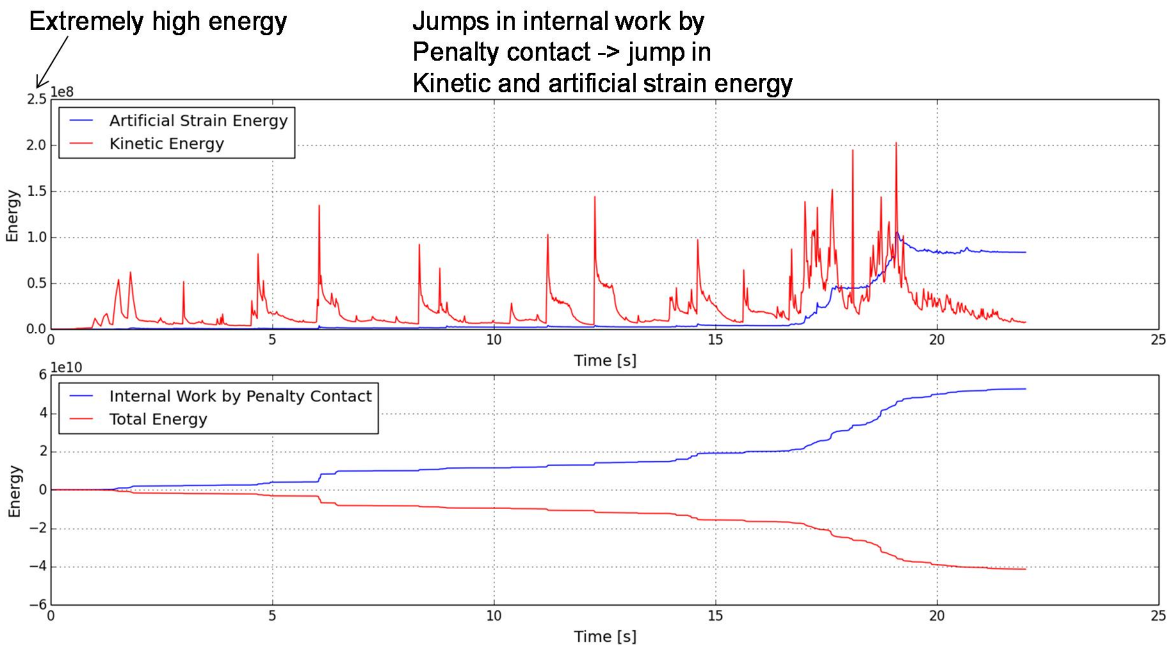


Figure 21. Energies of the coupled Eulerian-Lagrangian model

In Abaqus Eulerian element is fully occupied by the fuel when material fraction is one whereas zero indicates lack of material (Figure 22). Simulia has applied a material outflow property to Abaqus. It takes place when less than 0.5 of material fraction is void. In addition, Eulerian element type is always rectangular prick. The leakage problem takes place when double curvature shell element is embedded inside rectangular prick element. Thus, it is difficult or impossible create a mesh where material fraction is always more than 0.5.

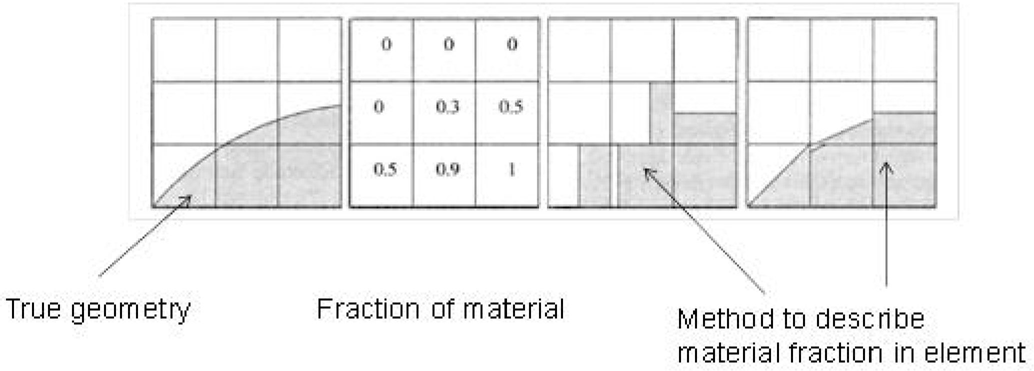


Figure 22 Description of material in Eulerian element

It should emphasize that our Eulerian elements was filled with diesel, void or both. It is clear that this procedure does not provide good solution in terms of energy plots as shown in Figure 21. However, there is still one untested option. It is worth of try to replace void by an ambient air. By doing so, all Eulerian elements are filled with material which can prevent leakage.

4.3.1 Smoothed Particle Hydrodynamics (SPH) model

The steel part of the day-tank is modelled with shell element as in the previous case. However, fuel is initially modeled with tetrahedral elements C3D4 with four nodes which are transformed in the initial step of the simulation into small spherical particles (Figure 23, Figure 24 and Table 2). Thus each node is transformed to a particle. This modeling includes inertia and mass effects. Abaqus uses kernel function to describe relationship between neighboring particles. Once observed particle moves in arbitrary direction it has a certain influence to the behavior of neighboring particles which are covered by the kernel function. If any of the particles is completely outside of influence volume of a kernel function it is treated as a free body. Thus, SPH is not similar to a traditional discrete element method (DEM) in which all particles can be treated as free bodies. Alternatively, one can define cohesion between particles in DEM. However, this is not required in SPH. As a conclusion SPH is a fully Lagrangian method in which element nodes are replaced with particles which can undergo huge deformation without worries of the element distortion.

The material model of diesel fuel was identic with the one used in couple Eulerian-Lagrangian simulation.

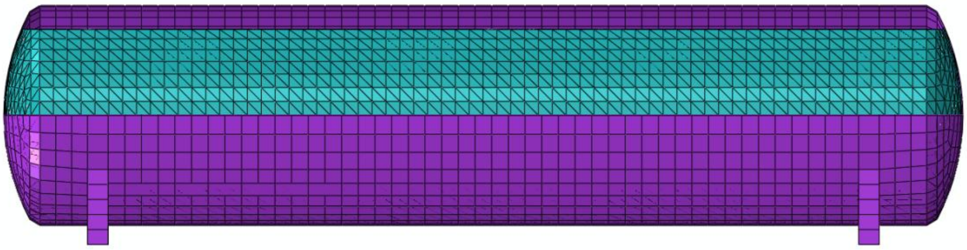


Figure 23 Inital state before fuel mesh is transformed to SPH particles

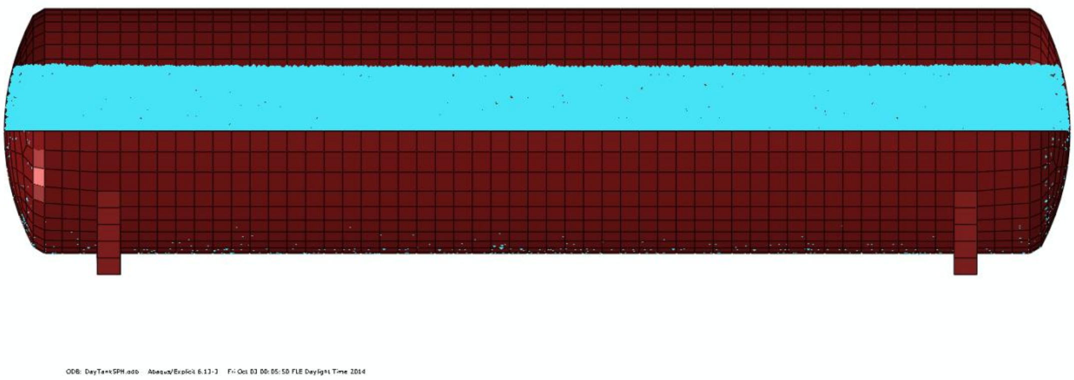


Figure 24. Cut-view of the SPH model, with the spherical particles modeling the liquid in blue

Using the above model, the response of the day-tank has been calculated for simultaneous shaking of the three base accelerograms (Figure 3). The total base forces in the three directions are reported in Figure 25. The maximum value in longitudinal direction is 14kN whereas in transversal direction the maximum is 24kN. Most of the forces in vertical direction are result of the mass of the tank and diesel. The power density spectrum (PSD) plot of the base shear force signals reveal that longitudinal direction strongest contribution is above 20Hz whereas transversal and vertical direction has strongest contribution approximately at 17Hz.

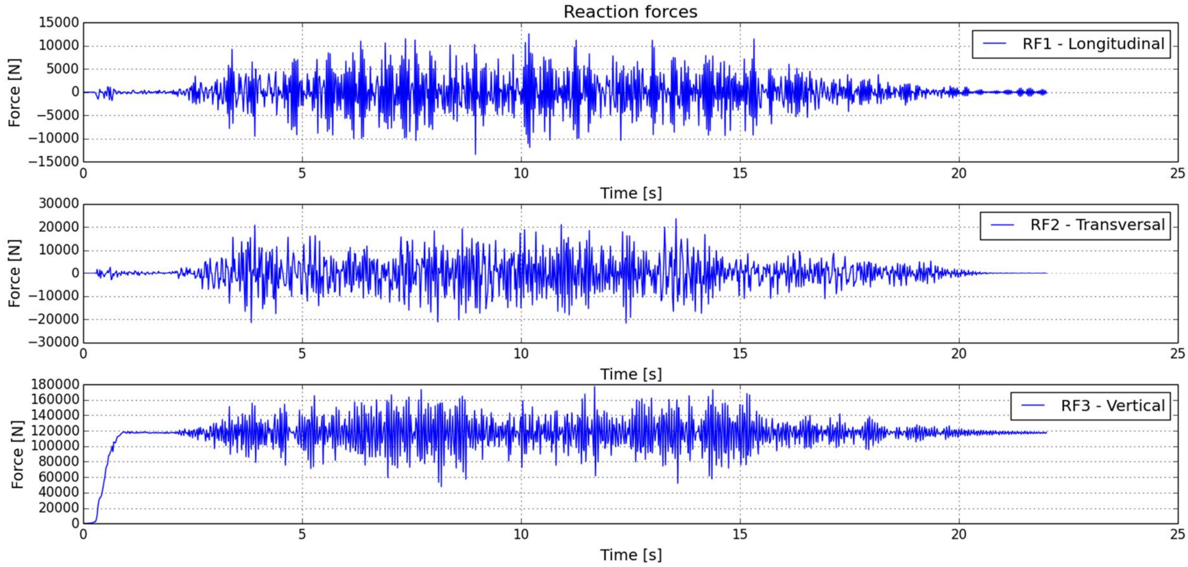


Figure 25. Base forces of the SPH model. Longitudinal/X, transversal/Y and vertical/Z directions peaks due to earthquake acceleration are ~17kN, 25kN and 7kN. The weight of the tank and liquid is stabilized in the first part of the modeling at about 12kN.

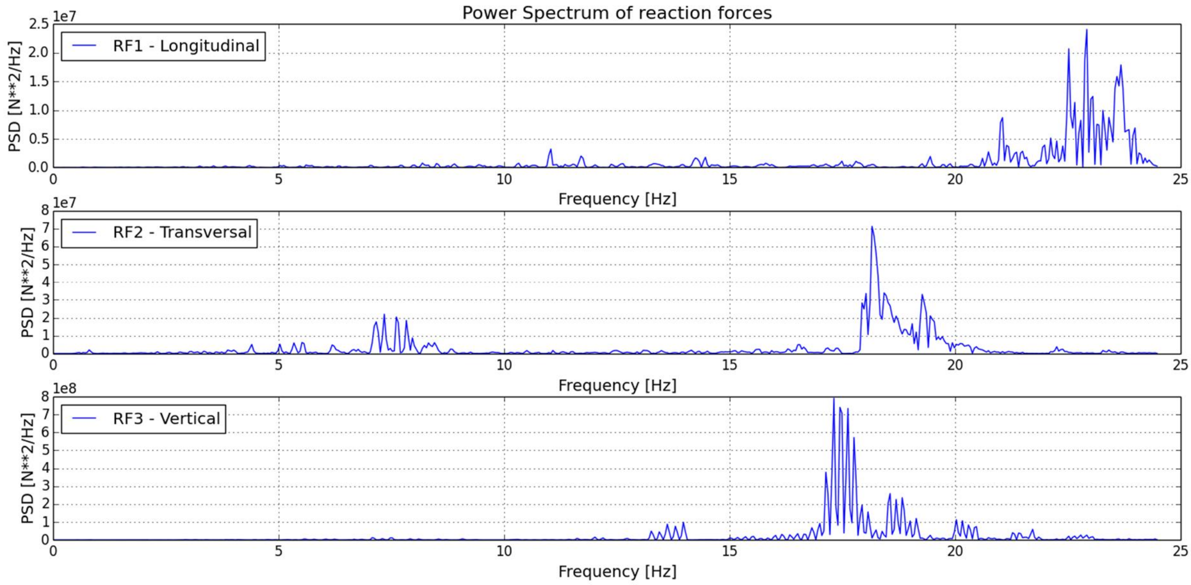


Figure 26. FFT of the base forces signals in Longitudinal/X, transversal/Y and vertical/Z directions.

The accelerograms corresponding to the nodes 380 and 632 (Figure 27) are reported in Figure 28 and Figure 29. The quality of the simulation is shown in Figure 30. In general, it is important minimize the artificial strain energy whereas kinetic energy should be interpret in a light of the external kinetic energy sources. It is clearly visible that the artificial strain energy is always lower than the kinetic energy which is a prerequisite for a stable the simulation. On the other hand the kinetic energy has a high peak at the beginning of the simulation. This indicates situation where the particles are settling due to gravity. It is much larger than exciting base acceleration. After two seconds the base acceleration begins control the kinetic energy which was our purpose.

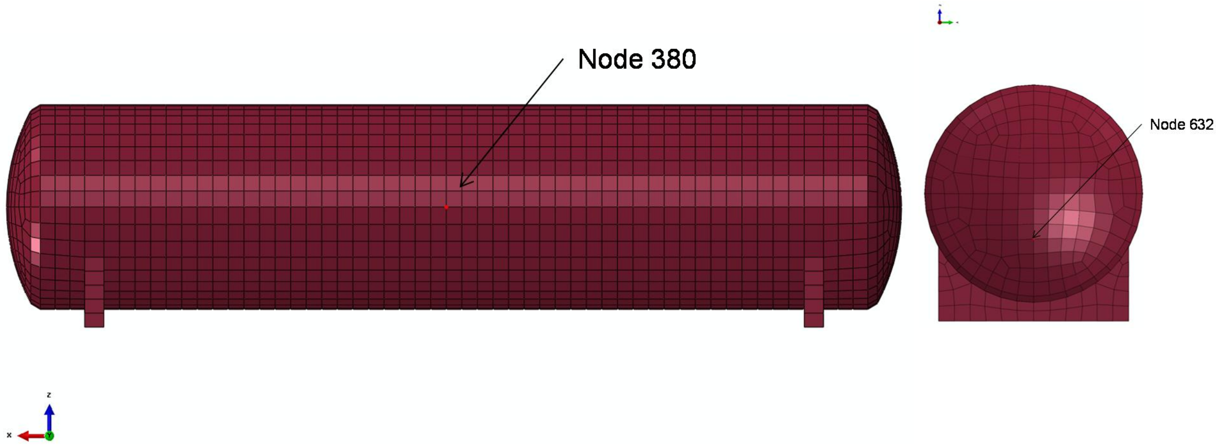


Figure 27. Position of Node 380 and 632 corresponding to the locations of the "low level sensor" and "drain valve". Both these two components need seismic review in order to ensure functionality of the tank during and after earthquake (Table 1).

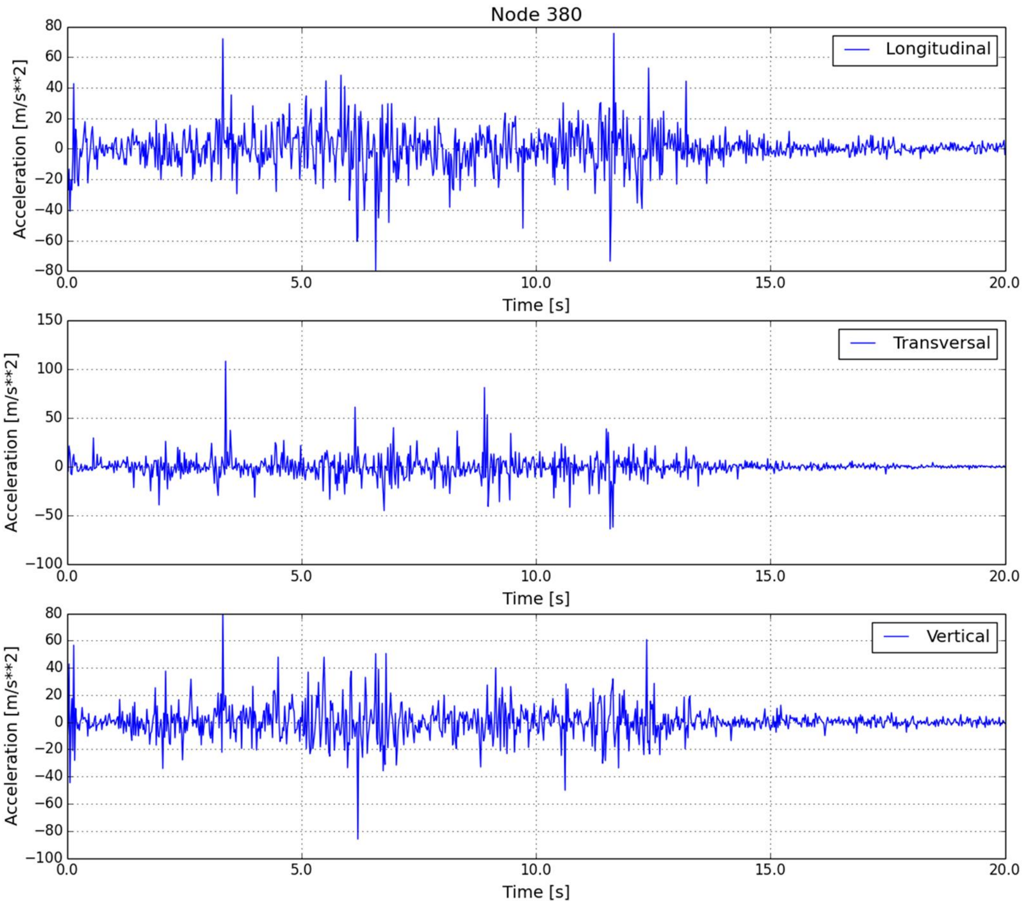


Figure 28 Acceleration signals in Node 380

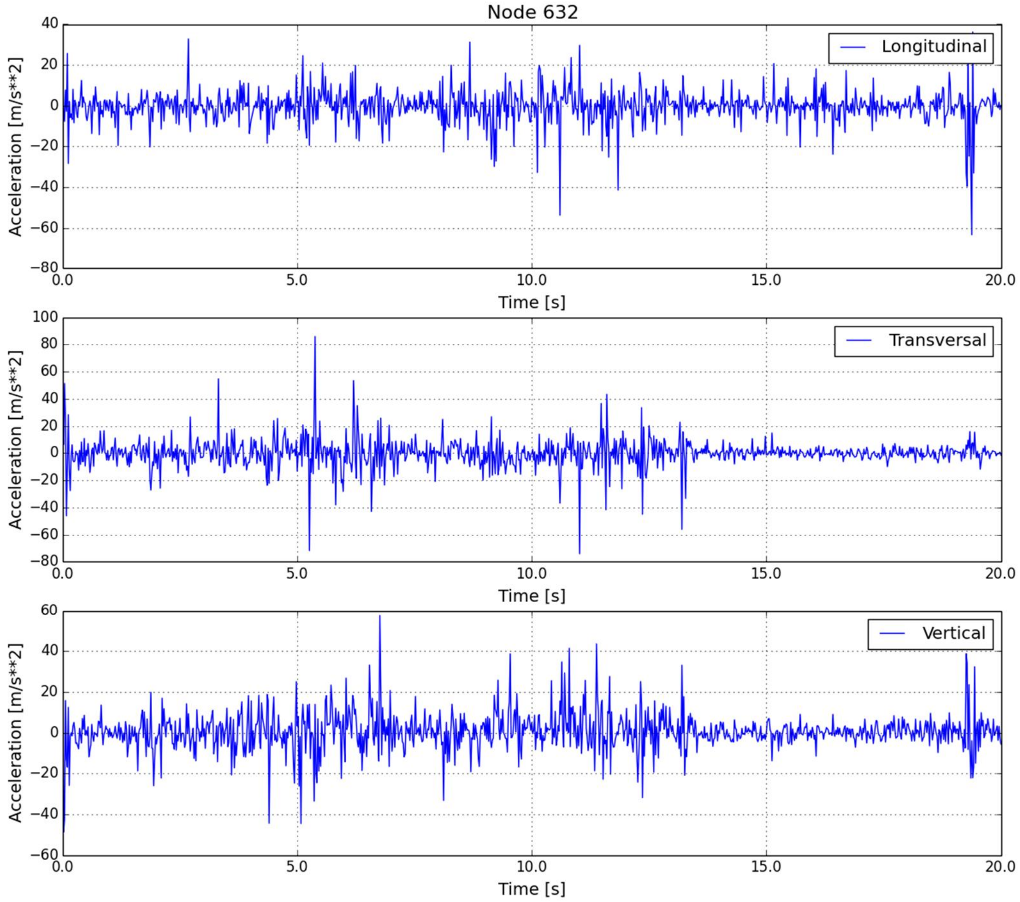


Figure 29 Acceleration signals in Node 632

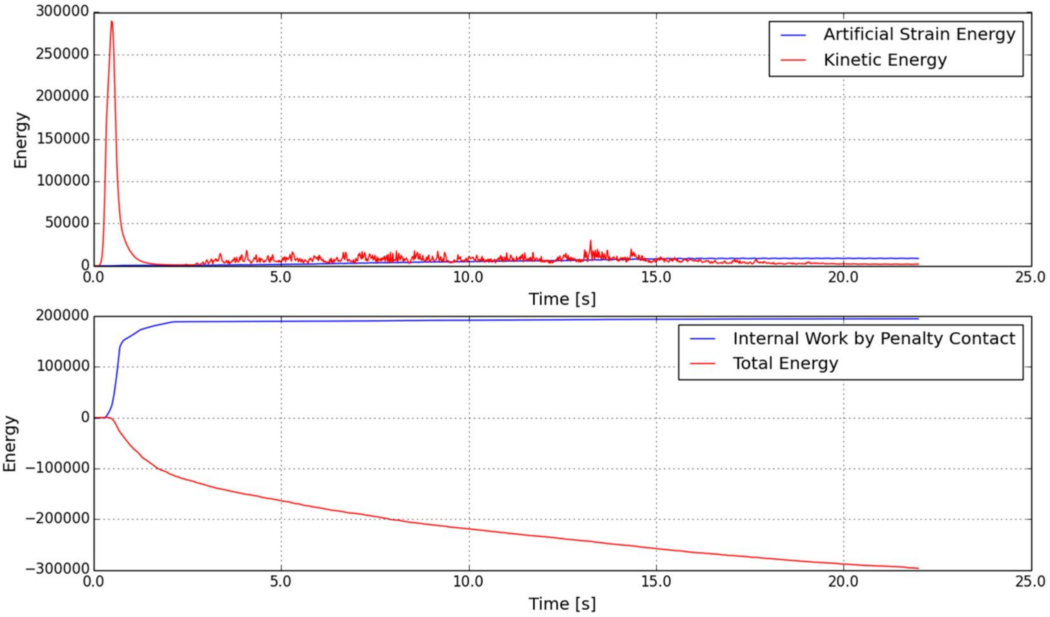


Figure 30 Energy plots

4.4 Qualification plan for the sub-components

For sub-components located on the day-tank (Table 1) there are two ways of qualification:

- If component are mechanical, the forces can be evaluated by including the sub-component within the FEM based day-tank. This has not ben done for most of the sub-components listed in Table 1, because the presence of small elements would complicate the FEM model too much. The different mesh sizes required for the reservoir and e.g. outlet pipe would unnecessarily increases the number of finite elements in the global model. Also, as it has been shown before, the FE models used here turned out un-conservative response estimates.
- The second option of modeling mechanical components is to do a separate detailed model and use the accelerations measured on the reservoir as base input for the detailed model. The most suited acceleration inputs from this study would be the acceleration signal corresponding to the impulsive mass in the 2-DOF model (Figure 17.d and Figure 18.d).
- If the component is non-mechanical, and certain functionality needs to be ensured, a realistic option for the qualification is testing. This applies for the “Low level sensor/switch” form Table 1. In this case the input should also be accelerations collected form the location of the equipment. In this case te recommended acceleration input would be corresponding to the impulsive mass in the 2-DOF model (Figure 17.d and Figure 18.d).

5 Conclusions

The following conclusions can be drawn from this study:

- FE modeling of the liquid interaction with the day-tank is a challenging task, requiring constant checking using simplified models;
- The two simplified models used here, the one cased on the IITK recommendation and EN1998-4, show remarkable similarity in assessing the impulsive and convective components of the liquid motion;
- Given the shape of the design floor spectra (Figure 2) and the prevailing frequencies of vibration in the impulsive and convective modes (Figure 11), it is clear that the main source of base force for the 2-DOF simplified model is resulting from the impulsive mode of vibration. This is true even in the longitudinal direction, where 65% of the mass is assigned to the convective mode. The spectral ordinate is much smaller at 0.25Hz corresponding to the convective mode (0.05*g), compared to the 27Hz corresponding to the impulsive mode (0.6*g), that the mass difference is compensated. For this reason, the impulsive mass (m_i in Figure 11) and of the impulsive mass stiffness (K in Figure 12) are the strongest drivers of the performance of the simplified 2-DOF model.
- The main vibration characteristics of the day-tank system in the horizontal direction are identified with all models. In the transversal direction, the significant modes predicted are 6.8Hz (Table 7) with the concentrated mass model, 7.8Hz with the 2-DOF model (Figure 14) and 7-8.5Hz from

the SPH model (Figure 26). In the longitudinal direction we have 15Hz (Table 7), 27Hz (Figure 14) and 23-24Hz (Figure 26). The transverse direction peak at 17-19Hz in the SPH model remains unexplained.

- In the vertical direction the vibration modes are less well understood, since the concentrated masses would predict 33Hz significant mode (Table 7) while the SPH model has a distinctive peak already at 17Hz (Figure 26).
- The 2-DOF system provides a more conservative estimate of the base forces compared to the SPH models. In the longitudinal direction the base force are 31kN and 14kN respectively. In the transverse direction we obtain 65kN and 24kN. The exact source of the conservatism was not identified. It appears that the SPH model has higher damping compared to the 2% used for the 2-DOF model; as shown by the faster attenuation of the signals in Figure 25 compared to Figure 17.a) and Figure 18.a).
- The expected amplification of accelerations from the base of the day-tank system to locations on the reservoir itself was found to be in the range of 3.5-4.7 times.
- The complex 3D FEM SPH model had the good quality solution in terms of energy plots. However, the gap in base shear forces between SPH model and simple 2-DOF system is too high. In order to use SPH model for design purposes it requires careful modelling which can be heavily time consuming.
- The complexity of SPH model makes them vulnerable to input variable sensitivity. Hence, the use of such models for design is not recommended, without calibration against simplified modeling.
- CEL modelling failed because of the leakage of diesel from the tank. The leakage was result of complex double curvature geometry. In further it can worth of try to replace void by an ambient air. By doing so, all elements are filled with a material which can prevent leakage.

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