Validation of the ALE Methodology by Comparison with the Experimental Data Obtained from a Sloshing Tank[1]

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Abstract

Arbitrary Lagrangian – Eulerian (ALE) methodology has been used in Fluid - Structure Interaction (FSI) analyses with LS-DYNA® for a variety of problems. Validation of ALE solutions by comparison with experimental data provides assurance that the solutions represent the physical world. A water tank under horizontal harmonic excitation tested by O. M. Faltinsen and O. F. Rognebakke [1] is used for validation. The experimental time histories of water surface motion are compared to those obtained from the ALE solution. Both free surface sloshing and the wave impact with the roof are analyzed and compared. The LS-DYNA analytical results match the experimental data very well. Different ALE formulations and mesh densities are explored and their respective solution times are compared. In addition, the ALE and experimental maximum wave heights are compared with the prediction by closed form solutions.

Introduction

The ALE method in LS-DYNA has been extensively used for the analysis of sloshing tanks, e.g. [3], [4], [5]. Other methods are also available, including a Lagrangian solution. The ALE method has multiple variations in terms of fluid-structure coupling and formulation that are explored in this study:

- ALE coupling: tank shares nodes with fluid
- ALE coupling: tank is defined as Constrained Lagrangian in Solid
- ALE formulation: multi-material (air is a separate material)
- ALE formulation: single material and void (air is a void space)

Each of these analysis methodologies is examined to determine the effect of the analysis option choices on the results. In addition, the effects of rigid and elastic tanks on the analysis results are examined in both ALE and Lagrangian solutions. The results of the analyses are compared to experimental results from O. M. Faltinsen and O. F. Rognebakke [1].

The experiments were conducted with a tank (Figure 1) of dimensions as follows: height H = 1.02 m, breadth L = 1.73 m, length W = 0.2 m, water depth h = 0.5 m. The prescribed harmonic motions (amplitude ε_0, period T) were applied in horizontal direction in the XZ plane. The forced oscillation period T was close to that of the fundamental mode of the fluid motion, T_0. The h/L ratio of 0.289 was close to that of the critical ratio of 0.337, under which the

[1] Some contents of this paper was presented at EMI 2015 conference [2] but have never been published in any conference proceedings or journals.

amplification of theoretical fluid response at the highest resonance period is largest [1]. The wave probe was used to measure the free surface elevation at the wall.

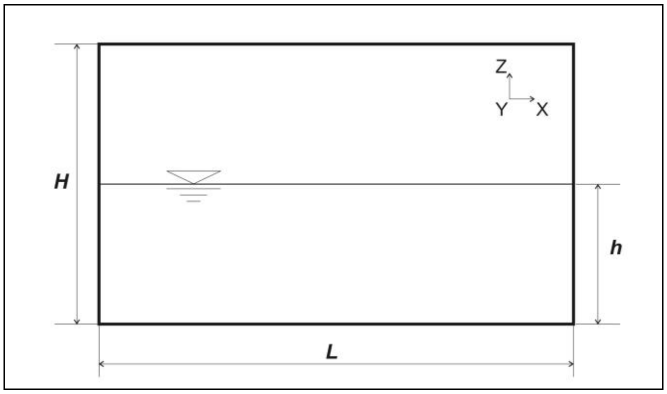

Figure 1: Tank Dimensions

The finite element meshes used in the analyses are shown in Figure 2:

- ***a*** is the basic mesh where fluid and structure share nodes (1500 3D fluid/void elements, 160 shell elements);
- ***b*** is the refined version of mesh ***a*** (6000 3D fluid/void elements, 320 shell elements);
- ***c*** is the basic mesh where the Lagrangian elements of the tank is constrained within the ALE domain (2604 3D fluid elements, 160 shell elements).

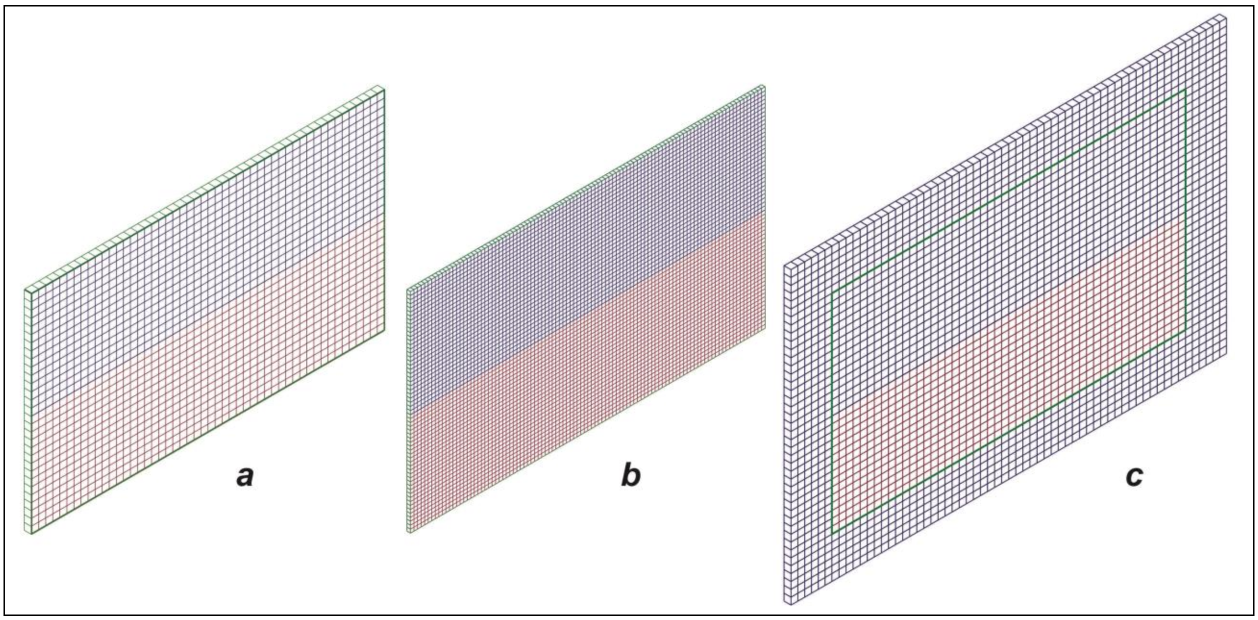

Figure 2: Finite Element Meshes

Wave Height Extraction from the ALE Results

The time histories of the wave height at the tank wall obtained from the experiments were compared with those extracted from the numerical simulations.

An automated technique was developed to calculate the wave height time history using the ALE analysis data. Using LS-PrePost®, the volume fraction of the water material, *F*, was extracted for all finite elements of the tank internal volume at each time step of the analysis. The volume fraction of the water is unity ($F = 1$) if the entire finite element is filled with water, $F = 0$ if the element is filled with air (void), and $0 < F < 1$ if only part of element volume is occupied by water. Then, an in-house code was invoked to calculate the wave height at each column of the finite elements as follows (Figure 3). The elements are analyzed from the bottom to the top. It is assumed that the free surface is located within the element below the one where $F = 0$ (the element outlined with white in Figure 3). Then, the free surface elevation, *Zw*, is calculated as

$$Zw = Zb + Hw = Zb + He \cdot F,$$

where *Zb* is the bottom elevation of the selected element, *Hw* is the free surface distance from the bottom of the selected element, *He* is the selected element vertical dimension. The wave height is the vertical displacement of the water free surface from its static position.

After some calibration, it was assumed that at each time step the analytical upward free surface movement (wave height) at the tank wall is calculated as the maximum of the first 7 finite elements (24.2 cm) adjacent to the wall (see the wave height calculation area in Figure 3). The downward free surface movement (trough depth) was calculated as the minimum of the same 7 elements.

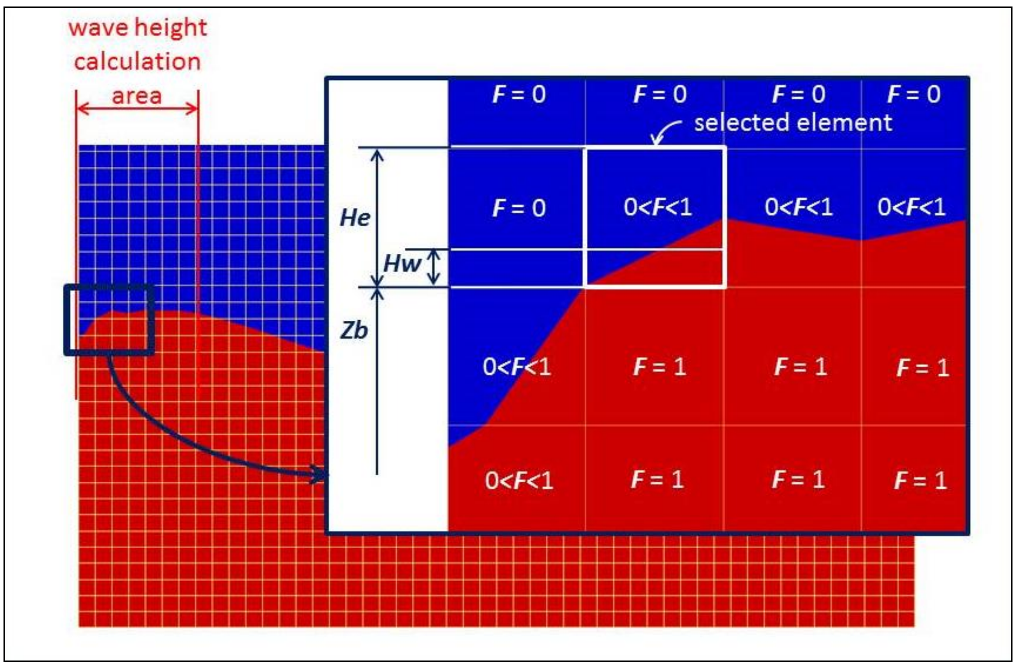

Figure 3: Wave Height Calculation

Comparison of FSI Analysis Results to Experiments

A total of 8 comparisons of analytical results are made here. In all cases, the start time of the experiment and analysis did not exactly coincide, so the analytical results were shifted slightly in time.

a. ALE, rigid tank, fluid and structure share nodes, no roof impact, varying fluid material models
   - Model 1: multi-material elements (ELFORM = 11), elastic fluid material for water, NULL material and linear polynomial EOS for air
   - Model 2: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water
   - Model 3: multi-material elements (ELFORM = 11), NULL material and Gruneisen EOS for water, NULL material and linear polynomial EOS for air

The prescribed harmonic motions amplitude ε_0 = 0.048 m, period T = 1.4 sec, T/T_0 = 0.80. No roof impact was observed in the experiment. The results of these three analyses are compared to the experimental results in Figure 4. The three analytical curves are nearly on top of each other, with good agreement with the experimental results. The choice of fluid modeling option has negligible effect on these results.

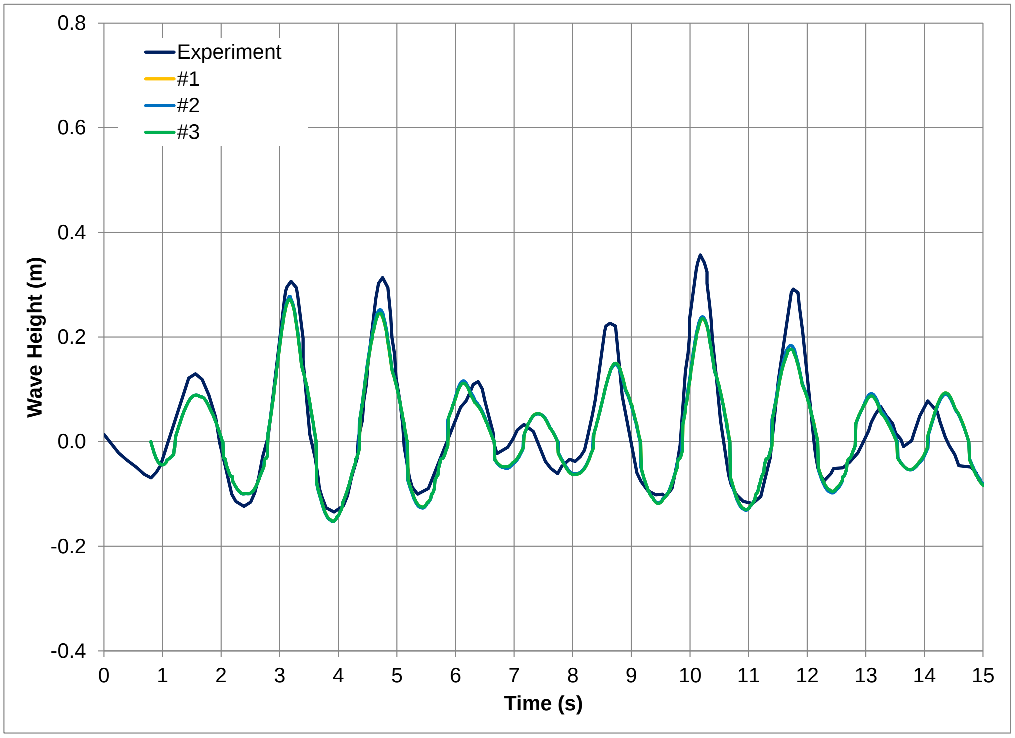

Figure 4: ALE Comparison to Experiment, No Impact, with Varying Fluid Models

b. ALE single material and void, rigid tank, fluid and structure share nodes, no roof impact, varying mesh density
   - Model 2: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, basic mesh
   - Model 4: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, refined mesh

The prescribed harmonic motions amplitude and period are the same as in the previous comparison (a). The results of these two analyses are compared to the experimental results in

Figure 5. The mesh refinement provides higher wave peaks and better correlation with the experiment.

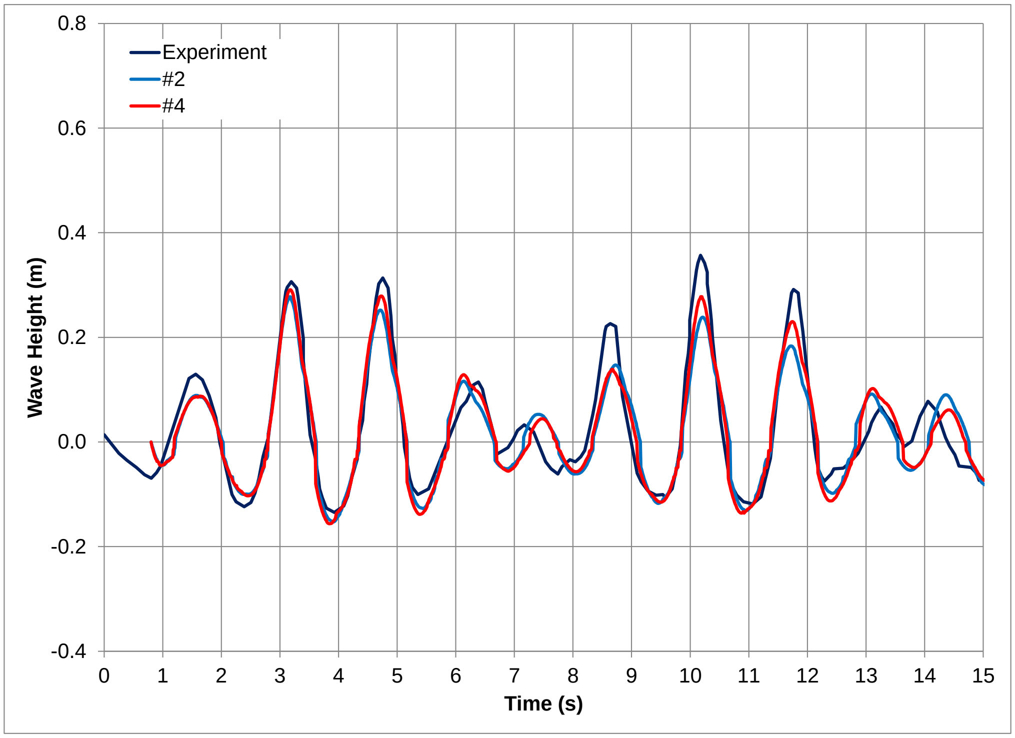

Figure 5: ALE Comparison to Experiment, No Impact, with Varying Mesh Density

The fluid free surface deformation (wave profile) at the time of maximum wave height for Model 4 is shown in Figure 6 as a representative result for cases with no roof impact.

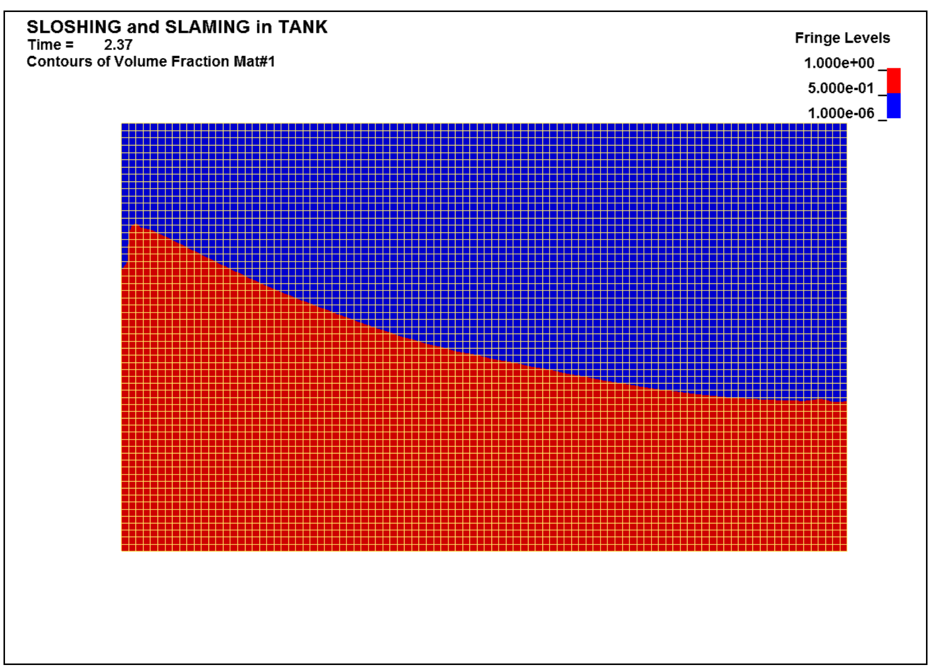

Figure 6: Maximum Wave Profile – No Roof Impact

c. ALE, rigid tank, fluid and structure share nodes, with roof impact, varying fluid material models the same as the previous case
   - Model 5: multi-material elements (ELFORM = 11), elastic fluid material for water, NULL material and linear polynomial EOS for air
   - Model 6: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water
   - Model 7: multi-material elements (ELFORM = 11), NULL material and Gruneisen EOS for water, NULL material and linear polynomial EOS for air

The prescribed harmonic motions amplitude and period were increased: ε_0 = 0.050 m, period T = 1.71 sec. The period T was even closer to that of the fundamental mode: T/T_0 = 0.98 as compared to the previous case. In this experiment, the fluid contact with the roof was achieved. The results of these three analyses are compared to the experimental results in Figure 7. Model 6, single material and void, provides the best agreement with the experiment in such aspects as reaching the roof, duration of the contact with roof, and depth of the troughs.

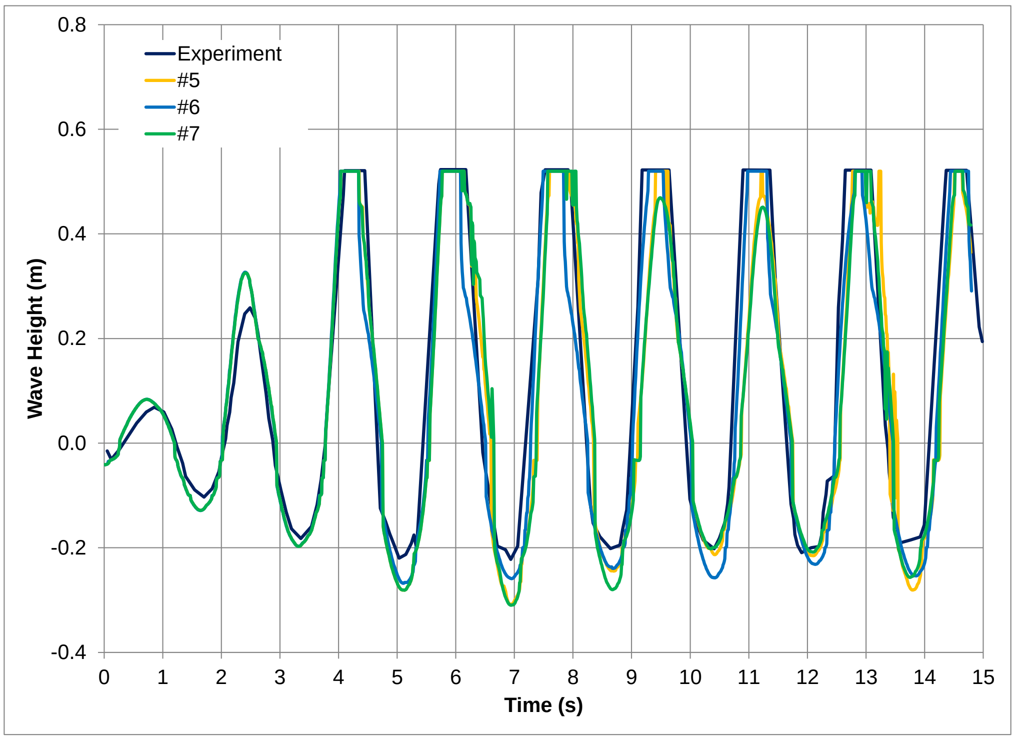

Figure 7: ALE Comparison to Experiment, with Impact, with Varying Fluid Models

d. ALE single material and void, rigid tank, fluid and structure share nodes, with roof impact, varying mesh density
   - Model 6: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, basic mesh
   - Model 8: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, refined mesh

The prescribed harmonic motions amplitude and period are the same as in the previous comparison (c). The results of these two analyses are compared to the experimental results in

Figure 8. The mesh refinement produces slightly less deep troughs, and better correlation with the experiment.

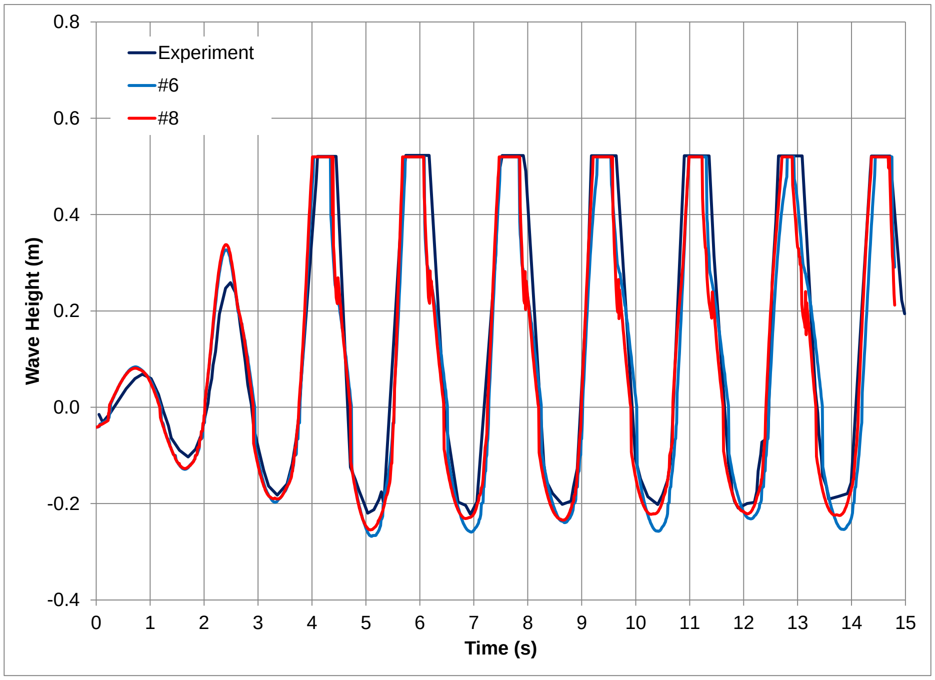

Figure 8: ALE Comparison to Experiment, with Impact, with Varying Mesh Density

The fluid free surface deformation (wave profile) at the time of maximum wave height for Model 8 is shown in Figure 9 as a representative result for cases with roof impact.

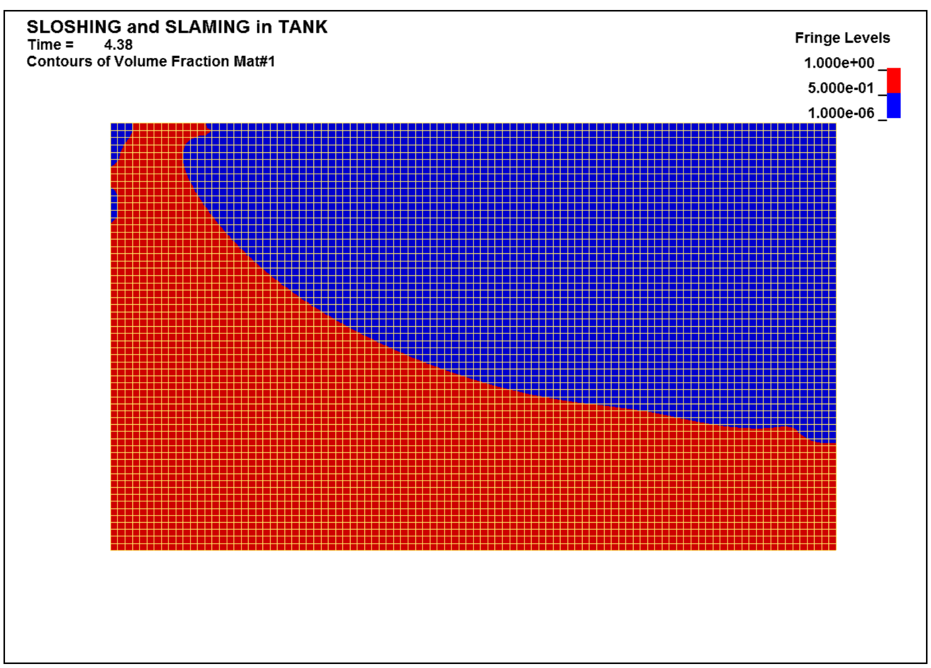

Figure 9: Maximum Wave Profile – With Roof Impact

e. ALE, rigid tank, no roof impact, comparing fluid – structure coupling methods, i.e. sharing nodes versus constrained Lagrange tank in ALE fluid
   - Model 2: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, fluid and structure sharing nodes
   - Model 9: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, structure is a Constrained Lagrange in Solid fluid (CLiS)

The prescribed harmonic motions amplitude and period are the same as in the comparison (a): ε_0 = 0.048 m, period T = 1.4 sec, T/T_0 = 0.80. The results of these two analyses are compared to the experimental results in Figure 10. The two analytical curves are nearly on top of each other. The choice of fluid – structure interaction modeling option has negligible effect on these results.

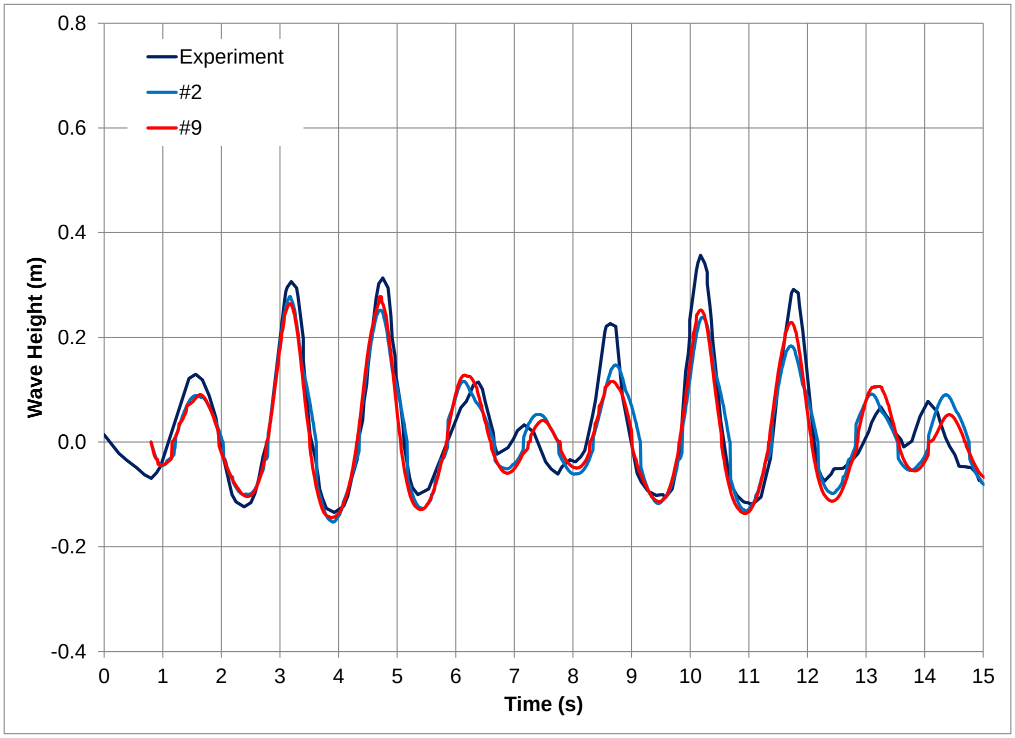

Figure 10: ALE Comparison to Experiment, No Impact, Shared Nodes and CLiS

f. ALE, no roof impact, tank is a Constrained Lagrange in Solid, comparing rigid versus elastic tank
   - Model 9: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, rigid tank
   - Model 10: single material and void (ELFORM = 12), NULL material and Gruneisen EOS for water, elastic tank

Although a rigid tank was under consideration in [1], an elastic tank ALE analysis is performed in order to study its effect on the analytical wave height. The elastic tank is assumed 5 mm thick. The material is steel. The prescribed harmonic motions amplitude and period are the same as in the previous comparison (e). The results of these two analyses are compared to the experimental results in Figure 11. The two analytical curves are nearly on top of each other, with good agreement with the experimental results. The choice of rigid or elastic tank has negligible effects on these results.

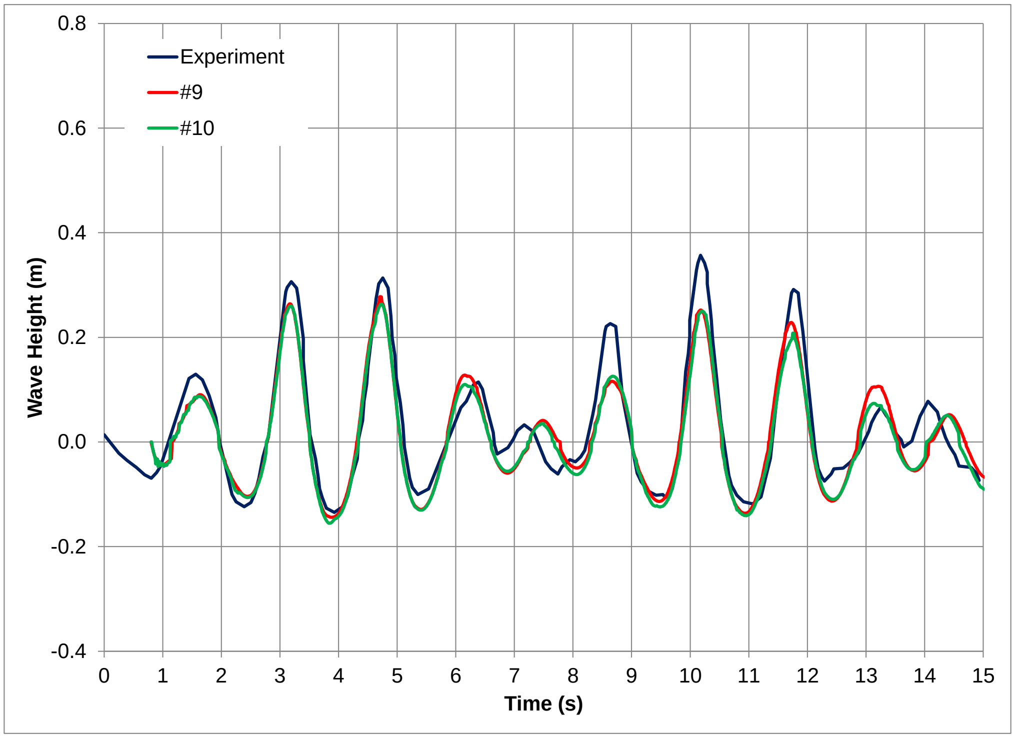

Figure 11: ALE Comparison to Experiment, No Impact, Rigid vs. Elastic Tank

g. ALE vs. Lagrangian, elastic fluid, no roof impact, comparing rigid and elastic tanks
   - Model 1: ALE, multi-material elements (ELFORM = 11), elastic fluid material for water, NULL material and linear polynomial EOS for air, fluid and structure share nodes, rigid tank
   - Model 11: Lagrangian fluid, elastic fluid material, contact fluid – structure interaction, rigid tank
   - Model 12: Lagrangian fluid, elastic fluid material, contact fluid – structure interaction, elastic tank

The prescribed harmonic motions amplitude and period are the same as in the comparison (a): ε_0 = 0.048 m, period T = 1.4 sec, T/T_0 = 0.80. The Lagrangian fluid has a contact surface for interaction with the tank. The results of these three analyses are compared to the experimental results in Figure 12. The curve for the ALE solution (#1) is the same as in Figure 4. The two Lagrangian solutions show much lower sloshing wave amplitudes than the ALE solution. The waves observed in the experiment are very large compared to the tank dimensions and fluid depth. In the Lagrangian solution, the mesh must deform to simulate the sloshing wave, so the elements would become very much distorted with these large wave heights. Such large deformations cannot be accommodated by a Lagrangian fluid. Also, as the Lagrangian fluid separates from the tank wall, it retains the shape of the tank rather than flowing into a natural fluid shape. The mesh smoothing formulated in the ALE solution steps allows the fluid material to move through the mesh, which keeps the mesh from distorting. The rigid and elastic tank models of the Lagrangian solutions are nearly identical, and do not provide a good estimate of the sloshing wave height for this experiment.

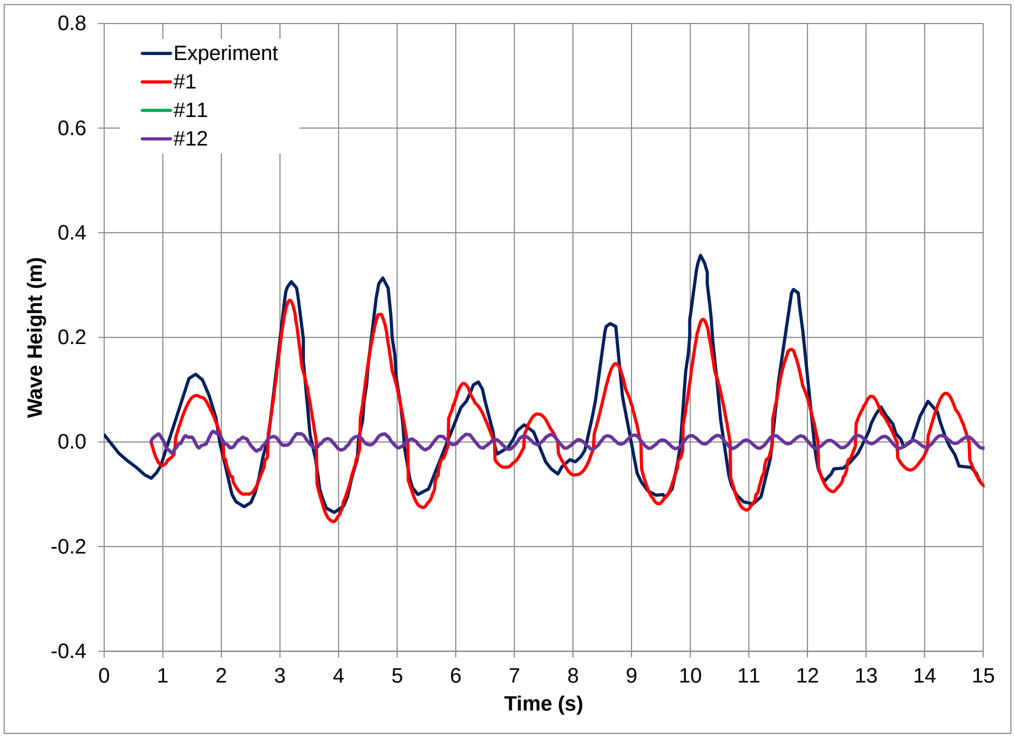

Figure 12: ALE vs. Lagrangian, Rigid and Elastic Tanks, no Roof Impact

h. ALE vs. Lagrangian, elastic fluid, no roof impact, comparing rigid and elastic tanks, lower amplitude and higher frequency excitation than in previous comparison
   - Case 13: Model 1 – ALE, multi-material elements (ELFORM = 11), elastic fluid material for water, NULL material and linear polynomial EOS for air, fluid and structure share nodes, rigid tank
   - Case 14: Model 11 – Lagrangian, elastic fluid material, contact fluid – structure interaction, rigid tank
   - Case 15: Model 12 – Lagrangian, elastic fluid material, contact fluid – structure interaction, elastic tank

The prescribed harmonic motions amplitude and period are $\varepsilon_0 = 0.02$ m, and $T = 0.7$ sec respectively. The total analysis time is 7 sec for these cases as opposed to 15 sec in the previous analyses. The Lagrangian fluid has a contact surface for interaction with the tank. The results of these three analyses are compared in Figure 13. This case does not have corresponding experimental results. The two Lagrangian solutions show lower sloshing wave amplitudes than the ALE solution. However, they are much closer to the ALE solution than in Figure 12. With the smaller amplitude of motion, the mesh in the Lagrangian model is better able to handle the deformations. The rigid and elastic tank models of the Lagrangian solutions are nearly identical, and still do not provide a good estimate of the sloshing wave height.

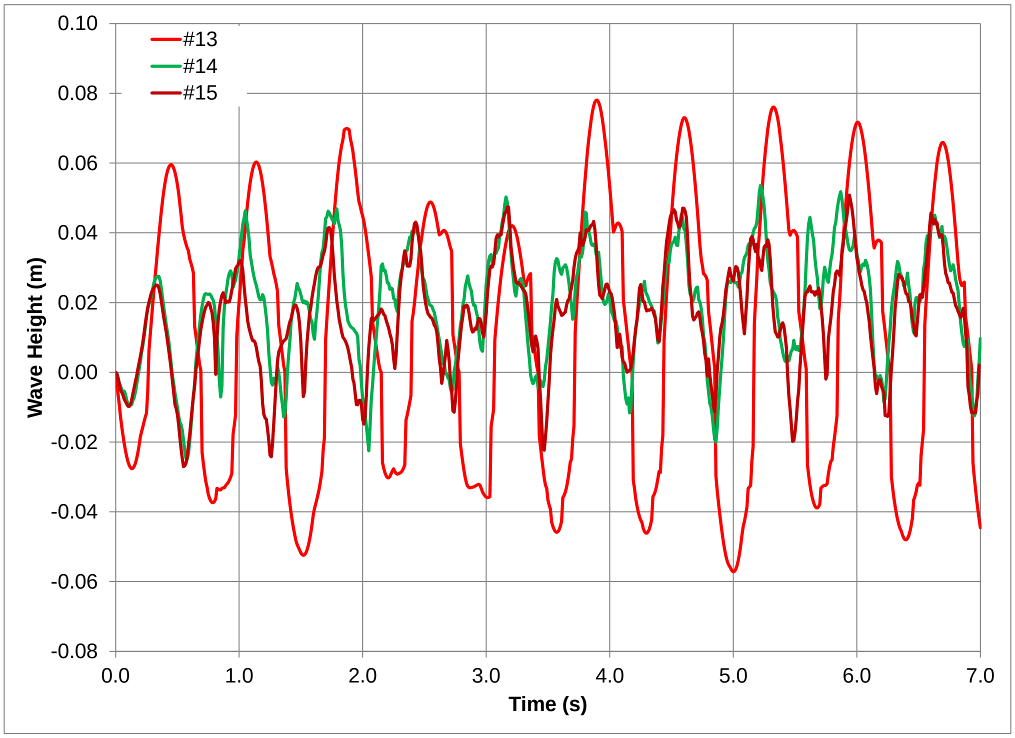

Figure 13: ALE vs. Lagrangian, Rigid and Elastic Tanks, no Roof Impact, Low Amplitude, High Frequency

Solution Time Comparison

The solution time of all analyses considered in this study are summarized in Table 1. All analyses were performed with 8 cores on a computer with 3.47 GHz Intel® Xeon® CPU X5690, 192 GB RAM under 64-bit Windows operating system with MPP version of LS-DYNA.

Table 1: Solution Time

##	formulation / ELFORM / fluid material	roof impact	mesh	tank	FSI	solution time
1	ALE / 11 / elastic fluid	no	basic	rigid	shared nodes	10 min 10 sec
2	ALE / 12 / NULL EOS Gruneisen	no	basic	rigid	shared nodes	7 min 8 sec
3	ALE / 11 / NUL EOS Gruneisen	no	basic	rigid	shared nodes	8 min 8 sec
4	ALE / 12 / NULL EOS Gruneisen	no	refined	rigid	shared nodes	42 min 4 sec
5	ALE / 11 / elastic fluid	yes	basic	rigid	shared nodes	10 min 6 sec
6	ALE / 12 / NULL EOS Gruneisen	yes	basic	rigid	shared nodes	7 min 0 sec
7	ALE / 11 / NULL EOS Gruneisen	yes	basic	rigid	shared nodes	7 min 56 sec

8	ALE / 12 / NULL EOS Gruneisen	yes	refined	rigid	shared nodes	40 min 56 sec
9	ALE / 12 / NULL EOS Gruneisen	no	basic	rigid	CLiS	16 min 51 sec
10	ALE / 12 / NULL EOS Gruneisen	no	basic	elastic	CLiS	56 min 7 sec
11	Lagrangian	no	basic	rigid	contact	7 min 12 sec
12	Lagrangian	no	basic	elastic	contact	19 min 11 sec
13	ALE / 11 / elastic fluid	no	basic	rigid	shared nodes	10 min 2 sec*
14	Lagrangian	no	basic	rigid	contact	7 min 36 sec*
15	Lagrangian	no	basic	elastic	contact	18 min 45 sec*

* Solution time is scaled up to 15 sec of the analysis time as in all previous analyses.

Apparently, ALE analysis with a single material and void (ELFORM = 12, NULL material and Gruneisen EOS for water) is the most efficient formulation, which also provides the best agreement with the experiment in case of the roof impact. When the tank was made elastic in this study, the solution time increased dramatically since the time step was controlled by the tank's shell elements. Although the Lagrangian formulation is much less time consuming compared to a coupled CLiS-ALE, its applicability to a given tank geometry and loading condition should be carefully checked. Finally, the comparison of the run times between case 2 and case 9 reveals that the fluid – structure coupling through CLiS would significantly increase the computational cost.

Comparison to Closed Form Solution

Three closed form solutions methods of computing sloshing effects have been used for many years: [6], [7], and [8] which refers to [9]. It is still a common approach in the engineering practice so the comparison of the experimental and ALE results to the prediction by closed form solutions is valuable.

Only the case without roof impact can be compared (Figure 4 and Figure 5), as these solutions do not account for roof impact. The calculations use the amplitude of the fundamental sloshing mode obtained from the spectra analysis of the exciting motion with a certain damping. It is suggested [8] that the damping shall be assumed between 0.1% and 1.0%. In our comparison (Table 2), damping value of 1.0% is used. The maximum experimental wave height is 0.36 m.

Table 2: Closed Form Solution Maximum Wave Height Comparison to That of Experiment

[6]		[7]		[8], [9]	
height, m	diff., %	height, m	diff., %	height, m	diff., %
0.45	25	0.58	62	0.46	28

All closed form solutions overestimate the experimental results by a significant margin. This may be due to the large amplitude of free surface motion extended into a nonlinear range that reduced the actual wave height.

The ALE solution maximum wave height using a rigid tank and the basic mesh is 0.27 m whereas the mesh refinement provides 0.29 m (Figure 5). The refined mesh underestimates the experimental wave height by 19%. It should be noted that the ALE solution provides a realistic trend of the fluid surface motion over time. At some wave peaks, difference from the experimental wave height is as little as 5% whereas it is greater at others. The average of four major wave peaks in the experiment (at 3.19 sec, 4.75 sec, 10.17 sec and 11.76 sec) is 0.32 m. The corresponding average wave height of the refined mesh ALE solution is 0.27 m resulting in difference from the experiment of 15%.

Thus, the ALE solution provides a closer estimation of the wave height than the three closed form solutions examined.

Conclusions

- Predictions by ALE formulation matched both sloshing frequency and free-surface large deformations/wave heights measured in the experiment.
- The tank flexibility does not significantly affect the wave height and sloshing frequency.
- Lagrangian formulation with fluid material should be used with caution. Wave heights may be significantly underestimated.
- FSI results presented should not be generalized to other tank geometries and excitation scenarios.
- The three closed form solutions significantly overestimate the sloshing wave height when using the upper bound 1% damping ratio for the spectral displacement of fluid. The ALE solution provides much better although slightly unconservative correlation with the experiment.
- ALE analyses with fluid – structure coupling through CLiS and including the tank flexibility had only minor effects on the wave heights, but significantly increased the computational cost. All other analysis options had only minor effects on the run time. While the Lagrangian solutions run quickly, the results are not reliable for large amplitude surface motions.

References

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