A REVIEW OF STUDIES ON THE SLOSHING EFFECT OF LIQUID IN PARTIALLY FILLED TANK

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ABSTRACT

Partially filled liquid tanks are exposed to dynamic loads and seismic movements of the surface. This situation causes the start of the sloshing, the fluid levels to change and additional internal pressures along with hydrostatic pressure on the tank wall. Sloshing occur in some cases, which can cause structural damage. In engineering applications, it is important to be able to determine in advance all the interactions seen during the sloshing. There are lots of numerical models that can be used to describe the sloshing. Smoothed Particle Hydrodynamics, Fluid Volume Method, Boundary Element Method, Finite Difference Method and Moving Particle Method are the numerical methods used in sloshing problems. This study investigates numerical and experimental studies on tanks used to reduce sloshing effects and also it shows which method gives better results in which situations to solve the sloshing problem. The liquid sloshing in a moving partially filled rectangular tank is investigated assuming inviscid, incompressible and irrotational flows. The accuracy, simplicity and convergence of the present method are demonstrated via numerical examples, and excellent agreement with the other method is observed. The studies on the baffles used to reduce the sloshing effect in partially filled tanks have been investigated. In this paper numerical and experimental studies for the solution of sloshing problem are investigated. At the end of the research, it is explained what types of studies are appropriate.

Key words: Sloshing, Free Surface Flow, Smoothed Particle Hydrodynamics, Numerical and Experimental Studies

1. Introduction

Partial liquid-filled tank, depending on the external influence that is exposed to, can be observed in very strong liquid movements. In such a case, an interaction between the liquid and the tank structure is inevitable. Possible scenarios are wave breaking, the formation of a mixture of liquid and gas, or air bubbles at every point in the most extreme condition. The hydrodynamics of the sloshing phenomenon is quite complex. The combination of computational fluid dynamics and experimental work is required to understand the sloshing. The most important problem that can be encountered with sloshing is the maximum impact pressure to the tank walls. In particular, progressive waves that can be observed at low occupancy rates can cause the tank to be exposed to destructive forces. Another phenomenon that can be seen is standing waves. This formation may cause destructive effect, especially on the tank top.

In the case of a partially filled tank, there is a natural period condition, depending on the geometry of the tank and the degree of occupancy. When the period of the external stimulus is, in fact, equal to the natural period, the sloshing will be observed. The problem of liquid sloshing requires estimation of the natural frequencies of hydrodynamic pressure distributions, forces, moments and liquid free surface. The sloshing must be taken into account for every vehicle or structure that is carrying liquid and in motion. In the event of sloshing, it may create a torque that may cause the vehicle to tip over. Structures fixed on land can also be exposed to sloshing effects in the event of an earthquake. In the design of LNG storage tanks, which are usually built on land, the effect of sloshing is taken into account. The broken waves mentioned above are often observed easily when the tank is half-full or low-filled. As a result of the breaking wave formation, an increase in impact is observed.

The sloshing problem is of particular interest to mathematicians and physicists working in the areas of space engineering, civil engineering, nuclear engineering and ship engineering. The sloshing problem has been a field of work for lots of scientists for many years. Lamb, in his well-known work of 1879, theoretically examined the sloshing [1]. When the related sources are examined, it is seen that the earliest date work was carried out by Euler in 1761 [2]. The sloshing problem has attracted a great deal of attention in academic circles especially in the last 50 years. First approaches to solve this problem are developed with the help of equivalent mechanical models [3, 4]. Frandsen examined the nonlinear potential flow problem using a finite difference method for a 2D tank [5]. In their work, Çelebi and Akyildiz used the volume of fluid (VOF) technique as a finite difference approach for monitoring free surface movements [6]. When the nonlinear waves and the structure-wave interaction are included, it is very difficult to reach the result with the help of numerical techniques. The first step in the operation of a numerical model that is supposed to be realized is the transfer of a physical problem to a numerical model. As can be seen in most studies, the modeling of free surface flows involves the solution of Navier-Stokes equations with the help of Euler-based approaches. In an Euler-based approach, it is mentioned a solution network fixed in space. For the Euler-based solution, the above mentioned VOF technique and MAC (Marker and Cell) method are the most promising solution tools. Examples of applying these methods to the sloshing problem are the work of Popov, Armanio, Zhong and Sames [7-10].

Ma (1994) studied the behavior of a tank containing two different liquids under seismic loads [11]. In this study, analytical and numerical approaches are used together. In his work Yao studied three-dimensional wave motion in a narrow tank [12]. Kim developed an analytical approach to reveal two- and three-dimensional responses of a partially filled rectangular tank under horizontal and vertical loads [13]. Taking into consideration the wave loads that have taken place during the sloshing, Bagnold was the first who examine the structural effect of these loads experimentally [14]. As a result of this study, a formula has been derived to predict the maximum pressure value in the tank. Another important experimental study on the sloshing problem was carried out by Akyıldız and Ünal [15]. The effect of sloshing on the stability of a vehicle has also been examined by another experimental study [16]. In this study, the effects on vehicle motion were evaluated considering 6 degrees of freedom. In the case of multi-storey buildings, structures that are filled with liquid are designed to quench vibrations that may occur in the building. These constructions are called Adjusted Fluid Dampers. There are many important studies carried out on this subject [17-19].

As can be seen examples of given above, the sloshing problem emerges as a problem involving many different disciplines. Sloshing is an effect that has to be considered for any structure containing liquid. When an aircraft's fuel tank is dealt with, the sloshing movement that may occur will have an impact on the vehicle's dynamic stability. Similarly, the sloshing movement will have an impact on stability of a liquid loaded cargo vessel. When considered on a large scale, a sloshing movement effect can also be observed in a lake or ocean scale. High-rise buildings can also be affected by sloshing movement. The hydrodynamics of sloshing are very complex. The intelligibility of the subject can be increased by the combination of computational fluid dynamics and experimental work. Especially when tank design is concerned, experimental work is at the forefront. There are lots of ships that are traveling in the seas and have liquid storage tanks in different models. The transported material may be liquid crude oil, liquefied natural gas, water or caustic soda. The hydrodynamic loads to which the tank is subjected are proportional to the density of the liquid in the tank. Even if it is completely filled with liquid, it will be the case that the liquid will move as a result of the movement of the ship. There are many experimental and numerical studies about sloshing in liquid tanks and its effect on ship motions [16, 20-23].

Romero found that 4% of vehicle accidents involving liquid cargo came to the end of the sloshing. [24]. Especially in the event of sloshing that may occur when cornering, it is highly likely that the vehicle will be forced to change lanes on the highway. Otherwise, the sloshing movement of the tank may occur during a sudden braking that requires the vehicle to stop. The wave that will be generated during the sudden stop of the vehicle with a tank with a low occupancy rate will hit the tank and push the vehicle in the direction of the wave. The same effect applies to trains with liquid-filled tank. In 2004, Bogomaz wrote a book focusing solely on this subject [25].

Hatayama identified the sloshing effect in seven tanks damaged in the Tokachi Earthquake [26]. As a result of the study, the greatest damage was observed in cases where the natural periods of turbulence in the tanks were between 5 and 12 seconds. A large part of the weight of spacecraft before launching is the weight of the fuel they carry. It should be noted here that the effective sloshing frequency is close to the frequency of the system. This can cause dynamic inconsistencies in the rocket. Two important studies on this subject were carried out by NASA [27, 28]. The gravity-free environment that the spacecraft is subjected to when it enters the orbit is effective on the sloshing in the fuel tanks. Model tests are used by major classification agencies for testing of different types of tanks, while continuing their importance in the work on the subject.. The preferred scale for model tests is 1/25 to 1/70. Jeon revealed that scales from 1/25 to 1/50 are appropriate and 1/100 scale is very small. [29].

The SOLA scheme, introduced by Hirt, is a widely used solution for solving Navier-Stokes equations with a finite difference approach [30]. The solution approach was also used in simulating the three-dimensional sloshing problem in two studies of 2001 and 2007 [20, 31]. The Finite Difference Method is based on the principle of using differences from the finite Δx distance (or at time Δt) to approximate a derivative of a variable. When we make this distance infinitely small, the definition of the differential is reached. But in numerical study this difference is a finite difference, and gives its name to the method. If Taylor Expansion is applied around an x point, the solutions can be done by finding the terms of the finite difference convergence.

When studies done up to now are examined, it is seen that the numerical solutions of the sloshing problem are made through the methods mentioned above. Baffled tanks are usually used to reduce sloshing effect. There are mathematical studies on various baffled tank geometries [32-36]. As the tank geometry became complicated in those studies, the use of analytical methods became increasingly difficult.

Experimental studies are needed to verify numerical and mathematical studies. Very little experimental work is available, especially when compared with numerical studies. Akyıldız et al. aimed to reduce the sloshing effect by using a ring baffle in a partially filled cylindrical tank [37]. Using a partially filled liquified cylindrical tank, Lu et al. has compared impact pressures of experimental measurements and numerical calculations in 4 different fill rates and 3 different wavelengths [38]. The pressure values have been calculated in the short wave length are smaller than the measured values. Because there are openings on the top of tank, the measured values may have been different due to the influence of air motion. Mikelis and Journee, have designed a prototype of cargo tanks used to transport liquids on ships [23]. They have investigated the pressure distributions occurring on the walls of the tank due to the effects of forces and moments generated by the liquid movements and the effect of this situation on the tank structure and the ship. They also experimentally examined sloshing effect of semi-frozen liquid cargo and completely liquid cargo. As a result of the experiment, it has been observed that damping of the semi-frozen liquid is faster. Bredmose et al. have investigated horizontal sloshing experimentally and numerically [39]. The thought that they initiate their work: The acceleration of the tank can cause to two different reactions connecting to each other. These are a severe short effect of fluid on the tank walls and wide-amplitude sloshing movements. The severe effects cause very large pressures that can be analyzed by means of pressure-impulse theory. The long sloshing movement after the first steps of liquid acceleration / deceleration causes severe pressures between medium to high values on tank walls. Panigrahy et al. have measured different locations' pressure of a square tank at different occupancy cases and and showed in the pressure graph according to the time [40]. Supersession of free surface and the relationship between the wave length and the filling depth was determined. Experiments with ring baffles give encouraging results in the literature. Some of the results obtained are as follows : the pressure fluctuations occurring in the tank walls near the free liquid surface are greater than the depths. They have come to the conclusion that the ring-shaped baffles are more effective than the common horizontal, vertical baffles.

There are also lots of numerical studies of partially liquid filled tank about sloshing effects. The Finite Volume Method is based on the assumption that the spatial domain is divided into a continuous finite number of control volumes. The two group manager equations are used to express the time dependent change of mass and momentum in the control volume. Fundamentals of formulation, continuity of mass and Navier-Stokes equations. Details of the numerical solutions of the Finite Volume Method, have been shown in the studies of Muzaferija and Ferziger [41, 42]. This method is adapted to the sloshing movement in liquified gas-carrying tanks in the 2007 study of Peric [43]. The main difference in this work is that the Reynolds-averaged Navier-Stokes equations are solved.

The Finite Element Method is used to solve many different engineering problems. This method is also adapted to the sloshing problem in different studies. [44]. FEM is more complex than the other methods in solving Navier-Stokes equations. Herfjord and Tonnessen have achieved good results in the solutions of the flow around the two-dimensional bodies in their work [45, 46]. In this method, the flow field is divided into elements and the shape functions are used on these elements.

Smoothed Particle Hydrodynamic method, the flow field is defined by the finite number of particles. SPH can well describe nonlinear problems, especially sloshing. In this method, Navier-Stokes equations are used. The basic idea of the solution is to define the fluid with a group of (smooth) particles. Monaghan adapted this method, which was used in astrophysics until then, to the field of computational fluid dynamics [47-52]. The classical SPH approach is based on the interpolation around each particle to obtain the formulas of the method. The interpolation approach allows any function to be expressed in a group of irregular points (in the particle).

Research on free surface flows continues to raise interest in industrial establishments and academic circles. It is very difficult to solve this problem with Euler approaches. However, the main advantage of the SPH method is great identifying of complex problems. Monaghan gave examples of the application of SPH in 1994 [53]. Those examples include the analogy of a wave palette and a wave running along the shore, with a water movement that will eventually result in the collapse of a dam. The results have shown that SPH can be used in simulating free surface. Guilcher's study in 2007, the SPH method included the correction of Riemann solvers and Kernel Function [54]. Marrone has developed a very important algorithm for tracking the free surface in two and three dimensions [55]. The first step in this approach is the detection of particles that creating the free surface; the second step is the transfer of the function to be used in the interpolation. Bai et al. have developed a numerical model to simulate the sloshing in a two-dimensional rectangular section tank partly full of liquid [56]. The governing equations are solved using the finite difference approach with the staggered grids method. This model uses two phases of the fluid at the same time and aims to prevent wave breaks in the non-linear sloshing flows that occur. Model using moving coordinate system can easily simulate the sloshing waves in a rectangular tank moving randomly in three degrees of freedom. With developed numerical model mild and severe sloshing waves generated by single surge and pitch motion can be verified by simulating. Numerical results of the study are in harmony with the other experimental and numerical results of the present numerical model demonstrating its applicability in complex slushing problems. Wang et al. have analyzed sloshing effects with three baffled shape including surface-piercing baffle, bottom mounted baffle and their combination form of T and Y-shaped baffles on elliptical tank [57]. The proposed method, Scaled Boundary Finite Element Method (SBFEM), is formulated to solve the sloshing problem using the zoning method which initially includes velocity potentials. The SBFEM is first applied to the sloshing movements of T-baffled elliptical tanks. The flow velocity solution along the baffles for the SBFEM has also been developed. The relationship between the baffle parameters and the sloshing effect has also been studied. Numerical results show that the proposed method can achieve accuracy close to perfection. One of the biggest advantages of the program is that it results in fewer operations in a short time. Goudarzi and Farshadmanesh have studied Upper Mounted Baffles (UMB) and explained their advandages [58]. Using a UMB in a rectangular tank, it is possible to reduce the wave height caused by sloshing by 50%. Placing the baffles in this way also makes it easier to estimate the wave height in the tank.

2. Conclusions

When the nonlinear waves and the structure-wave interaction are included in the problem, it is very difficult to reach the result with the help of digital techniques. The first step in the operation of a numerical model that is supposed to be realized is the transfer of a physical problem to a numerical model. As can be seen in most scientific articles, the modeling of free surface currents involves the solution of Navier-Stokes equations with the help of Euler and Lagrange-based approaches. In an Euler-based approach, refered to a solution network fixed in space but Lagrange-based method has the advantage that it does not require any special effort to define complex free surface flows. The reason for this is that the method is Lagrange-based. This feature increases the applicability of the method to nonlinear problems.

It seems that the best choice to apply to the free surface problems in the literature review is "Smoothed Particle Hydrodynamics" method. Compared with the methods mentioned above, it can be seen that the equations belonging to the SPH method are more suitable for numerical modeling. This is because the method is simple and stronger.

If a numerical study on sloshing is to be worked, it is absolutely necessary to verify it with experimental work.

References:

[1] Lamb, H., 1932. Hydrodynamics: Cambridge university press.

[2] Euler, L., 1761. Principia motus fluidorum. Novi Commentarii Acad. Sci. Petropolitanae, 6(1756/7): p. 271-311.

[3] Graham, E. and A. Rodriquez, 1951. The characteristics of fuel motion which affect airplane dynamics. Douglas Aircraft Co Inc Santa Monica Ca.

[4] Lewison, G., 1976. Optimum design of passive roll stabilizer tanks. Naval Architect.

[5] Frandsen, J.B., 2004. Sloshing motions in excited tanks. Journal of Computational Physics, 196(1): p. 53-87.

[6] Celebi, M.S. and H. Akyildiz, 2002. Nonlinear modeling of liquid sloshing in a moving rectangular tank. Ocean Engineering, 29(12): p. 1527-1553.

[7] Popov, G., S. Sankar, and T. Sankar, 1993. Dynamics of liquid sloshing in baffled and compartmented road containers. Journal of fluids and structures, 7(7): p. 803-821.

[8] Armenio, V., A. Francescutto, and M. La Rocca, 1996. On the roll motion of a ship with partially filled unbaffled and baffled tanks-Part 1: Mathematical model and experimental setup. International Journal of Offshore and Polar Engineering, 6: p. 278-282.

[9] Zhong, Z., M. Falzarano, and R. Fithen., 1998. A numerical study of U-tube passive anti-rolling tanks. in The Eighth International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.

[10] Sames, P.C., D. Marcouly, and T.E. Schellin, 2002. Sloshing in rectangular and cylindrical tanks. Journal of Ship Research, 46(3): p. 186-200.

[11] Ma, D. C., Shin, Y. S., Brochard, D., & Fujita, K., 1994. Sloshing, fluid-structure interaction and structural response due to shock and impact loads. PVP-Vol. 272. New York, NY (United States); American Society of Mechanical Engineers.

[12] Yao, Y., M.P. Tulin, and A.R. Kolaini, 1994. Theoretical and experimental studies of three-dimensional wavemaking in narrow tanks, including nonlinear phenomena near resonance. Journal of Fluid Mechanics. 276: p. 211-232.

[13] Kim, J.K., H.M. Koh, and I.J. Kwahk, 1996. Dynamic response of rectangular flexible fluid containers. Journal of Engineering Mechanics, 122(9): p. 807-817.

[14] Bagnold, R., 1939. Interim report on wave-pressure research. Excerpt from the J. of the Institution of Civil Engineers.

[15] Akyildiz, H. and E. Ünal, 2005. Experimental investigation of pressure distribution on a rectangular tank due to the liquid sloshing. Ocean Engineering, 32(11): p. 1503-1516.

[16] Rognebakke, O.F. and O.M. Faltinsen, 2003. Coupling of sloshing and ship motions. Journal of Ship Research, 47(3): p. 208-221.

[17] Ikeda, T. and N. Nakagawa, 1997. Non-linear vibrations of a structure caused by water sloshing in a rectangular tank. Journal of Sound and Vibration, 201(1): p. 23-41.

[18] Anderson, J., S. Semercigil, and Ö. Turan, 2000. A standing-wave-type sloshing absorber to control transient oscillations. Journal of Sound and Vibration, 232(5): p. 839-856.

[19] Frandsen, J., 2005. Numerical predictions of tuned liquid tank structural systems. Journal of Fluids and Structures, 20(3): p. 309-329.

[20] Kim, Y., 2001. Numerical simulation of sloshing flows with impact load. Applied Ocean Research, 23(1): p. 53-62.

[21] Kim, Y., 2002. A numerical study on sloshing flows coupled with ship motion—the anti-rolling tank problem. Journal of Ship Research, 46(1): p. 52-62.

[22] Kim, Y., Nam, B. W., Kim, D. W., & Kim, Y. S., 2007. Study on coupling effects of ship motion and sloshing. Ocean Engineering, 34(16): p. 2176-2187.

[23] Mikelis, N., J. Miller, and K. Taylor, 1984. Sloshing in partially filled liquid tanks and its effect on ship motions: numerical simulations and experimental verification. Royal institution of naval architects transactions, 126.

[24] Romero, J. A., Hildebrand, R., Martinez, M., Ramirez, O., & Fortanell, J. A., 2005. Natural sloshing frequencies of liquid cargo in road tankers. International journal of heavy vehicle systems, 12(2): p. 121-138.

[25] Bogomaz, G., 2004. Dynamics of railway tank cars [Dinamika zheleznodorozhnyh vagonov-cistern]. Kiev, Naukova Dumka publ.

[26] Hatayama, K., 2008. Lessons from the 2003 Tokachi-oki, Japan, earthquake for prediction of long-period strong ground motions and sloshing damage to oil storage tanks. Journal of seismology, 12(2): p. 255-263.

[27] Abramson, H.N., 1966. The dynamic behavior of liquids in moving containers, with applications to space vehicle technology.

[28] Dodge, F.T., 2000. The new" dynamic behavior of liquids in moving containers".: Southwest Research Inst. San Antonio, TX.

[29] Jeon, SS., Kim, HI., Park, JS., Kwon, SH., Ryu, MC., Hwang, YS., Jung, JH., 2008. Experimental investigation of scale effect in sloshing phenomenon.

[30] Hirt, C., B. Nichols, and N. Romero, 1975. SOLA: A numerical solution algorithm for transient fluid flows. Los Alamos Scientific Lab., N. Mex.(USA).

[31] Kim, Y., 2007. Experimental and numerical analyses of sloshing flows. Journal of Engineering Mathematics,. 58(1): p. 191-210.

[32] Gavrilyuk, I., Lukovsky, I., Trotsenko, Y., & Timokha, A., 2006. Sloshing in a vertical circular cylindrical tank with an annular baffle. Part 1. Linear fundamental solutions. Journal of Engineering Mathematics, 54(1): p. 71-88.

[33] Maleki, A. and M. Ziyaeifar, 2008. Sloshing damping in cylindrical liquid storage tanks with baffles. Journal of Sound and Vibration, 311(1): p. 372-385.

[34] Hasheminejad, S.M., M. Mohammadi, and M. Jarrahi, 2014. Liquid sloshing in partly-filled laterally-excited circular tanks equipped with baffles. Journal of Fluids and Structures, 44: p. 97-114.

[35] Wang, J., S. Lo, and D. Zhou, 2013. Sloshing of liquid in rigid cylindrical container with multiple rigid annular baffles: Lateral excitations. Journal of Fluids and Structures, 42: p. 421-436.

[36] Liu, H., Lv, H., Wang, H., & Zhang, Y., 2016 Study on the Influence on Liquid Sloshing Caused by Baffle’s Parameter Changes in Tank. in International Conference on Green Intelligent Transportation System and Safety.

[37] Akyıldız, H., N.E. Ünal, and H. Aksoy, 2013. An experimental investigation of the effects of the ring baffles on liquid sloshing in a rigid cylindrical tank. Ocean Engineering, 59: p. 190-197.

[38] Lu, D., Zeng, X., Dang, J., & Liu, Y., 2016. A calculation method for the sloshing impact pressure imposed on the roof of a passive water storage tank of AP1000. Science and Technology of Nuclear Installations.

[39] Bredmose, H., Brocchini, M., Peregrine, D. H., & Thais, L., 2003. Experimental investigation and numerical modelling of steep forced water waves. Journal of Fluid Mechanics, 490: p. 217-249.

[40] Panigrahy, P., U. Saha, and D. Maity, 2009. Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks. Ocean Engineering, 36(3): p. 213-222.

[41] Ferziger, J.H. and M. Peric, Computational methods for fluid dynamics. 2012: Springer Science & Business Media.

[42] Muzaferija, S., 1998. Computation of free surface flows using interface-tracking and interface-capturing methods. Nonlinear water wave interaction.

[43Peric, M., Zorn, T., el Moctar, O., Schellin, T. E., & Kim, Y. S., 2009. Simulation of Sloshing in LNG-tanks. Journal of Offshore Mechanics and Arctic Engineering, 131(3): p. 031101.

[44] Solaas, F., 1997. Analytical and numerical studies of sloshing in tanks.

[45] Herfjord, K., 1997. A study of two-dimensional separated flow by a combination of the finite element method and Navier-Stokes equations.

[46] Tønnessen, R., 1999. A finite element method applied to unsteady viscous flow around 2D blunt bodies with sharp corners: Norwegian University of Science and Technology.

[47] Gingold, R.A. and J.J. Monaghan, 1977. Smoothed particle hydrodynamics: theory and application to non-spherical stars. Monthly notices of the royal astronomical society, 181(3): p. 375-389.

[48] Gingold, R. and J. Monaghan, 1982. Kernel estimates as a basis for general particle methods in hydrodynamics. Journal of Computational Physics, 46(3): p. 429-453.

[49] Monaghan, J. and R. Gingold, 1983. Shock simulation by the particle method SPH. Journal of computational physics, 52(2): p. 374-389.

[50] Monaghan, J., 1985. Extrapolating B splines for interpolation. Journal of Computational Physics, 60(2): p. 253-262.

[51] Monaghan, J.J., 1988. An introduction to SPH. Computer physics communications, 48(1): p. 89-96.

[52] Monaghan, J., 1989. On the problem of penetration in particle methods. Journal of Computational physics, 82(1): p. 1-15.

[53] Monaghan, J.J., 1994. Simulating free surface flows with SPH. Journal of computational physics, 1994. 110(2): p. 399-406.

[54] Guilcher, P. M., Ducorzet, G., Alessandrini, B., & Ferrant, P., 2007 Water wave propagation using SPH models. in Proc. SPHERIC, 2nd Intl. Workshop. Universidad Politecnica de Madrid, Spain, May..

[55] Marrone, S., Colagrossi, A., Le Touzé, D., & Graziani, G., 2010. Fast free-surface detection and level-set function definition in SPH solvers. Journal of Computational Physics, 229(10): p. 3652-3663.

[56] Bai, W., X. Liu, and C. Koh, 2015. Numerical study of violent LNG sloshing induced by realistic ship motions using level set method. Ocean Engineering, 97: p. 100-113.

[57] Wang, W., Guo, Z., Peng, Y., & Zhang, Q., 2016. A numerical study of the effects of the T-shaped baffles on liquid sloshing in horizontal elliptical tanks. Ocean Engineering, 111: p. 543-568.

[58] Goudarzi, M. and P. Farshadmanesh, 2015. Numerical evaluation of hydrodynamic damping due to the upper mounted baffles in real scale tanks. Soil Dynamics and Earthquake Engineering, 77: p. 290-298.