Study of the Sloshing of Water Reservoirs and Tanks due to Long Period and Long Duration Seismic Motions

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SUMMARY:
In liquid tanks, most damages during earthquakes occur due to liquid sloshing, especially in long period and long duration ground motions. Most long-period ground motions were generated by large earthquakes and effective propagation paths, such as accretionary prisms. For this purpose the computational fluid dynamics (CFD) simulation tool OpenFOAM (Open Field Operation and Manipulation) is applied to study the effect of ground motions inside a sloshing tank. An improved VOF method is used to assure an accurate description of water displacement. Computational results are validated and compared to obtain some useful insight into the effect of period and duration of seismic motions on the sloshing phenomena in water tanks.

Keywords: sloshing, seismic motion, water reservoir, long period & long duration

1. INTRODUCTION

One of the critical lifeline structures which have become widespread using during the recent decades is liquid storage tank. These structures are extensively used in water supply facilities, oil and gas industries and nuclear plants for storage of a variety of liquid or liquid-like materials such as oil, liquid natural gas (LNG), chemical fluids and wastes of different forms. Problems associated with liquid tanks involve many fundamental problems. The calculation of hydrodynamic forces on the wall of vibrating liquid tanks is an important issue for safegurding the structural integrity of industrial tanks and vessels.

Sloshing means any motion of the free liquid surface inside its container. It is caused by any disturbance to partially filled liquid containers. In particular, liquid sloshing on the free surface may have significant influence on the response of the container. The basic problem of liquid sloshing involves the estimation of hydrodynamic pressure distribution, forces, moments and natural frequencies of the free-liquid surface. These parameters have a direct effect on the dynamic stability and performance of moving containers. Generally, the hydrodynamic pressure of liquids in moving rigid containers has two distinct components. One component is directly proportional to the acceleration of the tank. This component is caused by the part of the fluid moving with the same tank velocity. The second is known as ‘‘convective’’ pressure and represents the free-surface-liquid motion. Mechanical models such as mass-spring-dashpot or pendulum systems are usually used to model the sloshing part. Sloshing waves have been studied numerically, theoretically and experimentally in the past several decades and many significant phenomena have been considered in those studies, especially the linear and nonlinear effects of sloshing for both inviscid and viscous liquids.

Analytical solutions are limited to regular geometric tank shapes such as cylindrical, and rectangular. The nature of sloshing dynamics in cylindrical tanks is better understood than for prismatic tanks. However, analytical techniques for predicting large-amplitude sloshing are still not fully developed. Sloshing in spherical or cylindrical tanks, however, is usually described by three-dimensional flow.

Tanks with two-dimensional flow are divided into two classes: low and high liquid fill depths. The low fill depth case is characterized by the formation of hydraulic jumps and traveling waves for excitation periods around resonance. At higher fill depths, large standing waves are usually formed in the resonance frequency range. When hydraulic jumps or traveling waves are present, extremely high impact pressures can occur on the tank walls. Impact pressures are only measured experimentally and cannot be estimated theoretically or numerically.

In last four decades many researchers have studied on the sloshing problem. And this text, as a brief review on these studies, introduces the most progressive and advantageous analytical solutions, numerical computer-aided simulations and physical models have been tried by researchers as well as their most effective assumptions and also findings. Finally, with a summary on their discussions and conclusions some outlines are issued for future works.

2. METHODS OF MODELLING

Modelling of new arisen engineering problems has evident effect in their solving evolution. And earlier researchers on them, who are dealing with a too unknown problems to be solved in a direct full analytical way, use reasonable simplicity assumptions to reduce physical concept of the event to simple and rough analytical model which can be described by initial known principles without any considerable deficiency occurrence in original problem.

Then, during the time, studies on the event will be continued by issuance some numerical models to find out the most effective parameters, their way of influence and also evaluation of the procedures by comparing their calculated and corresponding observed values due to real cases or experimental tests. And based on these findings, later researchers will try to issue more accurate analytical models and this improvement way will continue alternatively between analytical and numerical models until getting to a reasonably exact one and finally, principle establishment for considered event. Modelling of sloshing, as an imprecise and complicated engineering event, has a similar unfinished evolution history and herein we will have a brief review on the attempts done in this way which has started by Morse and Fesbach in 1953, and continued by many individuals all around the world.

2.1. Long period & long duration ground motions

Previously, most structures in earthquake-prone regions were low-profile structures, and so relatively short-period (1 s or shorter) ground motions, with which these structures might be resonant, were important. However, considering the increasing number of large structures, such as high-rise buildings, storage tanks, suspension bridges, off-shore oil drilling platforms, and recent base-isolated structures, long-period (1 to 10 s or longer) ground motions have been increasingly important (e.g., Kanamori 1979; Fukuwa 2008).

Hanks (1975) recovered 234 components of long-period ground motion in the source region of the 1971 San Fernando earthquake (MW=6.6), and the neighboring Los Angeles basin in California. He coined the term “long-period strong ground motion” in this paper (Zama 1993). Long-period ground motions are caused by the specific characteristics in the magnitude of earthquake, epicenter location and geological structure through which seismic waves propagates. Large subduction-zone earthquakes and moderate to large crustal earthquakes can generate far-source long-period ground motions in distant sedimentary basins with the help of path effects. Near-fault long-period ground motions are generated, for the most part, by the source effects of forward rupture directivity. Far source long-period ground motions consist primarily of surface waves with longer durations than near-fault long-period ground motions.

The predominant period of long-period strong ground motion can vary between earthquakes, meaning that it is necessary to consider the source and path effects as well as local site effects in the prediction of predominant periods of such ground motions at a certain site. Far-source long-period ground motion was identified, for the first time in Japan, in seismograms of the 1968 Tokachi-oki earthquake

(MW=8.2) observed with large amplitudes and a predominant period of 2.5 s at Hachinohe, northeastern Japan. They were also observed by strong motion seismographs installed in the first super high-rise building in Japan. The Kasumigaseki building was located in Tokyo, 650 km from the earthquake source (Shima 1970). Trifunac and Brune (1970) observed longperiod ground motion in distant seismograms of the 1940 Imperial Valley earthquake (MS=7.1) in California. Both the Japanese and Californian authors attributed these far-source long-period ground motions to regional surface waves. The most obvious difference is the duration of ground motion. The far-source long-period ground motions continue for 1 min or longer, whereas the near-fault longperiod ground motions last only for 10 to 20 s.

The sloshing inside tank occurs when the ground motion at the site contains the period which is the same as the fundamental period of tank sloshing. The tank sloshing period depends on the size and the amount of inside fluid. For instance, the fundamental sloshing period of large tank with radius of 100m is around 10 seconds. Long period ground motions mainly arrive as the surface wave after the arrival of the main waves during large earthquakes, and there is a time lag after the main waves. Sloshing is caused by the surface wave (long period ground motion) arriving after the main body waves. Therefore, the occurrence of sloshing can be predicted to a degree by clarifying the earthquake faults which generate long period seismic motions. In addition, there is a time lag for the arrival of surface waves after the main body waves.

The worst example of destruction caused by long-period ground motion occurred in Mexico City, 400 km from the 1985 Michoacan earthquake (MW= 8.0; e.g., Beck and Hall 1986). Another example is the 2003 Tokachi-oki earthquake (MW=8.3) that occurred in Hokkaido, Japan (e.g., Koketsu et al. 2005).

The generation of long-period ground motion can be identified based on damage to large tanks. This damage is caused primarily by sloshing of the liquid inside the tanks. Because the excitation of liquid sloshing appears to require long duration seismic ground motion, it can be linked to far-source long-period ground motion. Ohta and Zama (2005) documented 14 cases of tank damage because of liquid sloshing (Table 2.1).

Table 2.1.Tank damages due to liquid sloshing

Earthquake	Year	MW	Damage	Reference
Kanto	1923	7.9	6,000 t oil tank	Hirano (1982)
Long Beach	1933	6.2	Water tank	Steinbrugge (1970)
Kern County	1952	7.5	Oil tanks	Steinbrugge and Moran (1954)
Alaska	1964	9.2	Many oil tanks, fires	Rinne (1967)
Niigata	1964	7.6	Many oil tanks, fires	FDMA (1965)
Central Chile	1965	7.1	Oil tanks	Shibata (1974)
San Fernando	1971	6.6	Oil tanks	Shibata (1974)
Miyagi-oki	1978	7.4	Oil tanks	FDMA (1979)
Imperial Valley	1979	6.5	Oil tanks	Horoun (1983)
Coalinga	1983	6.2	Many oil tanks	Manos and Clough (1985)
Japan Sea	1983	7.7	Many oil tanks, fires	Yoshiwara et al. (1984)
Kocaeli	1999	7.6	Many oil tanks, fires	JSCE (2000)
Chi-Chi	1999	7.7	Oil tanks	Yoshida et al. (2000)
Tokachi-oki	2003	8.3	Many oil tanks, fires	Ohta and Zama (2005)

The 2003 Tokachi-oki earthquake was the first M 8-class event to be recorded by the Japanese nationwide strong ground motion seismograph networks, K-NET and KiK-net. It was thus the first time that large-amplitude long-period ground motions, which are a characteristic of large earthquakes, were recorded at a high station density in Japan. The resultant dataset makes it possible to study the detailed features of shaking, such as the spatial variation in amplitudes of long-period strong ground motions.

In the 1983 Nihonkai- Chubu earthquake, oil tanks were damaged by liquid sloshing caused by long-period ground motions. In particular, liquid in oil tanks overflowed at Niigata during this earthquake, in spite of an epicentral distance of about 300 km. Kudo and Sakaue(1984) found that earthquake ground motion at a period of about 10 sec at Niigata was about ten times as strong as the one at Aikawa, whose location is much the same as Niigata. This fact means that the regionality of long-period ground motion is very important. It is often observed that seismic waveform from earthquakes in a seismic source zone is very similar with one another. In this case, two events occurred in the Izu region, southwest of Tokyo, but had different magnitude. This suggests that the effects of source mechanism and path on the ground motion are almost same, and that it is possible to explain the ground motion characteristics at an observation point for a seismic source zone, by only considering the scaling law of earthquake.

Figure 2.1 and 2.2 show the velocity waves and Fourier spectra for Chisimarettou-Oki earthquake and Iwate-Miyagi-Nairiku earthquake with long period ground motions being observed, respectively. At the Akita oil storage base, it is confirmed that there had been long period ground motions with period of 6-10 seconds, which are the sloshing periods of some tanks. And the ground motions during Niigata-Chuetsu earthquake, which occurred soon after the start of the observation, was also observed, and the components with period of 3-7 seconds were confirmed which displays the possibility that the components of the same period might be predominant in the seismic waves propagating in Nihon-Kai coast.

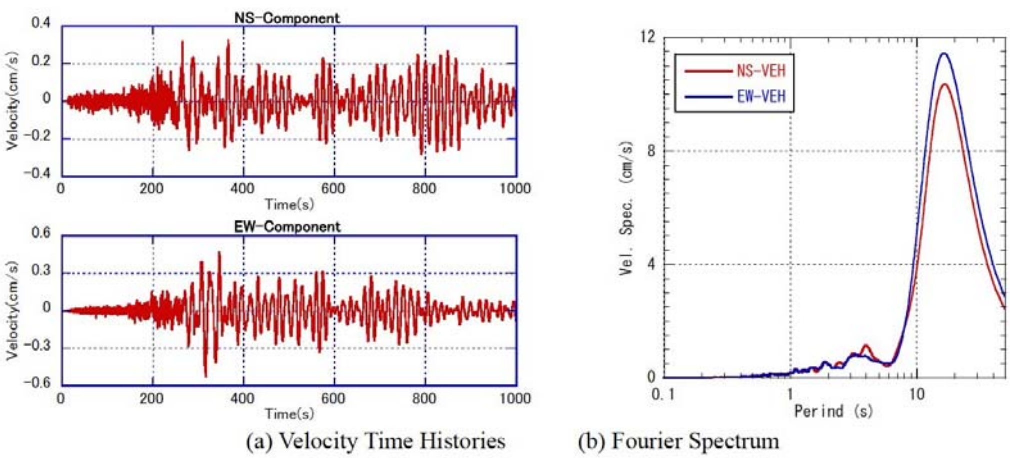

Figure 2.1. Chisimarettou-Oki earthquake

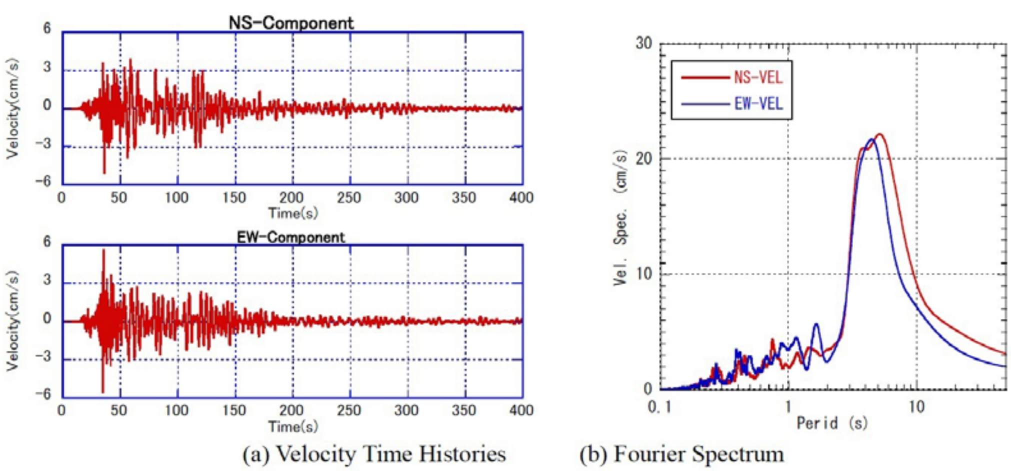

Figure 2.2 Iwate-Miyagi-Nairiku earthquake

Murata and Miyajima have considered that one of causes of the unusual phenomena seems to be sloshing of water in receiving water tank. If sloshing of water in many receiving water tanks occurred simultaneously, an abrupt increase in flow rate and a decrease in water pressure may be occurred. Occurrence of sloshing of water in receiving water tank depends on the dimensions of receiving water tank and the height of water in the tank. Murata and Miyajima have investigated dimensions of receiving water tank in a water distribution block of Osaka City and estimated the natural period of sloshing of the water. Figure 2.3 shows cumulative percentage of natural period of water in receiving water tank in case that the height of water is 3/4 and 1/2 of the height of water tank. The height of water is variable and depends on use of water. The natural period of sloshing is more than 1.0 second of more than 80% of the water tank in the direction of long side in the water distribution block in Osaka City.

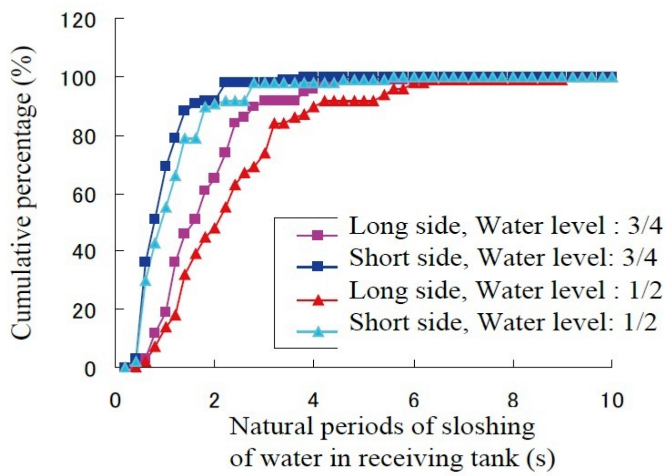

Fig. 2.3 Cumulative percentage of natural period of water in receiving water tank

2.2. Theoretical & numerical solutions

Although sloshing is a difficult mathematical problem to solve analytically, early treatments of this problem were carried out with analytical methods established on potential flow theory disregarding all viscous effects. In these studies, the irrotational motion of invicid and incompressible fluid inside the rigid container was represented with Laplace equation. The first approximate solution for a rigid cylindrical tank under horizontal motion was provided by Jacobsen on the basis of a closedform solution of the Laplace equation that satisfies specified boundary conditions. Housner used an approximate method idealizing the liquid as being constraint by rigid membranes to compute the hydrodynamic pressures developed in a rigid cylinder and rectangular fluid container subjected to horizontal accelerations. Veletsos and Yang split hydrodynamic effects obtained from Laplace equation in two parts namely the “impulsive” and the “convective” motions. Faltinsen derived a linear analytical solution for liquid sloshing in a horizontally excited 2D rectangular tank considering damping due to viscous effects. Fischera and Rammerstorferb investigated analytically the overall effect of pressure generated by interaction forces between sloshing and the wall motion modifying the free surface boundary conditions.

Since analytical methods are restricted to small motions of the sloshing fluid, the numerical solution algorithms, which take into account accurately the all source of nonlinearity of the sloshing problem have been developed over the years. In these methods, fluid motion inside the container have been represented with either Laplace, Euler, wave or Navier-Stokes equations which have been solved employing boundary element method (BEM), finite difference method (FDM), the finite-element method (FEM). Lay developed a numerical model for the seismic analysis of tanks with singleand double curvatures, which was achieved by transforming the boundary-element equations of the incompressible and inviscid fluid region governed by the Laplace equation into an equivalent finite-element mass matrix, which was then combined with the shell finite-element equations of motion. El-Zeiny formulated fluid motion with Laplace equation and developed a finite-element program, which uses an updated Eulerian-Lagrangian description of the liquid-structure interface in order to enforce compatibility between structure and liquid elements, to analyze the large amplitude liquid sloshing and nonlinear liquid-structure interaction. Chen and Chiang employed time independent finite difference method to study sloshing inside 2D tank with rigid walls solving incompressible Euler equation under fully nonlinear kinematic free-surface condition. This study was extended by Chen adding fluid viscous effects. Souli et al. and Souli and Zolesio developed a procedure for fluid-structure interaction problems based on Arbitrary Lagrangian Eulerian (ALE) algorithm of finite-element method and validated the applicability of the procedure for sloshing problems. For low magnitude loading, the sloshing problem can be solved using incompressible Navier Stokes equations with an implicit or explicit coupling to the structure. Longatte et al. applied this methodology where the fluid structure interface is described by the mesh nodes at the interface. For large amplitude loading that generates large structure deformation and fluid high mesh distortion, a coupling between Lagrangian structure and Eulerian fluid formulation can be used as detailed by Aquelet et al. The sloshing behaviors of fluid in 3D rigid cylindrical and rectangular tanks subjected to horizontal oscillations were addressed with a numerical and experimental study by Chen et al. Liu and Lin adopted finite difference method which solves Navier-Stokes equations to study 2D and 3D viscous and inviscid liquid sloshing in rectangular tanks and verified the results with the linear analytical solution and experimental data. Mitra et al. used finite element method to solve wave equation to quantify liquid sloshing in partially filled 2D rigid annular, horizontal cylindrical and trapezoidal containers.(Ozdemir et al 2010)

In order to validate theoretical and numerical solutions, experiments are the very powerful source to obtain information about sloshing and tank response due to external loadings. Several laboratory measurements have been conducted to quantify sloshing wave height, hydrodynamic pressure and shell stresses. Manos carried out experiment to determine impulsive mode frequencies and base-overturning moments of broad and tall tanks. Kana measured wall stresses of cylindrical flexible tank induced by sloshing and inertial loads experimentally. Tanaka et al. conducted dynamic tests on small and large scale models under earthquake loading in order to investigate elephant foot buckling and side slipping behavior of cylindrical tanks. The sloshing wave heights in 2D and 3D rectangular tanks subjected to external loads were measured experimentally by Liu and Lin. The more extensive literature review and detailed investigation of sloshing problem from basic theory to advanced analytical and experimental studies can be found in the work of Ibrahim.

2.2.1. FEM sloshing analysis

The conventional finite element procedure for the solution of engineering and academic problems including fluid-structure interaction effects are usually based on a purely Lagrangian algorithm because of easy implementation of this algorithm. But, these problems generally involve large deformations and construction of new free surfaces and cannot be handled by the same Lagrangian mesh during the entire simulation since severely distorted elements have low accuracy and their stable time step sizes are small for explicit time integration algorithms to continue the simulation. In this case, a new mesh must be generated and the old solution must be transferred from the old mesh onto the new mesh. This remeshing process can be achieved by a rezoning method where automatic mesh generators are called internally to create a new mesh with a new topology. In the rezoning methods, the dependent variables, such as velocity, pressure, internal energy, stress components and plastic strain, are updated on the new mesh by using a remap algorithm. The other alternative to construct undistorted mesh is to use The Arbitrary Lagrangian-Eulerian (ALE) algorithm which control mesh geometry independently from material geometry. Unlike a rezoning method, the topology of the mesh is fixed in an ALE algorithm where only the mesh nodes are relocated to obtain a homogeneous and undistorted mesh. The accuracy of an ALE calculation is often superior to the accuracy of a rezoned calculation because the algorithms used to remap the solution from the distorted to the undistorted mesh is second order accurate for the ALE formulation when using second order advection algorithms, while the algorithm for the remap in the rezoning is only first order accurate.

In order to compute interaction forces between fluid and structure, balance equations of both materials are defined with one of the kinematical description of continuum mechanics (Lagrangian Eulerian and arbitrary Lagrangian Eulerian) and solved utilizing boundary conditions and constitutive relations of materials. The balance equations for fluid and structure are formulated with three conservation equations of mass, momentum and energy. Although fluid and structure are governed by the same balance equations, the constitutive equations, which describe material behavior and relate stress to a measure of deformation, of two materials are different. The conservation equations of mass momentum and energy of fluid are formulated with Navier-Stokes equations which are solved to compute the fluid properties such as density, velocity and pressure.

There are two ways to solve Navier-Stokes equations in ALE form. In the first method, these equations with fully coupled form are solved by integrating forward in time which is very time consuming. The more widely favored approach is to employ operator split method which treats these equations in two distinct phases namely, Lagrangian and advection phases, in each time step. In the first phase all advective effects are neglected and the reference system is forced to follow the material flow as a Lagrangian manner. The physical material deformations are determined according to the equilibrium equations of Lagrangian phase (Eqs. (2.1) and (2.2)).

$$\rho \frac{d\vec{v}}{dt} = div\ (\sigma) + \vec{F} \tag{2.1}$$

$$\rho \ \frac{de}{dt} = \sigma : \dot{\varepsilon} + \vec{F}\vec{v} \tag{2.2}$$

Where ρ is the density, $\vec{v}$ is the velocity of the fluid particles, $\dot{\varepsilon}$ is the strain rate tensor, e is the internal energy per unit volume, $\vec{F}$ is the body force, t is time. Total Cauchy stress, σ, is defined as the summation of the pressure and deviatoric terms

ALE algorithm allows the finite element mesh to contain more than one material within the same element as well as each element can be restricted to contain a single material. For the single material ALE (SALE) case, the material interfaces are resolved directly by the finite element mesh as in the Lagrangian sense and no material fluxes over element boundaries have to be considered during the advection process. For the large deformation problems e.g. sloshing problems, it is advantageous to apply multi-material ALE (MMALE) approach, where the material boundaries can run freely through the finite-element discretization. For the multi-material ALE case, before the advection phase of operator split method, an interface-tracking algorithm is performed in order to compute accurately the material interfaces in the ALE elements containing several fluid materials. The most popular methods to track interfaces between multi-materials are the volume of fluid method (VOF), which was originally developed for the finite volume method (FVM) and the marker and cell (MAC) method.

The MAC method involves Eulerian flow calculation and Lagrangian particle movement. The velocity of the markers is found first by locating the fluid cell containing the particle and taking the average velocities of the cell nodes (the average is based on the finite element particles in the fluid cell). The particle cells have small inertia and tend to follow the fluid flow. However, the MAC method becomes complicated if the interfaces become highly distorted or if the geometry is complex.

2.2.2. Volume of fluid (VOF) method

The tracking of the material deformations can be performed by the VOF (Volume of Fluid) method or the Young method which is attractive for solving a broad range of non-linear problems in fluid and solid mechanics such as, sloshing and explosion applications, because it allows arbitrary large deformations and enables free surfaces to evolve. Moreover, the Lagrangian phase of the VOF method is easily implemented in an explicit ALE finite-element method. In this method, different material occurrences are considered by their respective volume fractions on the element level. For multi-material elements, the volume fraction of one fluid satisfies:

$$V_f \leq 1 \tag{2.3}$$

The total stress by σ is weighed by volume fraction to get the fluid stress fields:

$$\sigma_f \ = \ \sigma \, V_f \tag{2.4}$$

The material layout is described solely by the volume fraction repartition of the fluid material in the ALE elements. Specifically, a straight line using the simple linear interface calculation (SLIC) technique of Woodward and Collela approximates the interface in the cell. Interfaces are initially drawn parallel to the element faces. Then nodal volume fraction f is computed to each node based on the fraction volumes of elements that share the same node. This nodal volume fraction repartition determines the slope of the material interface inside the element. The normal vector to the interface inside the element is defined by

$$\vec{n} = \frac{\overrightarrow{grad}\, f}{|\overrightarrow{grad}\, f|} \tag{2.5}$$

The position of the interface is then oriented by the normal $\vec{n}$ so that it divides the element into two volumes, which correctly matches the element volume fraction (Figure 2. 4). The interface position is used to calculate the volume of the fluid flowing across cell sides. As the X-advection, Y -advection and Z-advection are calculated in separate steps, it is sufficient to consider the flow across one side only.

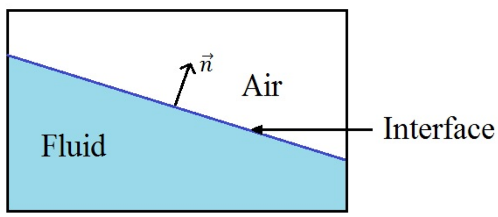

Figure 2.4. Interface between two materials, fluid and air.

For the single material and voided element case, the same procedure is applied. For voided elements, the stress is zero. In the computational process, the elements loop goes only through elements that are not voided. For free surface problems, the elements that are partially filled ($V_f \ < \ 1$) define the free surface. The location of free surface in a sloshing problem is defined with interface tracking algorithm. Tracking of interfaces of different materials in an element is followed by an advection phase in which the solution on the displaced mesh at the end of the Lagrangian phase is mapped into its original position for an Eulerian formulation or arbitrary position for an ALE formulation. In this phase, transport of history state variables: mass, internal energy and momentum across cell boundaries are computed. The transport equations for the advection phase are

$$\frac{\partial \emptyset}{\partial t} + c \; grad\; (\emptyset) = 0 \tag{2.6}$$

$$\emptyset(\vec{x}, 0) = \emptyset_0(x) \tag{2.7}$$

The transport equation (Eq. (2.6)) with initial condition (Eq. (2.7)) obtained from Lagrangian cycle of operator split method is applied for being the density, momentum per unit mass, and energy per unit mass:

$$\emptyset : \ \rho \, , \rho v \, , \rho e \tag{2.8}$$

Where $\vec{c}$ is the convective velocity. In the advection phase, the hyperbolic transport equation (Eq. (2.6)) is solved successively for the conservative variables mass, momentum and energy (Eq. (2.8)) with initial condition, $\Phi_0(x)$, which is the solution of Lagrangian phase at the current time. In equation (2.6), the time t is a fictitious time. (Ozdemiret al)

3. CONCLUSIONS

A state-of-the-art review on the sloshing of water reservoirs and tanks due to long period and long duration seismic motions is presented. An overview on previously in detail mentioned findings of reviewed subjects are stated.

The severity of sloshing and its dynamic pressure loads depend on the tank geometry, the depth of the liquid, the amplitude and the nature of the tank motions. They also depend on the frequency of excitation over a range of frequencies close to natural frequency of the fluid. In terms of analytical procedures for modeling of sloshing, although, most of earlier studies had focused on sloshing waves based on the regular excitation. Since the generation of liquid sloshing is explained by resonance between liquid in a tank and ground motions, it is very important, in predicting damage of tanks, to evaluate ground motions in the long- period range, including the natural period of liquid sloshing of a large storage tanks and water reservoirs.

Attempts for accurate numerical analysis of fluid-structure interaction by computer aided simulation have reached beyond the possibility. And now, researchers are trying to optimize the needed time and digital memory for such analyses by using alternative modeling approaches. However, a comprehensive approach with entire support of experimental tests or verified by comparison with previous real events has not issued yet and in future works more attention can be paid on it especially by considering the relation between the sloshing amplitude and the extent of damage, the responsibility of the higher-mode sloshing to the damage, the factor determining predominant periods of long-period strong ground motions, the extention of spatial variation of long-period strong ground motions, and the factor of underground structure controlling amplification of long-period strong ground motions.

The extensive parametric study of sloshing phenomena especially by considering long period and long duration ground motions leads to a simple and efficient methodology for predicting the dynamic response of liquid tanks.

REFERENCES

Ibrahim, R.A. (2005). Liquid Sloshing Dynamics: Theory and Applications, Cambridge University Press, New York, USA.

Ozdemir, Z., Souli, M., Fahjan, Y.M.(2010). FSI methods for seismic analysis of sloshing tank problems, *M´ecanique & Industries*, **11**, 133–147.

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, *Springer Science Business Media B.V. J Seismol* ***12***, 255-263.

Housner, G.W. (1954). Earthquake pressures on fluid containers. 8th Technical Report under Office of Naval Research, *California Institute of Technology*, Pasadena, California.

Veletsos, A.S, Yang, J.Y. (1977). Earthquake response of liquid storage tanks. *Advances in Civil Engineering Through Engineering Mechanics, Proceedings of the Engineering Mechanics Division Specialty Conferences*, ASCE, Raleigh, North Carolina, 1–24.

Fischera, F.D., Rammerstorferb, F.G. (1999). A Refined Analysis of Sloshing Effects in Seismically Excited Tanks, Int. J. *Press. Vessels Piping* **76**, 693–709.

Chen, B.F., Chiang, H.W. (1999). Complete 2D and Fully Nonlinear Analysis of Ideal Fluid in Tanks, *J. Eng. Mech. ASCE* **125,** 70–78.

Chen, B.F. (2005).Viscous Fluid in Tank under Coupled Surge, Heave, and Pitch Motions, *Journal of Waterway, Port, Coastal, and Ocean Engineering ASCE* **131**, 239– 256.

Souli, M., Ouahsine, A., Lewin, L. (2000). ALE formulation for fluid-structure interaction problems, *Comput. Methods Appl. Mech. Eng*. **190**, 659–675.

Koketsu, K., Hiroe Miyake, H.(2008). A seismological overview of long-period ground motion, *Springer Science Business Media B.V. J Seismol* **12**, 133-143.
Souli, M., Zolesio, J.P. (2001). Arbitrary Lagrangian-Eulerian and free surface methods in fluids mechanics, *Comput. Methods Appl. Mech. Eng*. **191,** 451–466.
Longatte, E., Bendjeddou, Z., Souli, M.(2003). Application of Arbitrary Lagrange Euler Formulations to Flow-Induced Vibration problems, *J. Press. Vessel Technology* **125,** 411–417.
Aquelet, N., Souli, M., Olovson, L.(2005). Euler Lagrange coupling with damping effects: Application to slamming problems, *Comput. Methods Appl. Mech. Eng*. **195,** 110–132.
Liu, D., Lin, P.(2008).A numerical study of three-dimensional liquid sloshing in tanks, *J. Comput. Phys*. **227**, 3921–3939.
Manos, G.C.(1986).Dynamic response of a broad storage tank model under a variety of simulated earthquake motions. Proc. *3rd U.S. Nat. Conf. on Earthquake Engrg., Earthquake Engineering Research Institute*, E1 Cerrito, Calif., 2131–2142.
Tanaka, Motoaki, Sakurai, Ishida, Tazuke, Akiyama, Kobayashi and Chiba.(2000). Proving Test of Analysis Method on Nonlinear Response of Cylindrical Storage Tank Under Severe Earthquakes, *Proceedings of 12th World Conference on Earthquake Engineering (12 WCEE)*, Auckland, New Zealand.
Chen, Y.H., Hwang, W.S., Ko, C.H. (2007). Sloshing Behaviors of Rectangular and Cylindrical Liquid Tanks Subjected to Harmonic and Seismic Excitations, Earthquake Engineering and Structural Dynamics **36**, 1701– 1717.
El-Zeiny, A. (1995). Nonlinear Time-Dependent Seismic Response of Unanchored Liquid Storage Tanks, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of California, Irvine.
Belytschko, T., Liu, W.K., Moran, B.(2000).Nonlinear finite elements for continua and structures, Wiley, New York.
Ghosh, S., Kikuchi, N.(1991). An arbitrary Lagrangian-Eulerian finite element method for large deformation analysis of elastic-viscoplastic solid, *Comput. Meth. Appl. Mech. Engng*. **86**, 127–188.
Benson, D.J. (1997). A mixture theory for contact in multimaterial eulerian formulations, *Comput. Meth. Appl. Mech. Eng.* **140**, 59–86.
Young, D.L. (1982). Time-dependent multi-material flow with large fluid distortion, Numerical Methods for Fluids Dynamics, K.W. Morton, M.J. Baines (eds.), Academic Press, New-York.
Mitra, S., Upadhyay, P.P., Sinhamahapatra, K.P.(2008). Slosh Dynamics of Inviscid Fluids in Two-Dimensional Tanks of Various Geometry Using Finite Element Method, Int. J. Num. Methods Fluids 56, 1625–1651.
Aquelet, N., Souli, M., Gabrys, J., (2003). Olovsson, L. A new ALE formulation for sloshing analysis, *Struct. Eng. Mech.* **16**, 423–440.
Zama, S.(1996). Regionality of long-period ground motion using JMA strong motion displacement records, *Eleventh World Conference on Earthquake Engineering*.
Iwaharai, T.(2008). Safety assessment of underground tank against long-period strong ground, The 14th *World Conference on Earthquake Engineering*, Beijing, China.
Murata, K. and Miyajima, M. (2007). Influence of Receiving Water Tank Sloshing on Water Distribution System, *Journal of Japan Earthquake Engineering*, **Vol. 7, No. 1**, 27-42.
OpenFOAM user guide, ver.2.0.0.(2010). < www.OpenFOAM.com >