Dynamic behavior of fluid rectangular container

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***Abstract*—**Liquid store tanks are used to store of fluid. This paper presents the theoretical background for fluid effect in moved container and Finite element method numerical simulation of response of fluid filled rectangular tank due to horizontal harmonic motion. The peak waves of fluid in fluid filled rectangular tank were analysed in depending of frequency and acceleration. The realised experiments confirm the 1th mode of circular frequency. The FEM numerical simulation of tank fluid filling was completed dynamic behaviour of fluid and its effect on tank solid domain.

***Keywords*—**Fluid, rectangular tank, Finite element method.

I. Introduction

THE natural vibration analysis of solids in contact with fluid has been an issue for many years.

It is knows that fluid in partially filled containers tends to experience under certain conditions [1]. When frequency of the container motion is close to the natural frequency of fluid in the container, localized high impact load on the tank walls occur due to extreme liquid motion [2]. More researchers have investigated sloshing phenomena using various analytic, numerical, and experimental approached, and these studies have revealed many significant phenomena in recent decades [3].

The potential formulation is often used in sloshing studies. This approach provides a simplified means of evaluating sloshing, but its use is limited in the case of real nonlinear liquid problems [4]. Many potential flow theory is not sufficiently reliable in many numerical studies based on Navier-Stokes equations have been performed to overcome the aforementioned problem. The calculation of the free surface profile inside a container is a key factor in the accurate approximation of loads generated by sloshing. As a result, many studies have been conducted using Two-Dimensional (2-D) and Three-Dimensional (3-D) simulations with the use of free-surface capturing models such as the Marker and Cell (MAC) approach, the Volume of Fluid method (VOF), and the Level Set Method (LSM), or a combination of LSM and VOF [5]. Also, recently, the Smoothed Particle Hydrodynamics (SPH) approach has been quite successful in simulating 2-D sloshing flows [6].

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Using numerical tools, investigators have examined characteristics of sloshing phenomena that depend on design variables such as depth of fluid, geometry of container, the frequency and amplitude of external excitation, and the position of the center of gravity. To suppress extreme sloshing, it is important to carefully consider these design variables [7]. One of the solutions used to prevent extreme free surface fluctuations is to install baffles inside a liquid tank. Many researchers have successfully demonstrated that installing baffles is useful in reducing the pressure loads on the walls or ceiling of a tank in combination with suppressing extreme fluid motion, using numerical simulation based on the NS equations. The filling level in the tanks is also a key element. The largest sloshing loads tend to occur at filling level (H) and tank length (L) filling ratios of $0.1 \le H/L \le 0.5$ [8].

Most of the aforementioned studies focused on a frequency of external excitation that is close to the natural frequency. However, to our knowledge, it is hard to find reports that describe a wide frequency ratio range for sloshing in 2-D and 3-D tanks, and especially for viscous flow conditions [9]. Recently focused on sway motion (horizontal amplitude excitation) and considered a broad range of frequencies, filling conditions, and amplitude excitations. However, the filling ratios they examined are quite small (to satisfy the shallow water regimes). A narrow tank has been used to limit 3-D effects and allow for an extensive study of 2-D waves [10].

The phenomenon of motion of liquids when fluid in containers can be excited and has an unrestrained surface, was referred as "sloshing" [11]. Liquid sloshing phenomena can be triggered e.g. by seismic effects in stationary containers or can be initiated by movements of the container itself. The sloshing characteristically of is a wave motion from side to side within the container [12].

The motion of the liquid storage tanks is, due to the high complexity of the problem, in fact, really complicated task. Number of particular problems should be taken into account, for example:

- dynamic interaction between contained fluid and tank,
- sloshing motion of the contained fluid,
- dynamic interaction between tank and sub-soil.

The fluid flows causes sloshing of free surface. The free liquid surface may experience different types of motion including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic [13]. The type of motion is depended on the container shape and type of excitation. The amplitude of slosh depends on the liquid-fill depth, liquid properties, tank geometry, frequency and amplitude of the tank motion. The fluid resonance in the case of horizontal excitation is activate when the external exciting frequency is close to the natural frequency of the liquid [14].

The liquid sloshing is important task with regard to the reliability and safety structures, because an eventual damages of containers used for storage of hazardous liquids, e.g. petroleum, liquefied natural gas industries, and different forms of chemical and radioactive waste, are catastrophic, consequences are financial, and environmental loses [15]. The knowledge of sloshing phenomenon of the contained fluid, dynamic interaction between contained fluid and tank, hydrodynamic pressures, as well as frequency properties of tank-fluid systems are played fundamental role for a reliability design of earthquake-resistant structures/facilities - tanks.

The container, full or partially filled with liquid, subjected to motion forms the basis for many complex problems [16].

The most common situation is that the liquid behaves as one interconnected mass, possessing an infinite number of degrees of freedom. The oscillation of such a liquid mass in a vessel is commonly known as "sloshing". If the motion is very vigorous and accelerations greater than gravity exist, the fluid may splash and separate [17].

The behaviour of fluid in a container was studied probably as first Westergaard, who determined, in 1933, hydrodynamic pressures acting on rectangular dam subjected to horizontal acceleration [18]. Then Poisson, Rayleigh, Lamb, Hopkins, Rodriquez, Jacobsen, Werner, Sundquist, Zangar dealt with this problem. Housner [19] in 1957 presented a simplified analysis for the hydrodynamic pressure develop on the tank walls and tank bottom when the fluid container fixed to base is subjected to a horizontal acceleration [20]. Hopkins and Jacobsen gave the analytical and experimental observations of rigid tank. Graham and Rodriguez used spring-mass analogy for this problem [21]. Housner recommended a simple procedure for estimating the dynamic fluid effect on rectangular tank [22]. Epstein extended of Housner concept of spring-mass of fluid filled container and gave the practical rule for design [23].

The seismic design of circular and rectangular tanks is recommended by various codes of practices. Their implementation strategy is rather varied leading to significantly different design forces in some cases [24]. Of the best structural engineering design codes that tackle fluid tank systems are the American Concrete Institute, ACI 350.3, the Euro Code 8, the Standards Association of New Zealand, NZS and Indian code IS 1893-1984 [25]. These codes address ground supported circular and rectangular concrete tanks with fixed or flexible bases.

European Committee for Standardization prepared code Eurocode 8 (2006). Part 4 of this code is related to tanks, silos and pipelines [26]. Eurocode 8-4 gives recommendation for hydrodynamic pressure in rectangular tanks from seismic excitation. Eurocode 8 recommends Malhotra simple procedure of mechanical model for seismic analysis of liquid-storage flexible cylindrical tanks to used for the design of rectangular tanks as well (with replacing of R with L), with considered error less than 15% [26].

II. Effect of Fluid on Moved Container

When container is subjected to external excitation, the fluid exerts hydrodynamic pressure together with hydrostatic pressure on walls and bottom of ground-supported liquid-containing or liquid-transporting structures [27].

The seismic analysis and design of liquid-containing or liquid-transporting structures is, due to the high complexity of the problem, really complicated task. A number of particular problems should be taken into consideration, for example dynamic interaction between contained fluid and structure, sloshing motion of the contained fluid, and dynamic interaction between structure and sub-soil [28].

We consider a rigid rectangular container partly filled with liquid. We assumed the incompressibility of the fluid (constant liquid volume) with density ρ.

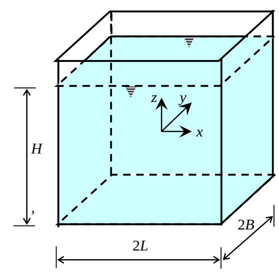

Fig. 1 Coordinate system and tank geometry for rectangular tank

The single-valued velocity potential of irrational flow in any simply connection region is $\Phi(x,y,z,t)$ [29].

The velocity is given by

$$\mathbf{V} = \nabla\Phi . \tag{1}$$

where ∇ is vector operator and Φ velocity potential function.

The components of the velocity vector V are

$$u = \frac{\partial\Phi}{\partial x}, \quad v = \frac{\partial\Phi}{\partial y}, \quad w = \frac{\partial\Phi}{\partial z}. \tag{2}$$

The vector definition of Newton second law of motion for a particle in a nonviscous fluid is

$$-\frac{1}{\rho}\nabla p + \mathbf{F}_B = \mathbf{A}, \tag{3}$$

where p is the intensity of normal pressures, $\mathbf{F}_B$ the body force vector, and **A** the acceleration vector.

The equations of motion are given

$$\begin{aligned}
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x},\\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x},\\
&\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x},
\end{aligned} \tag{4}$$

where *u, v, w* are rectangular velocity components and *x*, *y*, *z* rectangular coordinate, *p* is normal pressure, and *t* time [30].

The natural frequency for the n^{th} mode is given by Housner [31]

$$\omega_n^2=\frac{ng}{L}\sqrt{\frac{5}{2}}\tanh\left(\sqrt{\frac{5}{2}}\frac{nH}{L}\right), \tag{5}$$

where *n* is the mode number.

Accordingly the natural frequency for the n^{th} mode is given by Graham and Rodriguez [31]

$$\omega_n^2=\frac{n\pi g}{2L}\tanh\left(\frac{n\pi H}{2L}\right). \tag{6}$$

III. FEM NUMERICAL SIMULATION

The finite element method (FEM) is well established for the simulation of complex engineering problems involving structures and fluids [32].

A. The incompressible Navier-Stokes equations

We consider a fluid, liquid, or gas, moving in a domain **Ω**. The fluid motion is a difficult task since this is a nonlinear physical phenomenon involving many unknowns. The main unknowns are the mass density, the pressure, the velocity, and the temperature, but the list may be longer depending on the particular case [33].

The incompressible Navier–Stokes equations for Newtonian fluids is given by

$$\partial_t\mathbf{v}+\left(\mathbf{v}\cdot\nabla\right)\mathbf{v}-\nabla\cdot\left(2\nu\, D\mathbf{v}\right)+\nabla p=\mathbf{f}, \tag{7}$$

$$\nabla\cdot\mathbf{v}=0, \tag{8}$$

where *v* is the velocity of the flow, *p* is pressure, and its deformation tensor is $D\mathbf{v}=(1/2)(\nabla\mathbf{v}+\nabla\mathbf{v}^t)$. The momentum equation (28) is inherited from Newton's law, while equation (29) is the mass conservation equation for incompressible flow s [34].

The general mass conservation equation satisfied by v and ρ is given by

$$\partial_t\rho+\nabla\cdot\left(\mathbf{v}\rho\right)=0. \tag{9}$$

The pressure and velocity had to define for the fluid domain and the additional special conditions are considered:

- free surface, the interface between fluid and gas;
- common boundary between solid and fluid.

B.3.2 Boundary conditions

The moving boundary - free surface can be considered for the fluid flow equations. In case of moving boundaries, the condition $\hat{\mathbf{u}}\cdot\mathbf{n}=\hat{u}_s$ and $\hat{\mathbf{u}}\cdot\mathbf{t}=\hat{u}_t$, where $S_{\hat{u}}$ and $S_{\hat{u}}$ corresponds to the part of the surface with $\hat{u}_s$ and $\hat{u}_t$ are displacements in the normal and tangential directions, respectively. **n** and **t** are unit normal and tangent vectors to the boundary and $\hat{\mathbf{u}}$ is the boundary displacement [35].

When free surface is considered, the effect of air is usually included only as a pressure p_0

$$-p_0\mathbf{n}\text{ - }\tau\cdot\mathbf{n}\tau=\alpha\left(\frac{1}{R_t}+\frac{1}{R_s}\right)\mathbf{n}, \tag{10}$$

where $\boldsymbol{\tau}$ is stress tensor, **n** is a unit normal vector to the interface surface pointing outwards of the free surface, α is the coefficient of surface tension between the fluid and air and R_t and R_s are the principal radii of curvatures of the interface surface.

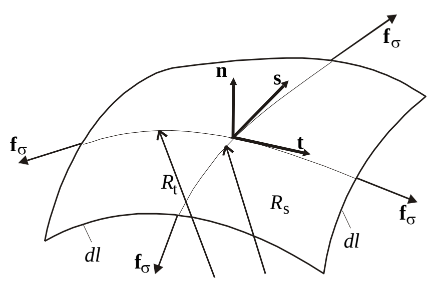

Fig. 3 Element of interface between fluid and gas

The condition must be satisfied

$$\frac{\partial\mathbf{S}}{\partial\mathbf{t}}+\left(\mathbf{v}\text{ - }\hat{\mathbf{v}}\right)\cdot\nabla S=\mathbf{0}, \tag{11}$$

which ensures that the particles, that are at the free surface at time t_0, will remain on that surface for all times [36].

Dynamic boundary conditions for free surface - forces between interactive forces of liquid and gas are given by

$$\begin{aligned}
&\mathbf{f}_l.\mathbf{n}+\sigma K=-\mathbf{f}_g\ \mathbf{n},\\
&\mathbf{f}_l.\mathbf{t}+\sigma K=-\mathbf{f}_g\ \mathbf{t},\\
&\mathbf{f}_l.\mathbf{s}+\sigma K=-\mathbf{f}_g\ \mathbf{s},
\end{aligned} \tag{12}$$

where $\mathbf{f}_l$ resp. $\mathbf{f}_g$ are forces exerted by a *liquid*, resp. *gas*, $\mathbf{t}$ a $\mathbf{n}$ tangent and normal to free surface and $\mathbf{s}$ is surface tension, Figure 3.

IV. Analysis, Results and Conclusion

The rectangular tank made of glass filled with water was used in the experiment. The tank's inner bottom dimensions were 19.2 cm and 39.2 cm. The inner tank height was 24.2 cm, consequently it is dimension of full fluid filling.

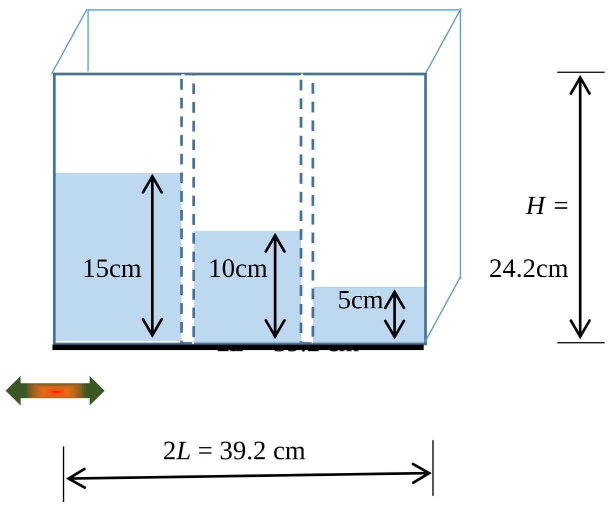

Fig. 3 The model of rectangular tank with variable fluid filling 5 cm, 10 cm and 15 cm

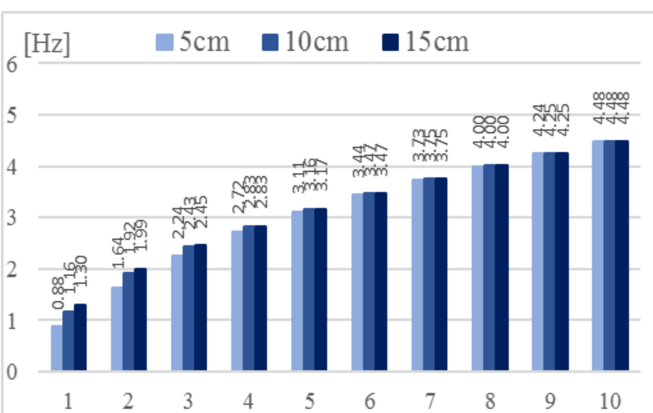

Fig. 4 The comparison of first then fluid natural frequencies for 5 cm, 10 cm and 15 cm fluid filling

The comparing of the first then circular frequencies for tank fluid filling using eq. (5), was documented in Figure 4. The values of first seven circular frequencies for tank fluid filling using eq. (26) are different. The eight and next natural frequencies for the fluid filling of height 5 cm, 10 cm and 15 cm give the same values.

A glass rectangular tank was used in the experiment. The tank was excited by horizontal harmonious motion with various frequencies with amplitudes 0.5 cm and 1.0 cm in the direction of tank longer bottom side 39.2 cm. The height of water filling in the container was 5 m, 10 cm and 15 cm. The tank was excited by a horizontal harmonious motion of various frequencies with amplitudes of 0.5 cm in the direction of tank longer bottom side 39.2 cm, see Figure 3.

The height of water filling in the container was 5 m, 10 cm and 15 cm. The tank was excited by a horizontal harmonious motion of various frequencies with amplitudes of 0.5 cm in the direction of tank longer bottom side 39.2 cm, see Figure 3.

In the case of a shallow filling of water, especially the filling height 5 cm, the phenomena of splashes appear more pronounced at the surface than at higher heights of fluid filling. The monitored wave heights were varied in depending of excited frequency and the amplitude. The Figures 8 and 10 are documented height if water waves in depending of frequencies, for 0.5 cm amplitude in Figure 8 and for amplitude 1.0 cm in Figure 10. On the other side, Figures 9 and 11 are documented heights of water waves in depending of acceleration, for 0.5 cm amplitude in Figure 9 and for amplitude 1.0 cm in Figure 11.

The peak waves of fluid for amplitude 0.5 cm fluid filling were shown:

- with black "+" for 5 cm fluid filling of tank,
- with blue "o" for 10 cm fluid filling of tank,
- with red "x" for 15 cm fluid filling of tank.

Using eq. (6), the first frequencies of the fluid filling in glass rectangular the frequencies are:

- f_1 = 0.875 Hz for 5 cm fluid filling of tank is shown by dash black line in Figures 8 and 10,
- f_1 = 1.156 Hz for 10 cm fluid filling of tank is shown by dash blue line in Figures 8 and 10,
- f_1 = 1.29 Hz for 15 cm fluid filling of tank is shown by dash red line in Figures 8 and 10.

The movement of fluid free surface and peak wave heights confirmed the correctness of the eq. (5) and eq. (6) for the calculation of the first natural frequency in all cases of water filling that is used in experiment. The culmination of the waves near the first frequency is evident.

The second sloshing frequency, f_1 = 0.875 Hz, was not seen in case of 5 cm water filling by exciting amplitude 0.5 cm, the flow of free surface of water was not observable. Obviously, it is due to the interference of waves on the surface. The other higher shapes could not be watched.

The water splashes were observed very strong in case of water filling 10 cm, 15 cm and water filling 5 cm with exited amplitude 1.0 cm, but the fluid gave marked splashes near the first mode of the liquid.

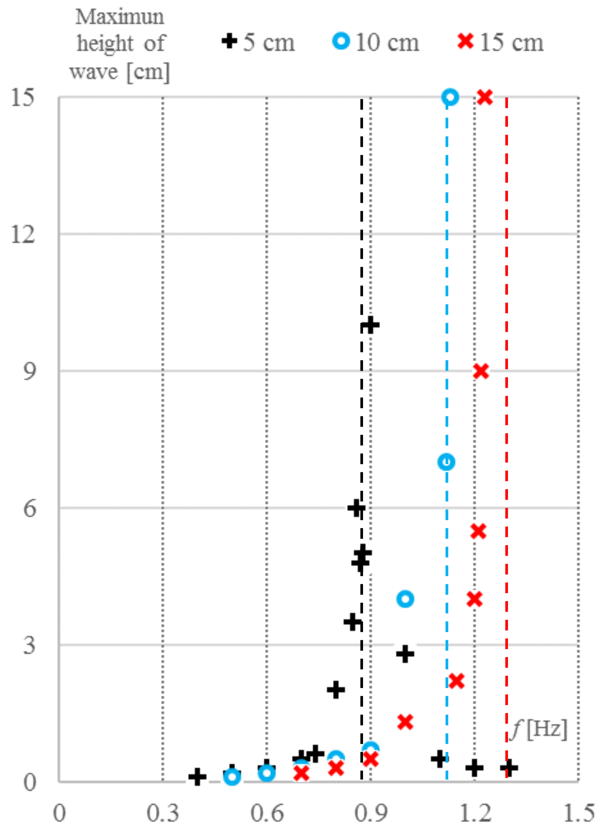

Fig. 8 The peak values of fluid waves in rectangular tank excited with amplitude 0.5 cm for 5, 10 and 15 cm fluid filling as function of frequency f [Hz]

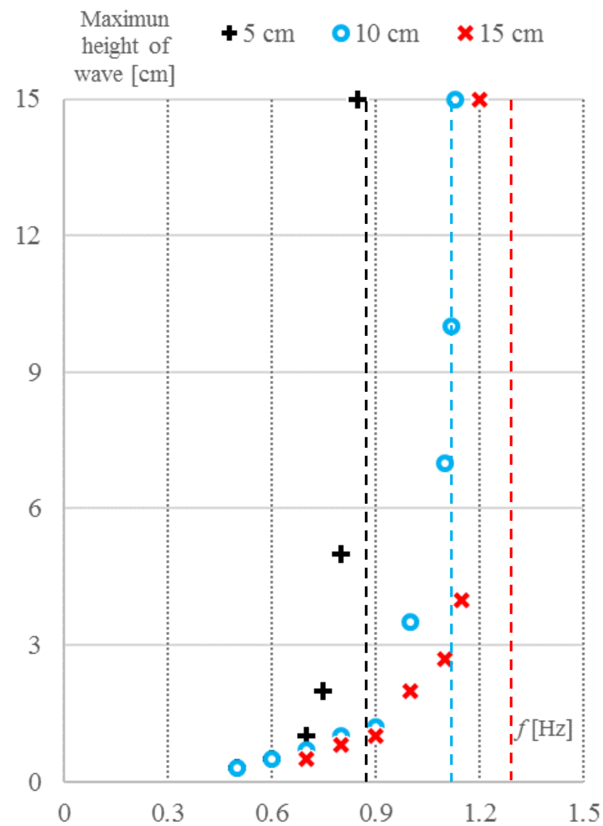

Fig. 10 The peak values of fluid waves in rectangular tank excited with amplitude 1.0 cm for 5, 10 and 15 cm fluid filling as function of frequency f [Hz]

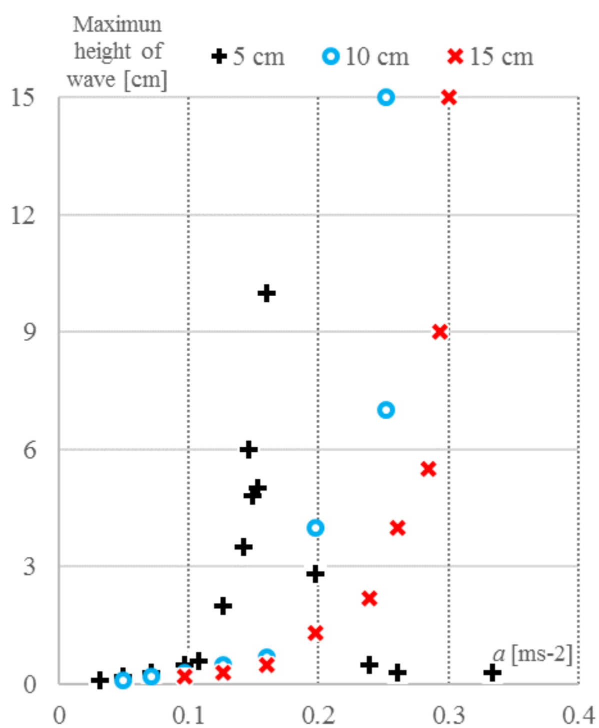

Fig. 9 The peak values of fluid waves in rectangular tank excited with amplitude 0.5 cm for 5, 10 and 15 cm fluid filling as function of acceleration a [ms^{-2}]

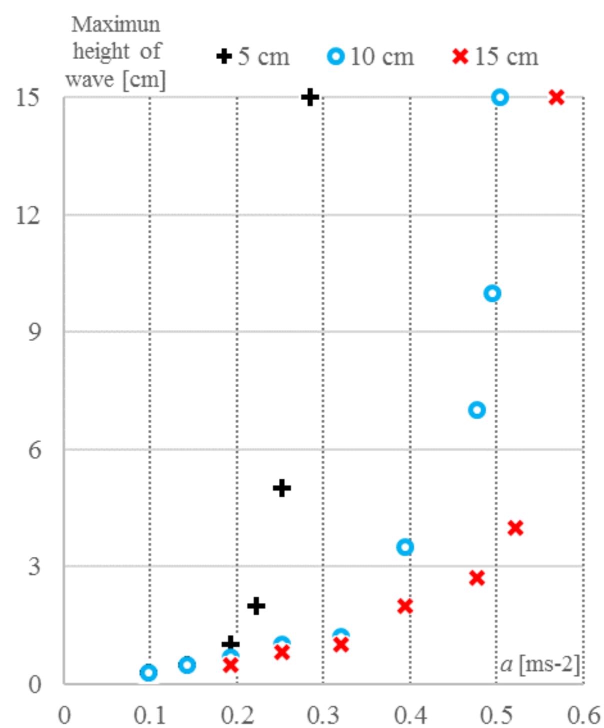

Fig. 11 The peak values of fluid waves in rectangular tank excited with amplitude 1.0 cm for 5, 10 and 15 cm fluid filling as function of acceleration a [ms^{-2}]

V. Numerical analysis

The experiment shown, if the exciting is in one direction only (along the length of one side of a rectangular tank) it is sufficient to simulate the problem as a 2D numerical model. The liquid was simulated as 2D model with fluid boundary conditions "BOUNDARY-CONDITION WALL". It is fictitious rigid wall with the possibility of rigid solids movement (bottom, left and right border) and free surface (upper border).

The results were obtained from the first four seconds of movement of the tank model with the dimensions in chapter 4, the height of fluid filling was considered 15 cm, the frequency of horizontal harmonious excitation was $f = 1$ Hz with amplitude 0.5 cm. The peak value of hydrostatic pressure 1471.5 Pa was given from analytical solution $p = \rho \cdot g \cdot h = 1000 \cdot 9.81 \cdot 0.15$. The peak values from numerical simulation were obtained in software Adina

- the hydrodynamic pressure 1571 Pa;
- the vertical displacement 1.109 cm.

The Figures 12 and 13 shows shape of the fluid domain with this pressure distribution in time 2.775 s and shows shape of the fluid domain with this vertical displacement distribution in time 1.325 s, respectively.

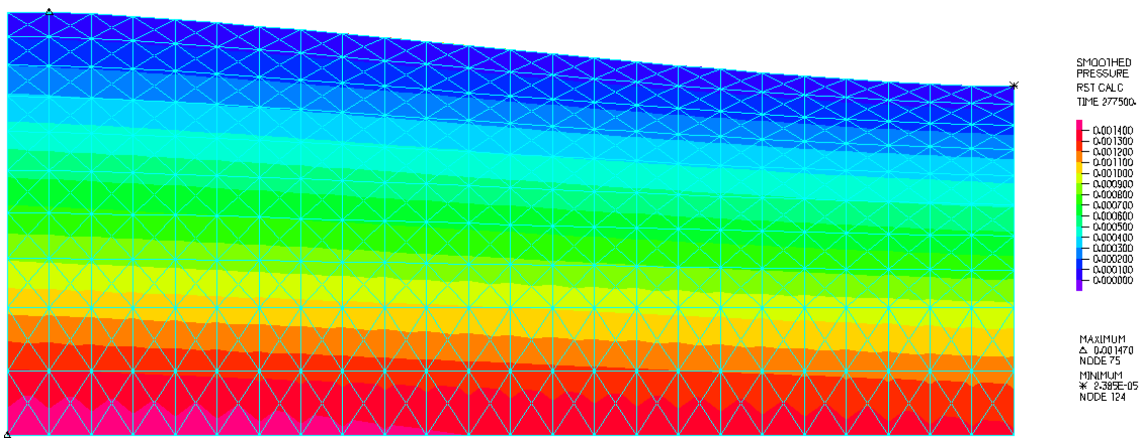

Fig. 12 Fluid domain shape and pressure in time 2.775 s

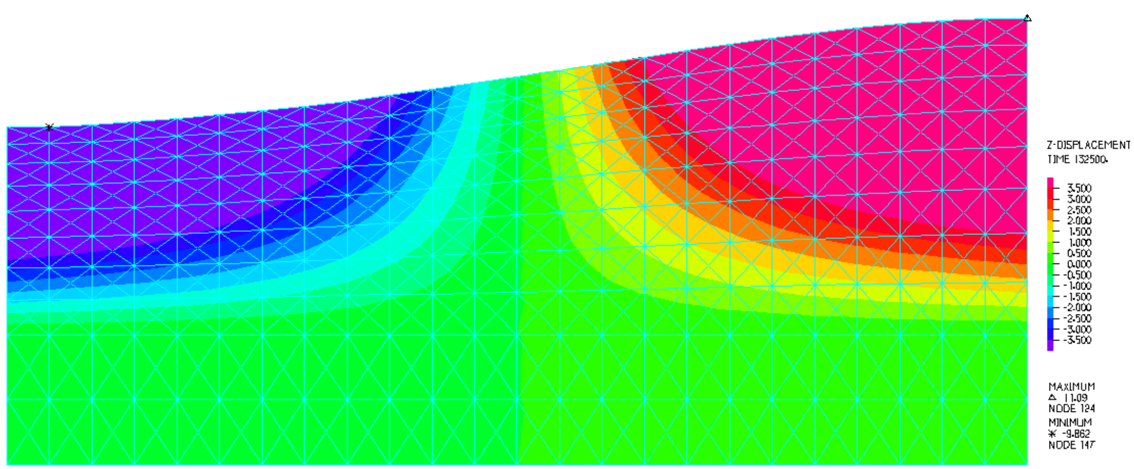

Fig. 13 Fluid domain shape and vertical displacement in time 1.325 s

The time-depended response of fluid pressure in fluid domain in node LDE (left down edge of fluid domain) with red color and RDE (left down edge of fluid domain) with blue color were documented in Figures 14 and the time-depended response of fluid pressure in fluid domain node MD (middle down of fluid domain) Figure 15. The time-depended response of fluid pressure on the tank in node LDE and RDE is colerated about value 1471.5 Pa that is the peak value of the hydrostatic pressure at the bottom of tank wall. The peak value of hydrodynamic pressure 1571 Pa arises in node LDE of fluid domain, see Fig. 12 and Fig. 14.

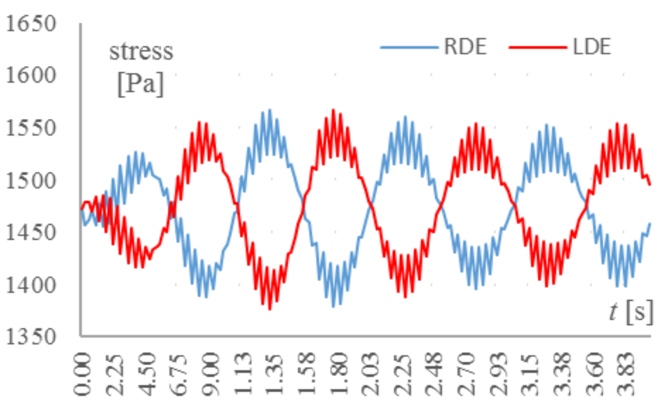

Fig. 14 Time-depended response of fluid pressure on the tank in node LDE and RDE

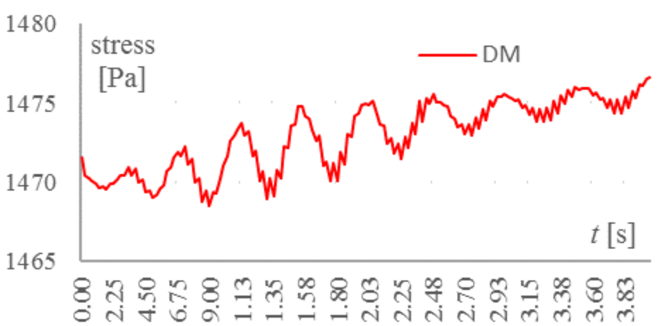

Fig. 15 Time-depended response of fluid pressure on the tank left bottom in node MD

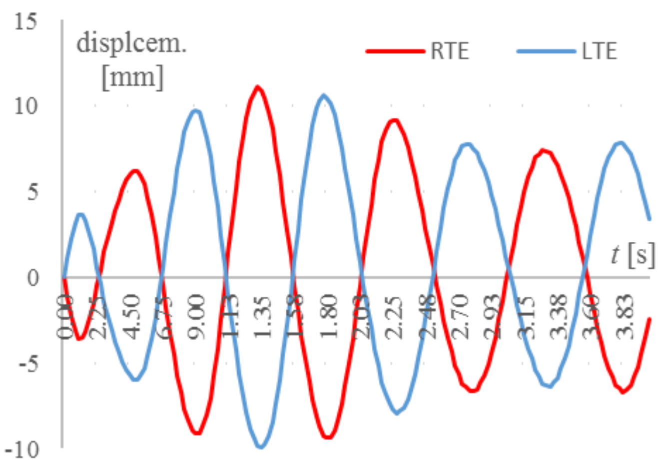

Fig. 16 Time-depended response of fluid vertical displacement on the free surface in node RTE and LTE

The Figures 16 and 17 show the time-depended response of fluid domain vertical displacement in node LTE (left top edge of fluid domain) and in RTE (left top edge of fluid domain) were documented and the time-depended response of fluid vertical displacement in fluid domain node MT (middle top of fluid domain), respectively. The time-depended response of fluid vertical displacement of fluid domain in nodes LDE and RDE is correlated about zero value, it is the original value of fluid vertical displacement of fluid domain in time of quit situation.

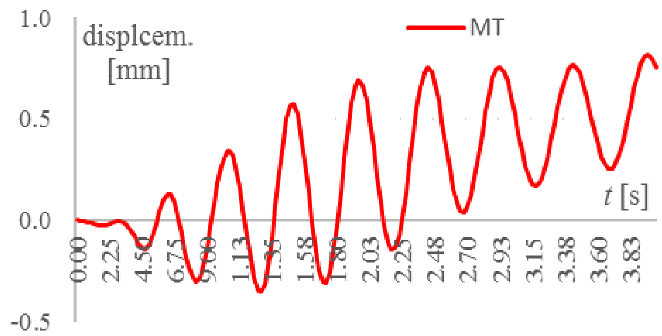

Fig. 17 Time-depended response of fluid vertical displacement on the free surface in node MT

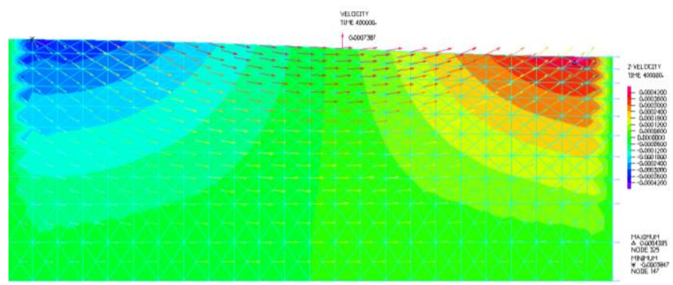

Fig. 18 Fluid domain shape and vertical velocity in time 4.0 s

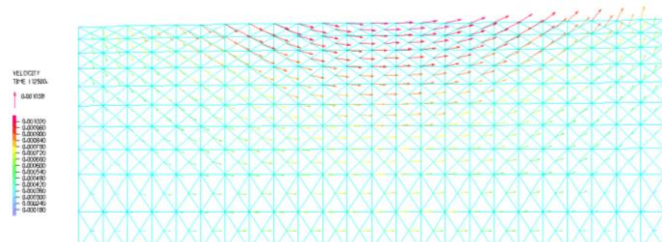

Fig. 19 Fluid domain shape and velocity vectors on right side

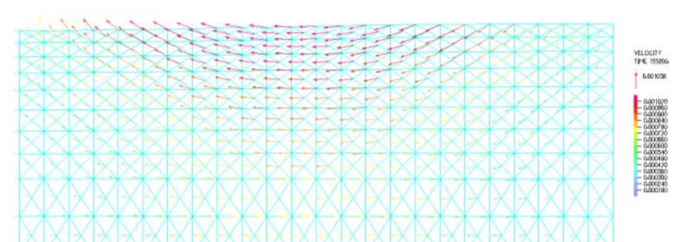

Fig. 20 Fluid domain shape and velocity vectors on left side

The shape of fluid domain and velocities distribution are seen in Figures 18 and 20:

- vertical velocity in time 4.0 s, fFigure 18,
- velocity vectors on right side, Figure 19,
- velocity vectors on right side, Figure 20.

VI. Conclusion

The fluid response on rectangular tank due to horizontal harmonic motion of tank bottom was analysed in this paper.

The rectangular tank made of glass was used in the experiment and was filled with water to the filling level 5 m, 10 cm and 15 cm. The first then frequencies were calculated and compared for three levels of water filling.

The observations of liquid behaviour and waves heights were summarized and from the experiment. The peak waves of fluid in of the glass rectangular tank were culminated near the first calculated natural frequency, es of fluid in fluid filled rectangular tank were analysed in experiment to the 1th mode of circular frequencies were confirmed.

The liquid behaviour was simulated by 2D model. The pressures, displacement and velocity were analysed and documented in this paper.

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