International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:5, No:6, 2011

Fuel Reserve Tanks Dynamic Analysis Due to Earthquake Loading

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***Abstract*—**In this paper, the dynamic analysis of fuel storage tanks has been studied and some equations are presented for the created fluid waves due to storage tank motions. Also, the equations for finite elements of fluid and structure interactions, and boundary conditions dominant on structure and fluid, were researched. In this paper, a numerical simulation is performed for the dynamic analysis of a storage tank contained a fluid. This simulation has carried out by ANSYS software, using FSI solver (Fluid and Structure Interaction solver), and by considering the simulated fluid dynamic motions due to earthquake loading, based on velocities and movements of structure and fluid according to all boundary conditions dominant on structure and fluid.

***Keywords*—**fluid and structure interactions, finite element method, ANSYS – FSI

I.INTRODUCTION

CYLINDRICAL layers with thin walls are widely being applied at different industries including storage tanks, silos, cooling towers, power plant reservoirs and so on. Thus, it is important to analyze such storage tanks from different views, and aspects. Among other subjects, storage tanks contained fluids as well as their interactions are of important issues in which researchers are interested.

Given that the equations of fluid and structure interactions are nonlinear, analytical solutions aren't often applied. Because by inserting inputs (entry data) in the equation to predict the interactions, the case becomes more complicated, therefore, numerical techniques are the only available procedures to achieve the accurate solutions.

Based on studies by researchers, various solutions have been presented to conduct the dynamic analysis of fuel storage tanks. Among them, it can be mentioned the analysis of the finite elements of storage tank by Zinkovitch et. al [1]. Furthermore, this subject has many applications in industry, so a proper technique has been offered according to the current standard (such as API650) [2]. The design standard of API650 is based on displacing the fluid impacts on the storage tank walls with mass and spring, while this standard has a certain relationship between spring stiffness and the mass equivalent to height of fluid within the tank. This technique was suggested by Aaron and Hanzer for the first time [3].

This paper tried to investigate the required equations for evaluating fluid motions caused by tank pillar vibrations, then a numerical method has been presented to analyze the case by using ANSYS software, finally the obtained results have been compared with the results produced by the standard.

II. THEORETICAL DISCUSSIONS

By considering a cylindrical tank in fig. (1), and assuming that there is an ideal fluid within the storage tank, the boundaries of 1 and 2 are common to fluid and structure areas so the following expression is established:

$$\nabla \phi . n^{f} = \dot{u}_{n} \tag{1}$$

Where ***ϕ*** is velocity potential function, ***n*** is single vector perpendicular to on fluid area and ***û*** is wall velocity.

If we want to show this expression based on acceleration and pressure, then we have;

$$\frac{\partial P}{\partial n} = -\rho \ddot{u}_{n} \tag{2}$$

also, for area 3 as a fluid free surface, at first it is assumed ***P=0*** for simplification.

But this equation isn't applied for every free surface gravity waves under different conditions, but considering the ratio of real level (height) of the fluid before earthquake to fluid level (height) after earthquake, *"η"* in figure (1), the pressure at that area will be $P = \rho g \eta$.

As we know, equation of motion differential for a homogeneous substance with Cartesian coordinates, in the absence of any outside forces, is equal to:

$$\rho . \frac{\partial v}{\partial t} = \nabla P \tag{3}$$

Besides, if a wave height is defined "η", the expression of $V_z = \frac{\partial \eta}{\partial t}$ is established, as well as by assuming that ***p*** value is constant, we will have:

$$\rho \frac{\partial^2 \eta}{\partial t^2} = -\frac{\partial P}{\partial z} \tag{4}$$

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Now according to the above presentations, the following expression can be presented for fluid free surface:

$$\frac{\partial P}{\partial z} = -\frac{1}{g}\frac{\partial^2 P}{\partial t^2} = -\frac{1}{g}\ddot{P} \tag{5}$$

A. Examining weakened version of fluid and structure interactions

Now for all fluids, the weakened version of the fluid interactions can be stated as follow:

$$\delta\pi_f = \int_{\Omega_f} \delta P\left[\frac{1}{C^2}\ddot{P} + \nabla^2 P\right] = 0 \tag{6}$$

And if we want to indicate all areas (equations) defined in previous section (2-1) in weakened version, based on boundary conditions of the tanks, we will have:

$$\int_{\Omega_f} \delta P\left[\frac{1}{C^2}\ddot{P} + (\nabla)^T \nabla P\right]\partial\Omega + \int_{\Gamma_1} \delta P n^T \ddot{u} d\Gamma + \int_{\Gamma_3} \delta P \frac{1}{g}\ddot{P} d\Gamma = 0 \tag{7}$$

In this equation, ***Ω*** is total fluid amplitude and ***Γ1*** is boundary conditions at defined sections.

Similarly, now for all structures, the weakened version of the interactions can be stated as follow:

$$\int_{\Omega} \delta u[\rho_s \ddot{u} + S^T D S u] d\Omega - \int_{\Gamma_t} \delta u^T \bar{t} d\Gamma = 0 \tag{8}$$

Where surface adhesion force defined as $\bar{t} = -Pn_s$ for pressure force, the surface adhesion force is created by fluid pressure exerted on the tank wall.

B.Separate Couple Systems

If we consider vibrational equations for structure and Galerkin equations for fluid, as follow:

$$M\ddot{\tilde{u}} + C\dot{\tilde{u}} + K\tilde{u} - Q\tilde{P} = 0 \tag{9}$$

$$S\ddot{\tilde{P}} + H\tilde{P} + Q^T\ddot{\tilde{u}} + q = 0 \tag{10}$$

In equation (9), *M*, *C* and *K* is mass, damper and hardness matrixes, respectively. In equation (10), by considering shape function, *S*, *H* and *Q* are stated as below:

$$S = \int_{\Omega} N_P^T \frac{1}{C^2} N_P d\Omega + \int_{\Gamma_3} N_P^T \frac{1}{g} N_P d\Gamma \tag{11}$$

$$H = \int_{\Omega} (\nabla N_P)^T \nabla N_P d\Omega \tag{12}$$

$$Q\tilde{P} = \int_{\bar{\Gamma}_f} N_u^T \bar{t}\,\delta\Gamma = \int N_u^T n p N_P d\Gamma \tag{13}$$

*C.*Free *Vibrations in Fluid and Structure*

To investigate free vibrations of fluid-structure with no external force, two structure and fluid equations can be stated as below:

$$\begin{bmatrix} M & 0 \\ Q^T & S \end{bmatrix}\begin{Bmatrix} \ddot{\tilde{u}} \\ \ddot{\tilde{P}} \end{Bmatrix} + \begin{bmatrix} k & -Q \\ 0 & H \end{bmatrix}\begin{Bmatrix} \tilde{u} \\ \tilde{P} \end{Bmatrix} = 0 \tag{14}$$

This expression indicates periodic vibrations of the structure and fluid. By changing matrix in symmetric form and reducing the interactions in standard form, the interactions can be predicted. In a similar method carried out by Ohayon, this matrix can be changed by changing variable numbers (variables). Based on expression (14), the figures such as $\tilde{u} = \breve{u}e^{i\omega t}$ & $\tilde{P} = \breve{P}e^{i\omega t}$ will be changed as below:

$$K\tilde{u} - Q\tilde{P} - \omega^2 M\tilde{u} = 0 \tag{15}$$

$$H\tilde{P} - \omega^2 S\tilde{P} - \omega^2 Q\tilde{u} = 0$$

In order to simplify equation (15), by changing variable number in $P = \omega^2\tilde{q}$, we will have:

$$\left\{\begin{bmatrix} k & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & 0 \end{bmatrix} - \omega^2 \begin{bmatrix} M & 0 & Q \\ 0 & 0 & S \\ Q^T & S^T & H \end{bmatrix}\right\}\begin{Bmatrix} \tilde{u} \\ \tilde{P} \\ \tilde{q} \end{Bmatrix} = 0 \tag{16}$$

Because the matrix and its symmetry become diametric, the matrix model was reduced by dynamic model appropriate for fluid and structure. [5]

D.Added Mass

When there are no surface wave effects and the pressure is non-zero, Galerkin equation can be stated as follow:

$$H\tilde{P} = -Q\ddot{\tilde{u}} \tag{17}$$

And by removing radial waves, the equation will be changed as below:

$$\tilde{P} = -H^{-1}Q^{T}\ddot{\tilde{u}} \qquad (18)$$

The pressure due to fluid motions which exerted on tank walls is considered as added mass to the structure mass.

$$\boldsymbol{M_{add}=QH^{-1}Q^{T}} \qquad (19)$$

Equation (19) is added to the structure dynamic equations as follow: [4]

$$(M + QH^{-1}Q^{T})\ddot{\tilde{u}} + K\tilde{u} = 0 \qquad (20)$$

E.The Equations of Waves Emission through Elastic Environment

To obtain an equation of a flux motion differential, it should be ignored its viscosity, and assuming that Reynolds number is small enough to be able to ignore the flow turbulences completely. Thus the equation of a flux motion differential may be showed as below:

$$\rho_{ij}\frac{\partial^2 x_i}{\partial t^2} = (\lambda+\mu)\frac{\partial\theta}{\partial X_i} + \mu\nabla^2 x_i \qquad (21)$$

Where $P_{ij}\frac{\partial^2 x_i}{\partial t^2}$ equivalent to shear and pivotal stresses, $\boldsymbol{\theta}$ is is volume expansion of a flux and $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are elasticity constants. By applying rotational operator device, the expression can be shown as below:

$$\rho\frac{\partial^2}{\partial t^2}curlx_i = (\lambda+\mu)curl\frac{\partial\theta}{\partial X_i} + \mu\nabla^2 curlx_i \qquad (22)$$

By this equation, it is possible to predict and calculate emissions of any earthquake waves. For fluid, because there is no rigid environment, $\boldsymbol{\mu}$ is equal to zero, so the equation can be simplified As below [3] , [8]:

$$\frac{\partial^2\theta}{\partial t^2} = C^2\nabla^2\theta \qquad (23)$$

Where **C** is sound velocity which equals to $\sqrt{\frac{\lambda}{\rho}}$.

III.NUMERICAL SIMULATION

Finite element simulation has performed in three steps by using main components of ANSYS software. In first step, it should be produced a model by using (Finite Element Modeling) FEMB inner preprocessor.

Second step includes dynamic analysis. In Ultimate step, the results should be post-processing by using Post-GL processor and ANSYS software, for the interpretation. In order to provide a finite elements model, Some special techniques are required for modeling, including:

1- To present finite elements model, any type of elements and their properties for different parts of the model.
2- To create and allocate physical properties.
3- To determine position equations.
4- To define initial and boundary conditions.
5- To define Common interface (area).
6- To define Controlling parameters.

A.Principals of Numerical Solution Method

A) numerical solution was performed according to ANSYS code by applying finite element method and ***Implicit*** technique.

B) In numerical solution method, Despite many changes in the shape of storage tank shell and fluid, (Arbitrary Lagrangian Eulerian) or ALE technique are used to analyze the case in question.

C) Given that the dynamic nature of this loading and that the motions are irregular and very fast, observing the events is very difficult, thus short time steps are chosen.

A.Description of Finite Elements Model

In figure (2), it is shown the model of some tank parts. Two-dimensional model of the tank having symmetric axis (Axisymmetric) with radius of 25 meters and height of 30 meters is used. In this model, element configuration is manually performed and the number of fluid elements and structure elements are 400 and 292, respectively. This mesh setting (arangement) is carried out in a way that fluid and structure elements will be completely symmetrical. Elements applied in the tank shell are made of ***Solid*** and ***Plane*** sub-elements and the type of ***Plane*** is selected to be a four-node element. ***Plain*** element is capable to analyze the interaction conditions. The type of the applied element in the fluid is 141 ***flatron***. The type of this element has conditions that are capable to include Mesh motion method. Thickness of the element Wall is 3cm. In figure (2), it is shown the elements arrangement.

B.Physical Models (Equations for Characteristics)

In the numerical analysis, an isotropic model is applied for structures and a ideal fluid model is used for fluids. Physical coefficients and physical constants are presented in table (1).

C. Boundary Conditions

In numerical analysis of the original data, the direction of structure-fluid movement is considered as velocity and movement. The given data are similar to Elsantro Earthquake data, which are regarded as parameters based on velocity-time and motion-time under all boundary conditions of fluid-structure. Because the calculations performed by the software are so complicated and the parameters during an earthquake are irregular, it is tried the earthquake data to be provided as velocity and motions, in order to insert them into the model as input; then during first 3 or 4 second, it is simulated: then to get more accurate results, the analysis is run about 10 seconds with entering no data.

D. Controlling Parameters

To control outputs, such as whole solution time, interrupting solution time, solution ramp computation in terms of time and calculations of accuracy, controlling parameters are applied. In this analysis, this control is performed in two steps. In first step, it is *flotran setup* and in second step, it refers to *Fluid and Structure Interaction setup (FSI setup).*

In first part, total solution time and each solution step are defined 10 and 0.01 seconds, respectively. Total number of steps is calculated based on total period of time over the time of one step, as well as the time of boundary conditions defined as *ramp* shape, not as *stairway* (or *step by step*) shape. In *FSI setup*, after defining the nodes that have common interface (area) of fluid and structure, the setup are activated and the rate of convergence analysis for the interactions that depends on the system memory, is assumed 0.01 in average. In addition, in the setup, repetition terms for the analytical solution are performed in step by step method, it must be greater than or equal to the repetition terms according to the fluid setup. In this analysis, repetition terms for the fluid and structure interactions are considered 20 and 30 times, respectively.

Finally, the type of analysis for large displacement was also assumed transient analysis, and in the overall part of the analysis, its increment time is regarded fit with the increment time of fluid and structure, which its value equals to 0.01.

IV. RESULTS AND DISCUSSIONS

In this section, in storage tank contained a fluid, the impacts of fluid motions on the tank walls are evaluated according to the obtained results of the numerical simulation (6).In dynamic analysis of earthquake loading, it is used data the velocities and movements of structure and fluid, based on the simulated model of Elsentro earthquake (figures 3, 4).While results which are in form of stress, according to Phonmises, based on height of a tank, are useful to investigate the impacts of pressure on tank walls, in the following steps, it is presented the beginning time of wall motions due to the displacement and velocity exerted on the structure, also at 1.38 seconds which is the highest velocity in velocity-time graph. At the end, the rate of stresses at the moment of final motion, that are stresses due to fluid turbulences after 5 seconds passed from final motion, are shown.

First stance: initial period of time for the solution which is about 0.5 seconds, are indicated in (figure 5, 8). In figures (5 to 9), the graphs or diagrams indicate the resulted stresses on the left and right walls of the storage tank. According to the diagram, initial motion due to stress on the left wall (several periodic movement) increase from down to up, whereas simultaneously the tension on the right wall decrease from down to up.

Second stance: at 1.38 seconds after initial motion, the wall stress diagram showed in figures (9, 6). Because the velocity at instant 1.38 seconds equals to 0.1 (its maximum rate) and its direction is from right to left. The rate of the stress on the left wall is at its maximum, conversely, the rate of the stress on the right walls, shows less value.

Third stance: at instant 8 seconds after initial motion, the walls stress diagram showed in figures (10, 7). Because the velocity and displacement at instant 8 seconds is zero, that is, as it is previously noted, from 3 seconds until 10 seconds after initial motion. In fact, as mentioned before, at the instant seconds 3 until 10 seconds, by more accurate and realistic analysis that displays the fluid and structure interactions after the exerted velocity and movement at instance 3 second, the rate of stresses on both left and right walls shows the minimum rate of time. From fluid turbulence until complete turbulence stabilization, the rate of the stresses exerted on the walls based on the height of wall, are variable and irregular.

V.CONCLUSION

1- The height of the created wave in a fluid has an inverse relationship with time and frequencies caused by the exerted velocity and displacement on boundary conditions in the fluid (figure 11).

2- the more increases the velocity and displacement, the more increases the pressure on the walls, and subsequently, the stresses will increase.

3- As mentioned before, in dynamic analysis, due to fluid motion, an additional pressure exerts on the walls, that it is called added mass. In figure (12). It is indicated the relationship between produced frequencies from the vibrations due to fluid dynamic motions and the added mass. It can be concluded that at initial dynamic variations, when the frequency is low, the rate of the assumptive added mass increase and when it is high, the added mass rate reach to constant value. However, by increasing the frequency, the added mass doesn't raise.

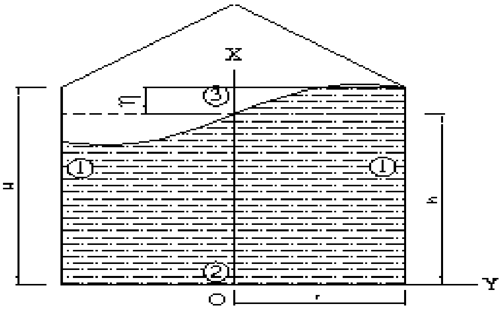

Fig. 1 different boundary conditions for the storage tank contained fluid

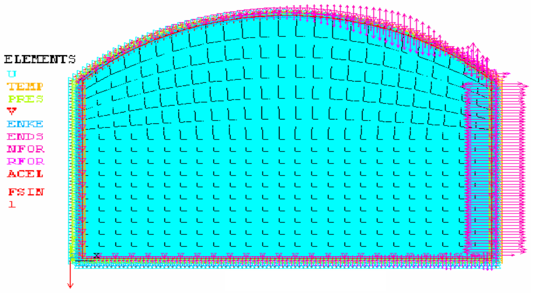

Fig. 2 meshwork and loading of the tank under stimulation

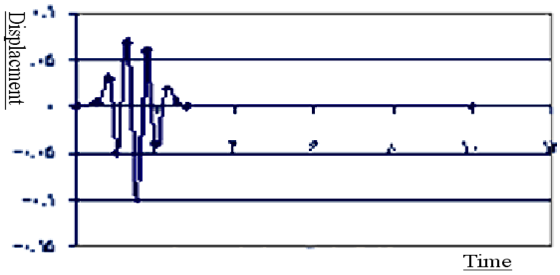

Fig. 3 displacement-time graph (Elsentro earthquake)

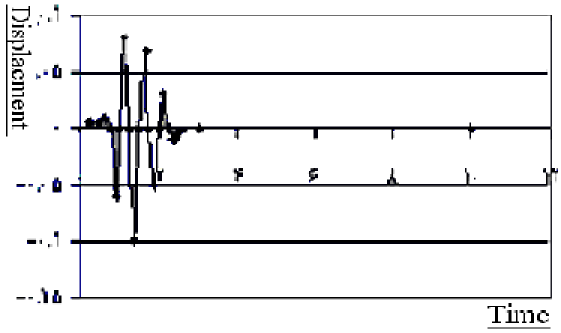

Fig. 4 velocity-time graph (Elsentro earthquake)

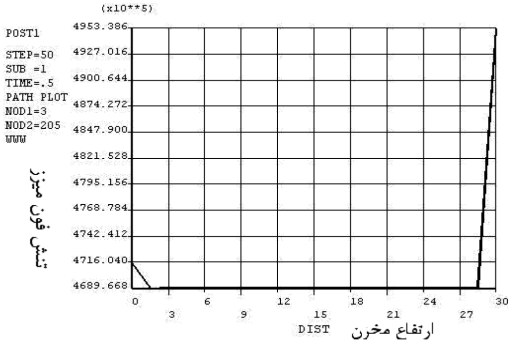

Fig. 5 stress on left wall of the tank at instant 0.5 second

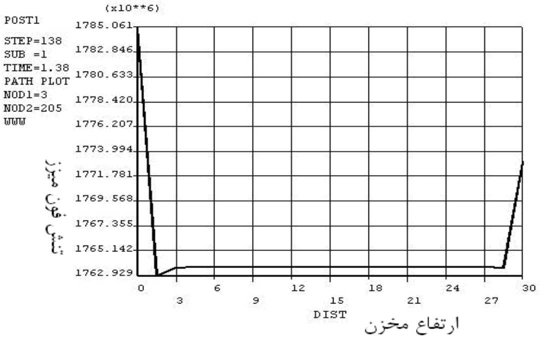

Fig. 6 stress on left wall of the tank at instant 1.38 second

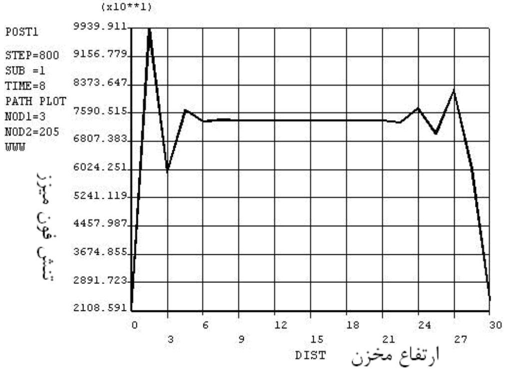

Fig. 7 stress on left wall of the tank at instant 8 second

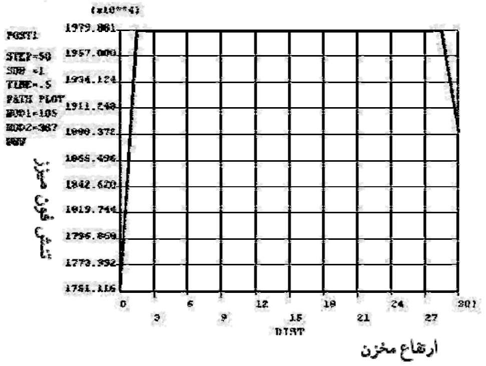

Fig. 8 stress on right wall of the tank at instant 0.5 second

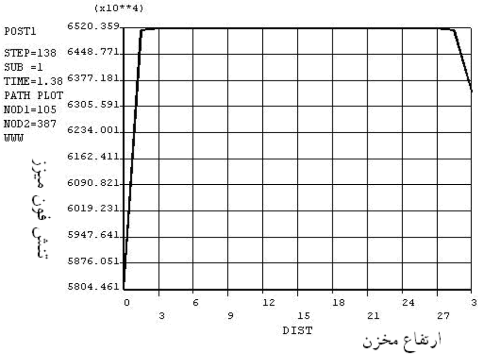

Fig. 9 stress on right wall of the tank at instant 1.38 second

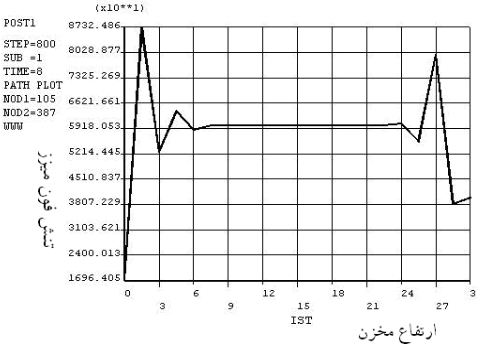

Fig. 10 stress on right wall of the tank at instant 8 second

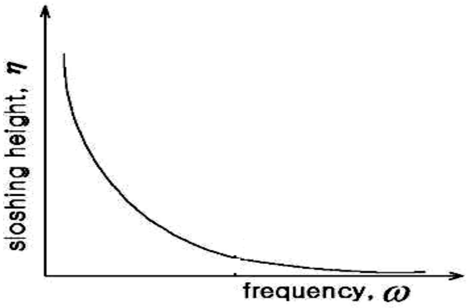

Fig. 11 the graph for the relation between frequency and the height of fluid wave

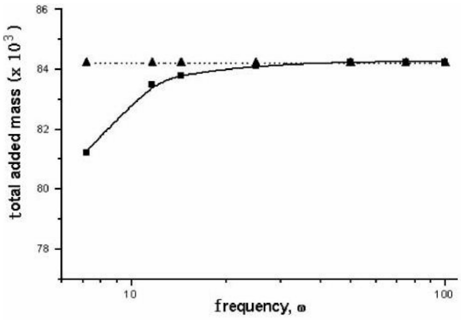

Fig. 12 the graph for the relation between frequency and added mass

TABLE I
CONSTANTS OF STRUCTURE AND FLUID MODEL

Properties	*symbol*	*Quantity value*
Young's moduls	***E***	***207E9***
Poisson's ratio	ψ	***0.3***
Mass density for strueture	ρ	***7860***
Mass density for fluid	ρ	***1000***
Viscosity property type	μ	***0.001***
Gravity	***g***	***9.81***

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