FREE VIBRATION ANALYSIS OF RECTANGULAR WATER TANK CONSIDERING BAFFLE-FLUID INTERACTION

A Thesis

Submitted by

SK MD SABIR ALI

(002110402005)

In partial fulfillment of the requirements for the award of the degree of

Master of Engineering

In

Civil Engineering

(Structural Engineering)

Under the Guidance of

Dr. Kalyan Kumar Mandal

DEPARTMENT OF CIVIL ENGINEERING

JADAVPUR UNIVERSITY

KOLKATA-700 032

(2023)

DEPARTMENT OF CIVIL ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY
KOLKATA – 700 032

CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled, "**FREE VIBRATION ANALYSIS OF RECTANGULAR WATER TANK CONSIDERING BAFFLE-FLUID INTERACTION**" submitted by **Sk Md Sabir Ali**, Class Roll No. **002110402005**, Exam. Roll No. **M4CIV23008**, Registration No. **123263 of 2013-2014** in partial fulfilment of the requirements for the award of Master of Engineering degree in Civil Engineering with specialization in "**Structural Engineering**" at Jadavpur University, Kolkata is an authentic work carried out by him under my supervision and guidance. I hereby recommend that the thesis be accepted in partial fulfilment of the requirements for awarding the degree of **"Master of Engineering in Civil Engineering (Structural Engineering)"**.

Dr. Kalyan Kumar Mandal
Associate Professor
Department of Civil Engineering
Jadavpur University
Kolkata- 700032

Dr. Partha Bhattacharya
Head of the Department
Department of Civil Engineering
Jadavpur University
Kolkata-700032

Prof. Ardhendu Ghoshal
DEAN, FET
Jadavpur University
Kolkata- 700032

DEPARTMENT OF CIVIL ENGINEERING
FACULTY OF ENGINEERING AND
TECHNOLOGY JADAVPUR UNIVERSITY

KOLKATA – 700 032

CERTIFICATE OF APPROVAL

This thesis paper is hereby approved as a credible study of an engineering subject carried out and presented in a manner satisfactorily to warrant its acceptance as a pre-requisite for the degree for which it has been submitted. It is understood that, by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approved the thesis paper only for the purpose for which it is submitted.

Committee of Thesis Paper Examiners

____
Signature of Examiner

____
Signature of Examiner

DECLARATION

I, Sk Md Sabir Ali, Master of Engineering in Civil Engineering (Structural Engineering), Jadavpur University, Faculty of Engineering & Technology, hereby declare that the work being presented in the thesis work entitled, "**Free Vibration Analysis of Rectangular Water Tank Considering Baffle-Fluid Interaction"** is authentic record of work that has been carried out at the Department of Civil Engineering, Jadavpur University, Kolkata under the guidance of **Dr. Kalyan Kumar Mandal**, Associate Professor, Department of Civil Engineering, Jadavpur University. The work contained in the thesis has not yet been submitted in part or full to any other university or institution or professional body for award of any degree or diploma or any fellowship.

Place: Kolkata
Date:

Sk Md Sabir Ali
Class Roll: 002110402005
Exam Roll: M4CIV23008
Regist. No.:123263 of 13-14

ACKNOWLEDGEMENT

I would like to take this opportunity to convey my sincere gratitude and appreciation for my supervisor **Dr. Kalyan Kumar Mandal.** I am indebted to him for his methodical guidance, motivation and constant support given to me throughout the thesis work. He has identified my potentials and kept faith in me. It is because of his confidence that I was able to successfully accomplish the targets. I am extremely thankful to him as without him my thesis could not have reached this state.

I also thankfully acknowledge my gratefulness to all Professors and staffs of Civil Engineering Department, Jadavpur University, Kolkata, for extending all facilities to carry out the present study.

I also thankfully acknowledge the assistance and encouragement received from my family members, friends and others during the preparation of this Thesis.

Place: Kolkata

Date:

Sk Md Sabir Ali

Roll No.: 002110402005

Regist. No.: 123263 of 13-14

ABSTRACT

In the present study, the convective time period of rectangular tanks with elastic baffle within it, is investigated by pressure based finite element method. The fluid within the tank is considered to be water and tank walls are assumed as rigid. The fluid with in the tank is considered as inviscid and fluid motion is irrotational. Galerkin approach is used for finite element formulation of wave equation fluid within tanks. However, displacement based finite element is used to simulate the elastic baffle. A direct coupling approach is used to incorporate the baffle-fluid interaction. The present algorithm also includes the compressibility of water in the reservoir.

The efficacy of the present algorithm has been demonstrated through numerous examples. The convective time period increases with the addition of elastic baffle within the tanks. The convective time period increases with the increase of length of tank. The height of fluid also increases this time period. However, the influence of change of height of fluid is greater than those for the change of length. The third convective time period of tank with and without baffle are equal for comparatively lower length but for first convective time period this occurs for comparatively large length. The free vibration responses also increase with the increase of flexibility of baffle wall because the convective time period increases with the increase of baffle height. Position of the baffle also influences the free vibration response of the tank with baffle. The first two convective time periods have the highest value when it is near to the tank wall and the lowest value when it is placed near the midpoint of tank. But for third convective time period has the highest value when it is placed at the middle and gains the least value at one-fourth distance from tank wall. Similar to the height of baffle, the thickness of baffle also changes the flexibility of baffle hence the increase of thickness of baffle reduces the convective time period of the tank.

KEYWORDS: *Compressibility of water, Finite element method, Baffle-fluid interaction, Free vibration analysis, Convective time period*

LIST OF SYMBOLS

Symbols	Description
a	Acceleration of excitation
Amp	Amplitude of excitation
C	Acoustic weave speed
C_P	Hydrodynamic pressure coefficient
g	Gravitational acceleration
H	Height of fluid, Height of tank
L	Length of the tank
ρ	Mass density of fluid
N_t	No of time steps
N_h	Nos. of horizontal division of mesh
N_v	Nos. of vertical division of mesh
P	Hydrodynamic Pressure
T	Time period of excitation
V_t	Velocity of fluid at time t
U_t	Displacement of fluid at time t
W	Exciting frequency
w	Fundamental frequency of water within tank

CONTENTS

List of Figures

List of Tables

CHAPTER-1
INTRODUCTION

1.1 Introduction

Tanks are commonly used to store water and various fluids in the oil industry. Damage in tanks may cause a loss of liquid content, which could result in economic damage, as well as in long-term contamination of soil for tanks resting on soil. The sloshing effect and the hydrodynamic pressure act on walls are the major guiding parameters in the design of such tanks. The clear understanding of sloshing characteristics is essential for the determination of required freeboard to prevent overflow the fluid and also for the estimation of hydrodynamic pressure on the fluid retaining container such as tank. It is also very important for water storage tank using for cooling in nuclear plant and fire demand supply, which has to withstand during earthquake. Different types of numerical schemes, such as the finite difference method, the finite volume method, the boundary element method and finite element method may be used to obtain the responses of the fluid within the tank.

The analysis of water tank is an example of fluid-structure interaction problem or in other word, the proper and precise responses of the tank is obtained if the fluid-structure interaction effect is considered in the analysis. Further, the responses will be so realistic if this problem is dealt in 3D. However, in existing literatures it is reported that the effect of the flexibility of the tank does not change the pressure distribution if the tank wall is sufficiently thick. Therefore, the assumption of rigid tank is a good approximation to evaluate the hydrodynamic pressures due to the sloshing component of the liquid in tanks. Similarly, 2D approximation of rectangular water tank may be considered for a certain value of width to length ratio of rectangular tanks.

The Hydrodynamic pressure exerted by the fluid on the tank wall and amplitude of slosh depends on the amplitude and frequency of the tank motion, liquid depth, liquid properties, tank geometry, and also the size, shape and location of the internal baffle. Abundant research has been carried out on the seismic response of cylindrical liquid storage tanks mainly to know the sloshing behavior and mode shape but very few contributions have been published for determining total hydrodynamic pressure of rectangular tank and analysis is carried out considering fluid as incompressible, irrotational and inviscid. However, the compressibility effect of fluid may play an important role for precise estimation of total hydrodynamic pressure and the sloshed deformation for calculation of free board in tanks.

1.2 Objective of Present Study

The objective of present thesis is to study the convective behavior of rectangular water tank with elastic baffle against different dynamic excitations.

CHAPTER-2
LITERATURE REVIEW

2.1 General

To provide a detailed review of the literature related to the dynamic analysis of liquid storage tank entirely would be difficult to address in this chapter. A brief review of previous studies about dynamic analysis of liquid storage tank is presented in this section which is related to the present study. This literature review focuses on recent contributions related to this work and past efforts most closely related to the needs of the present work.

2.2 Literature Review

A comparative study of the seismic analysis of rectangular tanks according to the codes of USA, European Community, New Zealand and Turkey was carried out by Doğangün. A. and Livaoğlu. R. (2008) considering hydrodynamics pressures, sloshing displacements, base shears, lateral displacements, bending and overturning moments. It was observed that ACI 350 gives smaller impulsive mass and bigger convective mass than those obtained for Eurocode 8. The hydrodynamic pressure distribution and magnitude obtained by Eurocode 8 and ACI 350 were generally in agreement. However, the differences between hydrodynamic pressures were occurred at top and bottom of the tank wall.

A Comparative study of the seismic analysis of rectangular tanks according to EC8 and IS1893 was carried out by Kotrasová. Kamila, Leoveanu. Ioan-Sorin and Kormaníková. Eva (2013) considering the adverse severe effects of uncontrolled fires and spillage of dangerous fluid subsequent to a major earthquake. The comparative study using the two different codes found the below result for Impulsive mass, convective mass and equivalent heights related to these masses, periods, base shears, bending moments and height.

Codes	m_i [kg]	m_c [kg]	h_i [m]	h_i' [m]	h_c [m]	h_c' [m]	T_i [s]	T_c [s]	V [kN]	M [kNm]	M' [kNm]	d_{max} [m]
Eurocodes 8	7267	5723	1.094	1.871	1.607	2.032	0.041	2.63	12.81	16.58	28.76	-
IS 1983	7266	6124	0.975	2.000	1.530	2.173	0.041	2.62	12.89	15.83	30.18	0.051

A review of water tank modeling of the convective atmospheric boundary layer was carried out by Yuan. Renmin, Wu. Xuping, Luo. Tao, Liu. Huizhi and Sun. Jianning (2011) considering similarity analysis of modeling, basic dispersion processes, characteristics of the convective boundary layer (CBL), parameterizations of the entrainment zone (EZ), the characteristics of turbulence in the CBL, and the influence of plain-valley terrain and other inhomogeneities on atmospheric boundary layer structure. It was observed that with continuous technological improvements, convective water tanks would make great progress in experimental measurements and data analysis, and the models would play a more important role in the study of the structure and characteristics of the ABL with regard to wind shear, the characteristics of unsteady turbulence, and the effects of complex terrain.

A seismic response analysis of a cylindrical liquid storage tank including the effect of sloshing was carried out by Katsuhisa, Fujita (1981). Here the kinetic and strain energies of an empty tank shell subjected to a horizontal earthquake were estimated and the virtual work of liquid pressure exerting on the tank wall was also estimated analytically by assuming that the behavior of the liquid follows the velocity potential theory which includes the effect of sloshing. Following observations had found out from the study - The natural frequencies for sloshing mode from the present solution were slightly lower than those obtained by assuming the tank wall to be rigid. The degree of coupled effect of sloshing and bulging was shown to be very weak according to the investigation. For an earthquake-proof design, the response due to sloshing of the free surface cannot be omitted.

A seismic response analysis of a cylindrical liquid storage tank including the effect of sloshing (2nd Report, Analysis Based on Energy Method) was carried out by Katsuhisa, Fujita (1982). This literature was connected with the literature which was reviewed previously. Here the kinetic energy and the potential energy of the liquid in the tank were estimated analytically by superposition of two types of velocity potentials, which was, one obtained by assuming the tank wall as rigid and the other obtained by considering the liquid to be coupled with the tank shell neglecting the oscillation of liquid free surface. Following results were observed - There were little differences between the present solution and the previous one with respect to vibration characteristics, i.e., natural frequency and mode. The deformation and the liquid pressure near the free end of tank side shell were apt to be influenced greatly by sloshing. The difference between the present solution and the previous one was observed only in the wave height and had little influence on the seismic response. It was known that the coupling effect between sloshing and bulging was very weak.

A study of hydrodynamic behavior of liquid in overhead tank as per IS 1893-Part II (2014) was carried out by Sharma. Vinod and Biag. Aamir Mirza (2019) to understand the dynamic behavior of elevated water tanks under earthquake loading including the sloshing effects. It was observed that time period in convective mode was greater than that of impulsive mode and both the time periods and the horizontal force acting on staging were increased but the deflection was decreased with the increase of capacity/ structural mass of the tank. Beside this it was found that sloshing wave height result represented that, it's necessary to provide free board for partially filled tanks or else the roof of tanks should be designed to resist the uplift pressure of liquid.

Analysis of hybrid staging systems for elevated storage reservoir was carried out by Prajapati. Keyur Y., Patel. Dr. H. S. and Darji. Prof. A. R. (2014) to conceptualize innovative hybrid staging systems, considering seismic loading and to understand the behavior of supporting system which is more effective under different response spectrum method with SAP 2000 software. It was observed that base shear, base moment and displacement increased from seismic zone IV to V for different types of staging patterns about 50%. Base shear, base moment and displacement increased from soil type I to III for different types of staging patterns. For hard soil these were about 35% to 37% less than that of medium soil, about 65% to 67% less than that of soft soil. For medium soil these were about 20% to 23% less than that of soft soil.

Behavior of concrete liquid structures subjected to seismic loading was carried out by Kianoush. M.R., Tso. W.K., and Hamidi. M. (1970) considering the major parameters affecting the response of concrete circular tanks for liquid concrete structure. It was observed that in designing of the tank walls, earthquake induced bending moment is more critical than shear. Earthquake load dominates the design of shallow water tanks, but for taller tanks, the static load becomes the dominating factor. Earthquake load is not affected significantly by the variation of wall thickness.

Behavior of elevated water storage tanks under seismic events was carried out by Waghmare. M.V., Madhekar. S.N. and Matsagar. Vasant (2015) to investigate the uncontrolled response of Steel and Reinforced Cement Concrete (RCC) Elevated Water reservoirs of different aspect ratio S = H/R (height of the container to its radius) and subjected to different strong ground motion earthquakes. It was observed that apart from frequency content material properties were also important for response. Base shear depended upon the amplitude, magnitude and on number of times the maximum amplitude frequencies hits the surface. Sloshing displacement was highly influenced by the characteristics of the time history compared to other response quantities.

Capillary effect on the sloshing of a fluid in a rectangular tank submitted to sinusoidal vertical dynamical excitation was carried out by Bachir. Meziani and Ouerdia. Ourrad (2014) in order to derive practical solutions to problems faced in several engineering considering tank containing a fluid with a free surface was submitted to gravity and capillary forces and subject to external dynamic excitation. It was observed that with increase of the sloshing Eigen frequencies wavelengths decreased. The analysis of sloshing in stable regions showed nonlinear effects depended on the frequency and the amplitude of the dynamic excitation.

Design criteria for water tank models of dispersion in the planetary convective boundary layer were carried out by Hibberd. M.F. and Sawford. B.L. (1992) considering the range of factors relevant to modeling both turbulent penetrative convection and the dispersion of buoyant point-source plumes within the convective boundary layer. It had been shown that saline convection was well suited to modeling turbulent convection in the atmosphere provided that the flux Rayleigh number of the model exceeds 10^{10} and that the aspect ratio of the tank width to mixed-layer depth is greater than about 5. Advantages were found for saline convection over thermal convection.

Discrete models for seismic analysis of liquid storage tanks of arbitrary shape and fill height were carried out by Drosos. G.C., Dimas. A.A. and Karabalis. D.L. (2008) considering a finite element method (FEM)-based formulation which was developed for an effective computation of the Eigen mode frequencies, the decomposition of total liquid mass into impulsive and convective parts, and the distribution of wall pressures due to sloshing in liquid storage tanks of arbitrary shape and fill height. It was observed that the results obtained by FEM analysis software for cylindrical and spherical tanks were in excellent agreement to those already available in literature.

Dynamic behavior and seismic response of ground supported cylindrical water tanks were carried out by Asha. Joseph and Glory. Joseph (2016) with different aspect ratios and was investigated using finite element software ANSYS. It was observed that sloshing behavior of fluid inside a ground supported circular tank is independent of rigidity parameters of the tank. The natural impulsive frequency increases as water level reduces and for low water height, there is significantly no change in impulsive frequency. Fundamental impulsive frequency of rigid tank is 2.8–3.2 times higher than flexible tank of same geometry depending on diameter and water height. With increase in aspect ratio from 0.35 to 0.86, both impulsive and sloshing frequency increases. Tank experiences maximum hoop force, base shear, bending moment and radial displacement when the tank is at its full capacity.

Dynamic behavior of elevated water tanks under seismic excitation was carried out by Hadj-Djelloul. Nasser Dine, Djermane. Mohammed, Sharari. Noor and Merabti. Soufiane (2020) using the finite element technique to study the seismic response of tanks with taking into account the interaction between fluid and structure in the presence of sloshing. It was observed that the period of the convective mode and the sloshing displacements are the same for the shaft and frame supports which mean that the convective component is independent of the supporting system whereas the period of impulsive mode and the displacement at the top of the tank are changed according to the rigidity of the structure and it can also be seen that the second type (shaft support) is more rigid than the first one (frame support).

Dynamic response of ground supported rectangular water tanks to earthquake excitation was carried out by Aregawi. Birhane and Kassahun. Abdulaziz (2017) using a linear three-dimensional finite element analysis and SAP2000 software over five tank models with a capacity of 216, 288, 360, 432 and 504 m^3 were developed and analyzed for hydrodynamic and hydrostatic effects. It was observed that there was a smooth increase in the moment and displacement of both hydrostatic and hydrodynamic analysis with a decrease in aspect ratio (A) and the maximum hydrodynamic moment is observed to be 91.3 % higher than the maximum hydrostatic moment.

Dynamics of internal waves in cylindrical tank was carried out by Helou. Amin H. (1985) to evaluate seismic-induced hydrodynamic forces in a rigid tank fully filled with two liquids. It was observed that for internal waves the second term contribution to the total hydrodynamic pressure due to seismic load was about ten times larger than that of the first term, thus it may be neglected in the dynamic analysis of fluid-tank systems.

Earthquake response of cylindrical storage tanks on an elastic soil was carried out by Meng. Xun, Li. Xuehong, Xu. Xiuli, Zhang. Jiandong, Zhou. Wenling and Zhou. Ding (2018). Here the continuous liquid in the tank was lumped as convective spring–mass, impulsive spring–mass and rigid mass. The soil impedance function was modeled as the lumped-parameter system. The governing equations of motion for the coupled system under horizontal earthquake excitations were developed from the Hamilton's principle, which were solved based on the Newmark-β method. It was concluded that the soil–structure interaction effect reduces the impulsive mass displacement, the base shear and base moment; however, it had no apparent effect on the convective frequency and liquid surface wave elevation.

Effect of geometric imperfection on the dynamic of elevated water tanks was carried out by Hadj-Djelloul. N. and Djermane. M. (2019) to demonstrate the local geometric imperfection effect on dynamic buckling of elevated water tank using the 3D finite element technique to study the seismic response of perfect and imperfect elevated water tank. It was observed that the convective frequency was remained the same for the perfect and imperfect elevated tank. The maximum deformations were located along the support-tank interface region.

Effect of natural frequency modes on sloshing phenomenon in a rectangular tank was carried out by Jung. Jae Hwan, Yoon. Hyun Sik and Lee. Chang Yeol (2015) in two-dimensional (2-D) and three-dimensional (3-D) rectangular tanks using a level set method based on the finite volume method. The mean maximum wall pressure showed an identical pattern of free surface deformation according to the natural frequency ratio. However, the mean maximum wall pressure of the 2-D results was larger than that of the 3-D results, especially at the first mode of the natural frequency, which could be induced by the 3-D effect.

Effect of the vertical baffle height on the liquid sloshing in a three-dimensional rectangular tank was carried out by Jung. J.H., Yoon. H.S., Lee. C.Y. and Shin. S.C. (2012) to investigate numerically the effect of a vertical blade baffle on liquid sloshing in a three-dimensional rectangular tank by solving three-dimensional unsteady incompressible Navier–Stokes equations with the turbulence closure model of the standard κ–ε turbulence model. It was observed that with increase in baffle height the liquid sloshing became more suppressed due to the augmentation of the blockage effect of the baffle, which resulted in additional viscosity and energy dissipation, also known as hydrodynamic damping.

Effect of viscosity on sloshing in a rectangular tank with intermediate liquid depth was carried out by Jin. Xin, Tang. Jinbo, Tang. Xiaochun, Mi. Shuo, Wu. Jiaxin, Liu. Mingming and Huang.

Zongliu(2020) choosing tap water and glycerin at different temperatures as the experimental fluids at four kinematic viscosities ranging from 1.14×10^{-6} m^2/s to 1.1×10^{-3} m^2/s. It was observed that due to large viscous dissipation, the sloshing process tended to turn from the typical transient to the harmonic pattern when the viscosity exceeded about 400 times of the water. The phase shift, also called hysteresis, increased with the growing viscosity and eventually approached a constant value close to one fifth of the forcing period, which was vital for the tank instability.

Investigation on sloshing and vibration mitigation of water storage tank of AP1000 was carried out by Zhao. Chunfeng, Chen. Jianyun, Xu. Qiang, Wang. Jingfeng and Wang. Bo (2015) to numerically investigate the influence of fluid–structure interaction (FSI) on the dynamic behavior of water tank and effects of water sloshing in reducing seismic response of the shield building considering six cases of water heights of water tank. The numerical results revealed that the FSI effects of various water levels had significant effects on the motion and structural response of water tank, and not all the water levels could reduce the seismic response of shield building.

Investigation on sloshing response of water rectangular tanks under horizontal and vertical near fault seismic excitations was carried out by Hejazi. Fatemeh Sadat Akhavan and Mohammadi. Mohammad Khan (2019) considering the sloshing response of liquid in partially filled rectangular tanks subjected to earthquake ground motions. It was observed that the liquid pressure induced on tank under vertical seismic loading could be increased especially in near-field earthquakes; however, its effect on sloshing wave height was negligible. Also, the results for different tanks under both horizontal and vertical earthquakes showed that free surface vertical displacement depends on the spectral response acceleration at the first fundamental period of sloshing behavior.

Laboratory experiments on convective entrainment using a saline water tank were carried out by Jonker. Harmen J. J. and Jiménez. Maria A. (2014) to measure the entrainment behavior for medium to high Richardson numbers and use a two-layer design, i.e., two stacked non-stratified (neutral) layers with different densities. It was observed that laboratory experiments on (convective) entrainment are still very much hampered by the low magnitude of the Reynolds number.

Liquid storage cylindrical tank - earthquake analysis was carried out by Kotrasová. Kamila and Kormaníková(2017). Eva considering concrete containers fixed to rigid foundations due to earthquake events, describing of fluid hydrodynamic impulsive and convective (sloshing) effects on tank. Using of theoretical background for definition of impulsive and convective effects of fluid in liquid storage circular container was calculated the seismic response of tank due to earthquake event: the total base shears of the wall and the total base bending and overturning moments, immediately above and below the tank bottom plate, for full water filling of tank 6 m.

Nonlinear analysis of liquid-filled tank was carried out by Liu. Wing Kam and Lam. Dennis (1983) considering a numerical tank model which accounts for the lateral pressure loading is developed to provide an understanding of this effect on the behavior of liquid storage tanks. It was observed that the tank model collapses at a critical load 20% lower than the classical prediction. It also observed that the axial stress is basically dominated by cosθ mode; higher order modes were significant in the hoop stress profile which is nonlinear in character.

Nonlinear sloshing and passage through resonance in a shallow water tank was carried out by Cox. E.A., Gleeson. J.P. and Mortell. M.P. (2005) considering the effect of slowly changing the length of a tank on the nonlinear standing waves (free vibrations) and resonant forced oscillations of shallow water in the tank. It was observed that the number of solitons in the tank changes as the tank length was (slowly) altered; moreover, the number of solitons was shown to depend not only on the instantaneous length, but on its time history.

Non-Linear vibrations of a structure caused by water sloshing in a rectangular tank were carried out by Ikeda. T and Nakagawa. N (1996) considering theoretical and experimental studies. It was observed that the modal equations which were needed to analyze the nonlinear coupled vibration of the structure with the sloshing could be obtained. Depending on the water depth the shapes of the resonance curves for the structure became soft spring types for a deep depth and hard spring types for a shallow depth. When the magnitude of excitation was small the amplitude of the structure became infinitesimal near the tuning frequency. If the magnitude of excitation was comparatively large, a super summed and differential harmonic oscillation may occur near the tuning frequency. The validity of the theoretical analysis was confirmed by the experiments.

Numerical modeling of cylindrical tank and compare with experiment was carried out by Norbert. Jendželovský and Ľubomír. Baláž (2014) for an ANSYS analysis of Eigen frequencies. It was observed that for the static analysis, it could be used among any of FLUID30 (Euler's approach) or FLUID80 (Lagrange's approach) element, but for the dynamic analysis the FLUID80 finite element was more suited.

Performance of RC elevated water tank for different bracing patterns under the effect of earthquake excitation was carried out by Shrigondekar. Anand. H and Padhye. Rajesh D(2016) considering a concrete elevated water tank with 400 m^3 had been studied and analysed by linear dynamic method and seismic response such as base shear, tank displacement, max Bending Moment at the base of column under tank reinforced empty condition, tank full condition and tank half full condition for different type of bracing arrangements. It was observed that base shear decreased as bracing level decreased for different types of bracings. Base Shear was higher for Octagonal and Radial bracing compared to other type of bracing. Storey displacement went on decreasing as level of bracing increased. Octagonal and

Radial bracing was experienced less Storey displacement as compared to other type of bracing. Maximum bending Moment at bottom of column decreased as level of bracing increased for all bracing patterns. Base Shear, Storey displacement and max BM at base were increased when water level was full as compared to half full and empty

Quantitative risk analysis of oil storage facilities in seismic areas was carried out by Fabbrocino. Giovanni, Iervolino. Iunio, Orlando. Francesca and Salzano. Ernesto (2005) by a representative study case regarding an oil storage plant with a number of atmospheric steel tanks containing flammable substances. It was observed that quantitative probabilistic seismic risk analysis (QpsRA) might be successfully carried out if seismic fragility analyses of critical components were developed in terms of limit states that may trigger industrial accidents (i.e., hazardous materials release).

Reliability-Based design of RC water tank structures under seismic action was carried out by Muller. Oscar and Rubinstein. Marcelo (1992) with a specified probability of failure in a 50-year design life and to evaluate the probability of failure the ultimate limit state was obtained when the top column displacement demanded by the earthquake, a random variable, reached the allowable displacement, which was here treated as deterministic. With the probabilistic model, charts were constructed allowing easy design of the structure for a tolerable probability of failure.

Seismic induced forces on rigid water storage tanks were carried out by Helou. Sameer H. (2014) where two 3D structural modeling were presented that accounted for the hydrodynamic pressure, indispensable for accurate evaluation of the induced forces on the outer shell, detailed study of the seismic parameters involved was also conducted. One model focused on a static treatment which considered the hydrostatic loads only while the second model was constructed in accordance with the ACI recommendations for seismic analysis. It was observed that the maximum circumferential moment shifted its position; instead of being at the base of the tank it happened at the height of the impulsive masses. With the inclusion of the convective water mass rendered the system to appear less rigid. It was also identified that soil flexibility increased both the circumferential and the longitudinal stresses and accordingly the plastic strains and radial deformations.

Seismic response evaluation of the rc elevated water tank with fluid-structure interaction and earthquake ensemble was carried out by Omidinasab. F. and Shakib. H. (2011). Here a reinforced concrete elevated water tank, with a capacity of 900 cubic meters and height of 32 meters, had been utilized and subjected to an ensemble of earthquake records considering Eulerian method for Fluid-structure interaction. It was observed that the maximum response did not always occur in the full tank. The system predominant frequencies were located on the range of high amplitude of frequency content of some of the selected earthquake records and caused amplification of responses. The increase in the percentage of container filling showed that the value of base shear force, overturning moments, displacement and hydrodynamic pressure increased in the range of mean plus and minus standard deviation. Evaluation of the convective pressure revealed that the earthquake records with low predominant frequency caused excitation in the oscillating modes with relatively high period and consequently resulted in high hydrodynamic pressure at fluid free surface.

Seismic response of elevated rectangular water tanks considering soil structure interaction was carried out by Visuvasam. J, Simon. J, Packiaraj. J S, Agarwal. R, Goyal. L and Dhingra. V (2017) considering the flexible base as spring stiffness in order to consider the effect of soil properties on the seismic behavior of water tanks using SAP2000 software and parametric studies had been carried out based on various types of soils such as soft, medium and hard. The following results are observed the ratio of fundamental time period of flexible base (T_f) to fixed base (T) behaved linearly in case of all types of soils such as soft, medium and hard and the soil structure interaction affects the T_f/T ratio by 20% and 10% for soft and medium type soils respectively. The ratio of base shear of flexible base (V_f) to fixed base models (V) was less in comparison to hard soil.

Seismic response of unanchored liquid storage tanks was carried out Malhotra. P.K., Velestos. A.S. and Tang. H.T. (1993) to highlight the principal effects of base uplifting on the seismic response of ground supported cylindrical steel tanks that were unanchored at their base. It was observed that an unanchored tank's response was characterized by significant values of base uplift, plastic rotation, and compressive stress in the tank wall and a significant loss in the viscous damping occurred as a result of base uplifting.

Simple procedure for seismic analysis of liquid-storage tanks was carried out by Malhotra. Praveen K., Wenk. Thomas and Wieland. Martin (2000) considering impulsive and convective (sloshing) actions of the liquid in flexible steel or concrete tanks fixed to rigid foundations and seismic responses — base shear, over-turning moment, and sloshing wave height calculated by using the site response spectra and performing a few simple calculations. It was observed that Elastic forces were so large that they were arbitrarily reduced by factors of 3 or more to obtain the design forces. Unlike ductile building systems tanks lack a mechanism to dissipate large amounts of seismic energy in a ductile manner.

Simplified model for the seismic performance of unanchored liquid storage tanks was carried out by Vathi. Maria and Karamanos. Spyros A.(2015) focusing on base uplifting mechanics and tank performance with respect to the shell/plate welded connection through a numerical two-step methodology: (1) a detailed finite element shell model of the tank for incremental static analysis, capable of describing the state of stress and deformation at different levels of loading and (2) a simplified modeling of the tank as a spring-mass system for dynamic analysis, enhanced by a nonlinear spring at its base to account for the effects of uplifting. Here the results were aimed at better understanding the uplifting phenomenon during seismic excitation, and developing a simple and efficient tool for the performance-based design of unanchored tanks towards improvement of the current design practice.

Simplified seismic analysis procedures for elevated tanks considering fluid–structure–soil interaction was carried out by Livaoğlu. R. and Doğangün. A. (2006) considering ten different conditioned models with four different subsoil classes which were evaluated by using mechanical and finite-element modeling techniques. It was observed that the impulsive mode of vibration strongly dominates the seismic behavior of elevated tanks. Periods for convective modes were not remarkably different according to the soil–structure interactions of elevated tanks. Sometimes, lateral displacements were ignored in the design. However, they might reach three or more times larger values and these large displacements leaded to instability of the elevated tank. It was also recommended that the distributed added mass approach for seismic analysis of elevated tanks be used in general-purpose structural analyses programs.

Sloshing effect, design and optimization of water ballast tank was carried out by Dumitrache. C L, Deleanu. D and Scurtu. C (2019) to evaluate different stages of sloshing effect when the total pressure exerted by the fluid was changing quickly with time. It was observed that there was a difference between the pressure values in the simple tank and those in the tank that was optimized with internal baffles.

Sloshing response of elevated water tank over alternate column proportionality was carried out by Patel. Chirag N., Vaghela. Shashi N. and Patel. H.S. (2012) to understand the seismic behavior of the elevated water tank under alternate column proportionality under different time history records using finite element software SAP 2000. It was observed that sloshing displacement was increased with the increase in the panel number and increased against high frequency earthquake. Rectangular deep type of column staging value of sloshing displacement was high compare to other types and for Rectangular wide type of column staging it was least. Sloshing displacement had been increased towards higher number of panels.

The study of seismic response on accelerated contained fluid was carried out by Kotrasova. Kamila and Kormanikova. Eva (2017) considering the hydrodynamic (impulsive and convective) pressures, impulsive and convective (sloshing) actions. It was observed that the hydrodynamic pressures are bigger in short and large-scale tanks (tanks with smaller tank slenderness parameter) than in narrow high (slender) tanks. The impulsive components of hydrodynamic pressures gave maximum values on the bottom of tank wall and they obtained bigger values in narrow high (slender) tanks. The convective components of hydrodynamic pressures received the maximum values on the tank wall at the original position of the fluid free surface and they were bigger in short and large-scale tanks than in narrow high (slender) tanks. The convective components of moments (bending and overturning) gave the bigger values in short and large-scale tanks.

2.3 Critical observations based on Literature Review

Based on the review of literatures, some critical observations are acknowledged. These observations are described below,

- Finite element analysis is recognized to be one of the numerical tools for dynamic analysis of water tanks.
- The water within the tank is expressed by several variables such as displacement, velocity potential and pressure. Out of these variables, it is advantageous to model the fluid within the tank by pressure, as the number of degrees of freedom per mode in this case reduced to one.
- In pressure-based formulation, the number of unknown per node is only one. Thus, it requires less storage place and computational time.
- In pressure-based formulation, fluid satisfies the irrotational condition automatically. Otherwise, a complicated condition has to be incorporated to satisfy the irrotationality condition.
- For dynamic analysis of water tank, the water within the tank may be modeled either as compressible or incompressible fluid.
- Linear and nonlinear wave theory may be used to model the reservoir. However, for water with comparatively smaller depth, linear wave theory is sufficient.
- At a certain limit of width to length ratio (*B/L*) the performance of tank in 2-D and 3-D are almost similar.
- The sloshed displacement of liquid depends on the tank size and the baffle within the tank.

OBJECTIVE: The objective of present thesis is to study the free vibration analysis of rectangular water tank considering baffle-fluid interaction.

2.4 Scope of Work:

In order to realize the objective of the present work, the scope of the present research has been defined as follows:

- Development of pressure based 2-D finite element formulation of water within the rectangular tank.
- Finite element formulation of elastic baffle.
- Numerical modeling of interaction between elastic baffle and fluid within containers

CHAPTER-3
THEORITICAL FORMULATION

3.1 Theoretical Formulation for Fluid

The pressure within a compressible fluid can be obtained from Helmholtz's equation and express as

$$\nabla^2 p(x,y,t) = \frac{1}{c^2}\ddot{p}(x,y,t) \tag{3.1}$$

Where, C is acoustic weave speed and if, the compressibility of fluid is neglected the eq. (3.1) will be modified as

$$\nabla^2 p(x,y,t) = 0 \tag{3.2}$$

Now, the pressure within the fluid may be obtained by solving eq. (3.1) with the boundary conditions given below. A typical geometry of water-tank with baffle is shown in Fig. 4.1.

i) *At surface I*

Considering the effect of surface wave of the fluid, the boundary condition of the free surface is taken as

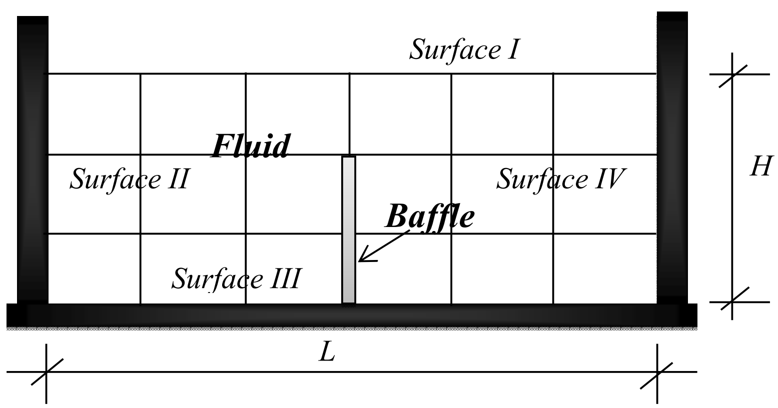

Fig. 4.1 Geometry of fluid-tank -baffle system

$$\frac{1}{g}\ddot{p} + \frac{\partial p}{\partial y} = 0 \tag{3.3}$$

ii) *At surface II* and *surface IV*

At water-tank wall interface, the pressure should satisfy

$$\frac{\partial p}{\partial n}(0,y,t) = \rho_f a e^{i\omega t} \tag{3.4}$$

Where $ae^{i\omega t}$ is the horizontal component of the ground acceleration in which, ω is the circular frequency of vibration and $i = \sqrt{-1}$,*n* is the outwardly directed normal to the element surface along the interface. ρ_f is the mass density of the fluid.

iii) *At surface III*

This surface is considered as rigid surface and thus pressure should satisfy the following condition

$$\frac{\partial p}{\partial n}(x,0,t)=0.0 \tag{3.5}$$

3.2 Finite Element Formulation for Fluid

By using Galerkin approach and assuming pressure to be the nodal unknown variable, the discretized form of eq. (3.1) may be written as

$$\int_{\Omega} N_{rj}\left[\nabla^2 \sum N_{ri} p_i - \frac{1}{c^2}\sum N_{ri}\ddot{p}_i\right] d\Omega = 0 \tag{3.6}$$

Where, N_{rj} is the interpolation function for the reservoir and Ω is the region under consideration. Using Green's theorem eq. (3.6) may be transformed to

$$-\int_{\Omega}\left[\frac{\partial N_{rj}}{\partial x}\sum\frac{\partial N_{ri}}{\partial x}p_i + \frac{\partial N_{rj}}{\partial y}\sum\frac{\partial N_{ri}}{\partial y}p_i\right]d\Omega - \frac{1}{c^2}\int_{\Omega} N_{rj}\sum N_{ri}\, d\Omega\ \ddot{p}_i + \int_{\Gamma} N_{rj}\sum\frac{\partial N_{rj}}{\partial n}d\Gamma\ \ p_i = 0 \tag{3.7}$$

in which i varies from 1 to total number of nodes and Γ represents the boundaries of the fluid domain. The last term of the above equation may be written as

$$\{B\} = \int_{\Gamma} N_{rj}\frac{\partial p}{\partial n}d\Gamma \tag{3.8}$$

The whole system of equation (3.7) may be written in a matrix form as

$$[\bar{E}]\{\ddot{P}\}+[\bar{G}]\{P\}=\{F\ \ \} \tag{3.9}$$

Where,

$$[\bar{E}]=\frac{1}{C^2}\sum\int_{\Omega}[N_r]^T[N_r]d\Omega \tag{3.10}$$

$$[\bar{G}]=\sum\int_{\Omega}\left[\frac{\partial}{\partial x}[N_r]^T\frac{\partial}{\partial x}[N_r]+\frac{\partial}{\partial y}[N_r]^T\frac{\partial}{\partial y}[N_r]\right]d\Omega \tag{3.11}$$

$$[F]=\sum\int_{\Gamma}[N_r]^T\frac{\partial p}{\partial n}d\Gamma=\{F_I\}+\{F_{II}\}+\{F_{III}\}+\{F_{IV}\} \tag{3.12}$$

Here the subscript *I, II, III and IV* stand for different surface conditions. For surface wave, the eq. (3.12) may be written in finite element form as

$$\{F_I\} = -\frac{1}{g}\left[R_f\right]\{\ddot{p}\} \tag{3.13}$$

In which,

$$\left[R_f\right] = \sum \int_{\Gamma_f} [N_r]^T [N_r] d\Gamma \tag{3.14}$$

At the *Surface II and Surface IV* if $\{a\}$ is the vector of nodal accelerations of generalized coordinates, $\{F_{II}\}$ and $\{F_{IV}\}$ may be expressed as

$$\{F_{II}\} \;\; and \;\; \{F_{IV}\} = -\rho\left[R_{II}\right]\{a\} \;\; and \;\; -\rho\left[R_{IV}\right]\{a\} \;\; respectively \tag{3.15}$$

In which,

$$\left[R_{II}\right] \;\; and \;\; \left[R_{IV}\right] = \sum \int_{\Gamma_{II \; and \; IV}} [N_r]^T [N_r] d\Gamma \tag{3.16}$$

At *Surface III*

$$\{F_{III}\} = 0 \tag{3.17}$$

After substitution all terms the eq. (3.9) becomes

$$[E]\{\ddot{P}\} + [G]\{P\} = \{F_r\} \tag{3.18}$$

Where,

$$[E] = \left[\bar{E}\right] + \frac{1}{g}[R_I] \tag{3.19}$$

$$\{F_r\} = -\rho_f [R_{II}]\{a\} - \rho_f [R_{IV}]\{a\} \tag{3.20}$$

For any given acceleration at the fluid-structure interface, the eq. (3.18) is solved to obtain the hydrodynamic pressure within the fluid. However, for free vibration analysis, $\{F_r\} = \{0\}$ and the eq. (18) becomes

$$[E]\{\ddot{P}\} + [G]\{P\} = \{0\} \tag{3.21}$$

3.3 Theoretical Formulation for Elastic Baffle

The baffle is discretized using Bernoulli 2-nodes beam elements with transverse and rotational degrees of freedom. Stiffness and mass matrices of baffle are defined as *[k]* and *[m]* respectively. The mass per unit length of the structure element is $m = \rho_b A$, where ρ_b and A are the mass density of baffle material and the cross-sectional area of the beam element. The structural displacements and accelerations within an element are expressed as

$$v(x,t)=\left[N_b\right]\{d\} \quad and \quad \ddot{v}(x,t)=\left[N_b\right]\{\ddot{d}\} \tag{3.22}$$

Where, *{d}* is the vector of time dependent nodal displacements and *[N_b]* is interpolation function and expressed as

$$\left[N_b\right]=[N_{b1}\, N_{b1}\, N_{b2}\, N_{b3}\, N_{b4}\,] \quad and \quad \{d\}=\begin{bmatrix} V_1(t) \\ \theta_1(t) \\ V_2(t) \\ \theta_2(t) \end{bmatrix} \tag{3.23}$$

and

$$\begin{aligned} N_{b1} &= 1-3\left(\frac{x}{l}\right)^2+2\left(\frac{x}{l}\right)^3 \\ N_{b2} &= x\left(1-\frac{x}{l}\right)^2 \\ N_{b3} &= 3\left(\frac{x}{l}\right)^2-2\left(\frac{x}{l}\right)^3 \\ N_{b4} &= \frac{x^2}{l}\left(\frac{x}{l}-1\right) \end{aligned} \tag{3.24}$$

l is length of the member.

The consistent element mass matrix for the beam element can then be written as

$$m_{ij}=\int_0^l mN_{bi}(x)N_{bj}(x)\,dx \tag{3.25}$$

The stress-strain relation *{**σ**} = [E]{ε}* and a strain-displacement relation *{ε} = [B]{d},* the elemental stiffness matrix can be obtained from the following relation:

$$k_{ij}=\int_0^l B^T E\, B\, dx \tag{3.26}$$

On integration using the element shape functions, the elemental stiffness *[k]* and consistent mass matrices *[m]* are found to be as follows:

$$[m]=\frac{ml}{420}\begin{bmatrix}156 & 22l & 54 & -13l\\ 22l & 4l^2 & 13l & -3l^2\\ 54 & 13l & 156 & -22l\\ -13l & -3l^2 & -22l & 4l^2\end{bmatrix} \quad and \quad [k]=\frac{EI}{l^3}\begin{bmatrix}12 & 6l & -12 & 6l\\ 6l & 4l^2 & -6l & 2l^2\\ -12 & -6l & 12 & -6l\\ 6l & 2l^2 & -6l & 4l^2\end{bmatrix} \quad (3.27)$$

The finite element discretized equation for dynamics excitations can now be written in the familiar form given below

$$[m]\{\ddot{d}\}+[k]\{d\}=\{F_{ext}\} \quad (3.28)$$

Where, $\{F_{ext}\}$ is external dynamic force

3.4 Coupling of Baffle-Fluid Systems

In fluid-baffle interaction problems, the fluid and baffle do not vibrate as separate systems under dynamic excitations, rather they act together in a coupled way. Therefore, the baffle-fluid interaction problem has to be dealt in a coupled way. In the present study, a direct coupling approach is developed to get the responses of baffle-fluid coupled system under external excitations. The coupling fluid and baffle may be formulated in following way. The discrete baffle equation may be written respectively as: Here the damping of baffle is neglected.

$$[m]\{\ddot{d}\}+[k]\{d\}-[Q]\{P\}=\{F_{ext}\} \quad (3.29)$$

Here, [Q] is coupling term arises to satisfy the compatibility condition at the tank baffle-fluid interfaces and is expressed in eq. (3.30). The term [Q]{P} comes to take care the addition force due to the hydrodynamic pressure within the water, adjacent to the baffle walls. Similarly, in eq. (3,31), the term $[Q^T\{\ddot{d}\}]$, is essential to take the effect of additional pressure due to the acceleration of baffle walls, as the flexibility of the baffle walls is considered in present analysis.

$$\int_{\Gamma_s} N_s^T npd\Gamma=\left(\int_{\Gamma_s} N_s^T nN_f d\Gamma\right)p=[Q]\{p\} \quad (3.30)$$

Where, n is the direction vector of the normal to the fluid-baffle interface. Ns and Nf are the shape functions of baffle wall and fluid at the interface are respectively. Similarly, the finite element equation for the fluid with elastic baffle may be written using eq. (3.18) as

$$[E]\{\ddot{P}\}+[G]\{P\}+[Q^T]\{\ddot{d}\}=\{F_r\} \quad (3.31)$$

Now, the system of eqs. (3.29), (3.31) and (74) are coupled in a second-order ordinary differential equations, which defines the coupled fluid-structure system completely. These equations may be written in a combined form as

$$\begin{bmatrix} m & 0 \\ Q^T & E \end{bmatrix} \begin{Bmatrix} \ddot{d} \\ \ddot{P} \end{Bmatrix} + \begin{bmatrix} k & -Q \\ 0 & G \end{bmatrix} \begin{Bmatrix} d \\ P \end{Bmatrix} = \begin{Bmatrix} F_{ext} \\ F_r \end{Bmatrix} \tag{3.32}$$

For free vibration analysis the eq. (3.22) reduced to

$$\begin{bmatrix} m & 0 \\ Q^T & E \end{bmatrix} \begin{Bmatrix} \ddot{d} \\ \ddot{P} \end{Bmatrix} + \begin{bmatrix} k & -Q \\ 0 & G \end{bmatrix} \begin{Bmatrix} d \\ P \end{Bmatrix} = 0 \tag{3.33}$$

CHAPTER-3
RESULTS AND DISCUSSIONS

4.1 Validation of the Proposed Algorithm

In this section, the present algorithm is validated by comparing the convective time periods obtained from IS 1893 (Part 2)-2014. The geometric and material properties of the tank are as follows: height of water in the tank (*H*) = 6.00 m, length of tank (*L*) = 30.0, 24.00 m, 15.00 m and 12.00 m, so that ratio of height to length (*H/L*) = 0.2, 0.25, 0.4 and 0.5 density of water = 1000 kg/m^3, pressure wave velocity = 1440 m/s. Here, the baffle is not considered within the tank. The fluid is discretized by 4 ×8 (i.e., N_h= 4 and N_v = 8). The fundamental convective time period of the water within the tank are listed and compared with those values obtained from IS 1893 (Part 2)-2014 in Table 4.1. The results obtained from the present study almost match with the results from IS 1893 (Part 2)-2014.

Table 4.1 Fundamental convective time period for tank with different height to length ratios

H/L ratio	Fundamental convective time period (sec)	
	Present Study	IS 1893 (Part 2)-2014
0.2	8.8103	8.7435
0.25	7.1251	7.0385
0.4	5.1003	5.0082
0.5	4.2180	4.1475

4.2 Selection of Suitable Mesh Size

The accuracy of the results depends on suitable size of mesh. Here, an attempt has been made to obtain the suitable mesh size. The following properties are considered. Water depth (*H*) = 6.0 m, length of tank (*L*) =30.00 m, acoustic speed (*C*) = 1440 m/sec, mass density of water (ρ) = 1000 kg/m^3. Fundamental convective time period for different mesh size is summarized in Table 4.2. From Table 4.2 it is observed that the Fundamental convective time period gets converged when the horizontal division (N_h) is equal or higher than 4 and the ratio of vertical division to horizontal division (N_v/N_h) is equal to 1.0. However, for further numerical study, N_h is considered as 4 and the higher value (Fig 4.2). The values N_h and N_v are mention in respective examples.

Table 4.2 Convergence of Fundamental convective time period different mesh size

Mesh Size ($N_h \times N_v$)	N_v/N_h	Fundamental convective time period (sec)
(1 ×1)	1	6.516
(1 ×2)	2	7.440
(2×1)	0.5	7.350
(2 ×2)	1	7.778
(3 ×1)	0.33	7.461
(3 ×2)	0.67	7.885
(3 ×3)	1	8.170
(4 ×2)	0.5	8.221
(4 ×3)	0.75	8.787
(4 ×4)	1	8.810
(4 ×6)	1.5	8.810
(6 ×6)	1	8.810

4.3 Analysis of tanks with elastic baffle

In this section, the convective time periods of rectangular tanks have been observed by changing various data like length and height of tank, height, thickness, position of baffle and height of fluid within tanks. The variations of convective time period are mainly shown in graphical form for three different modes. For Baffle the elasticity is 20760 MPa and density is 2300kg/m^3.

Here, R_T – Reservoir Time Period

Int_T – Coupling Time Period

4.3.1 Changing Tank Length Keeping Baffle in Middle

In this section, the tank with 5m fluid height, baffle of 4m height with 100mm thickness are considered. However, the length of tank has been changed keeping the baffle at the middle of the tank always. The graphs are plotted for changes in Time periods (TP) with respect to Length (*L*) and Fluid height(*H*)/Tank Length(*L*) ratio(*H/L*).

a) <u>Graphs for Tank Length vs Time period:</u>

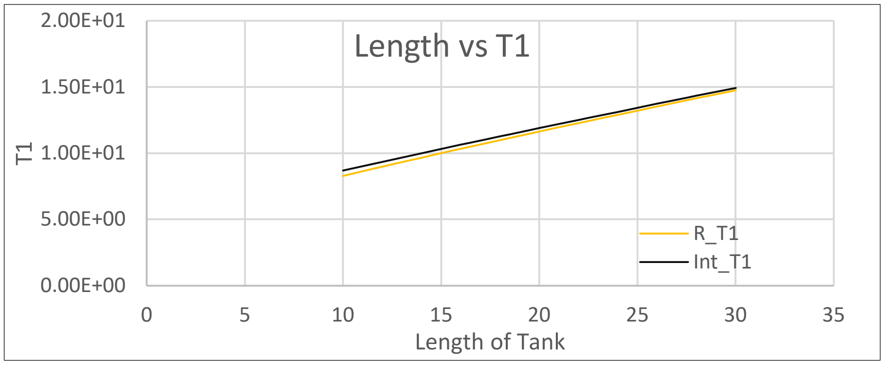

Fig.4.1 First convective time period for different length of tanks

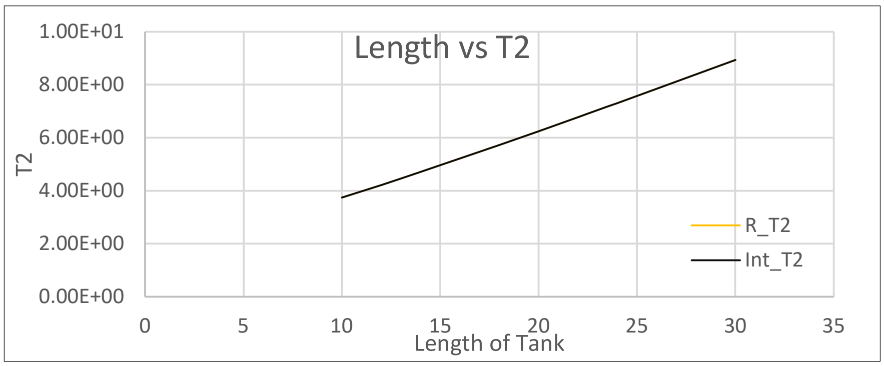

Fig.4.2 Second convective time period for different length of tanks

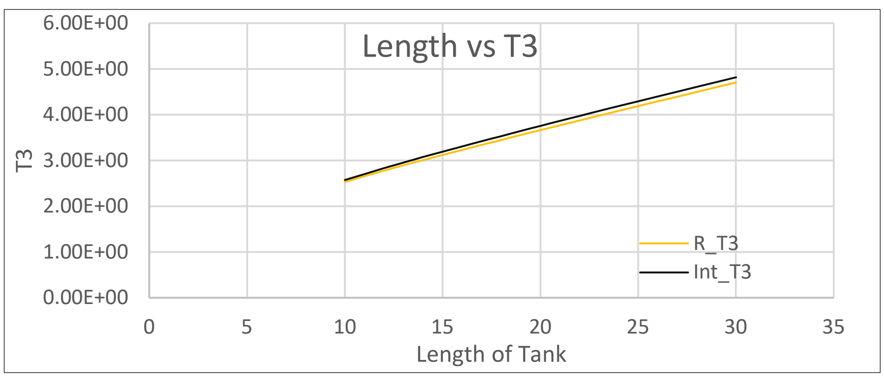

Fig.4.3 Third convective time period for different length of tanks

It has been observed for Fig. 4.1-Fig. 4.3 the length fundamental convective time period for tank with baffle and without baffle increases with increase in tank length. However, the differences in the fundamental time period between the tank with and without baffle decrease with the increase in tank length (Fig. 4.1). On the other hand, the third convective time period line for tank with baffle and without baffle lines are diverging from each other that mean the difference between the time period increases with the increase of tank length (Fig. 4.3). But for the second mode no difference is observed for both the time periods (Fig. 4.2).

b) Graphs for H/L vs Time period:

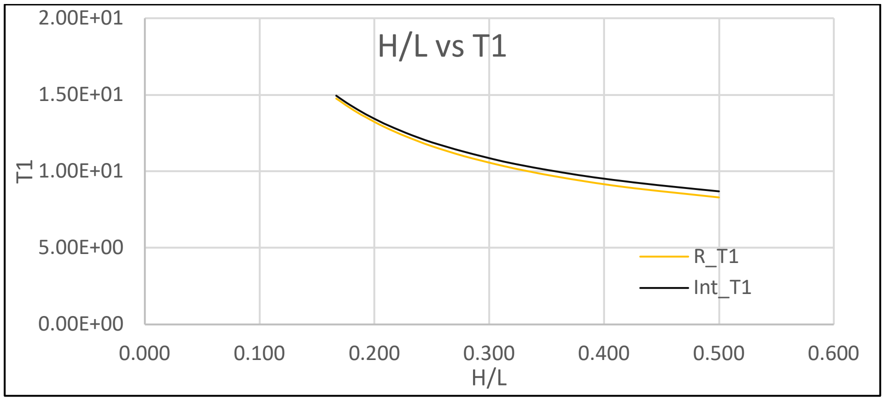

Fig.4.4 First convective time period for different *H/L* ratios

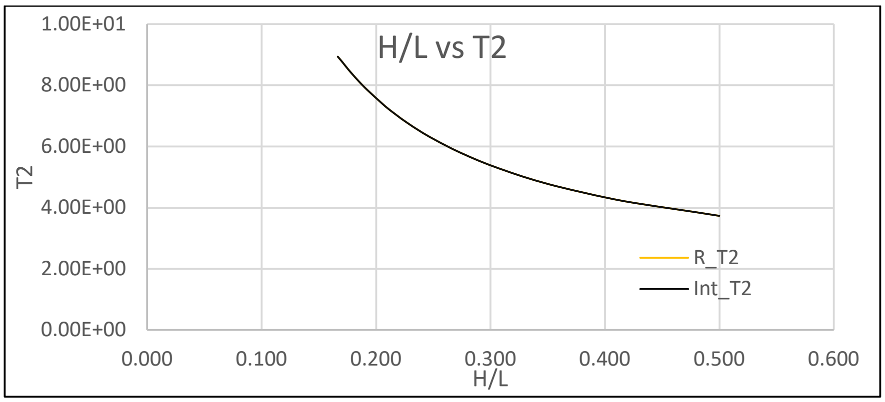

Fig.4.5 Second convective time period for different *H/L* ratios

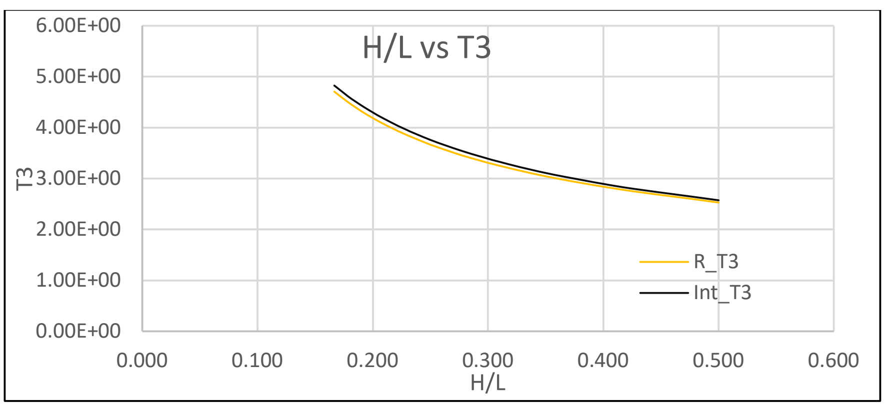

Fig.4.6 Third convective time period for different *H/L* ratios

Here with increase in *H/L* ratio for first convective time period lines for with baffle and without baffle diverge, whereas for third convective time period lines converge to each other. This observation implies that the difference between first convective time period of tank with and without baffle increase with the increase of tank length (Fig. 4.4). However, a reverse trend is observed for third convective time period (Fig 4.6). There is no difference is observed in second mode for both the time period (Fig.4.5).

4.3.2 Changing Fluid Height

In this section convective time periods are calculated for tanks of 20m long with baffle of 4m height and 100mm thickness. Different fluid height has been considered keeping the baffle in the middle. The graphs are plotted for changes in Time periods (*TP*) with respect to Fluid Height(*H*) and Fluid height(*H*)/Tank Length(*L*) ratio (*H/L*).

a) <u>Graphs for Fluid Height vs Time period:</u>

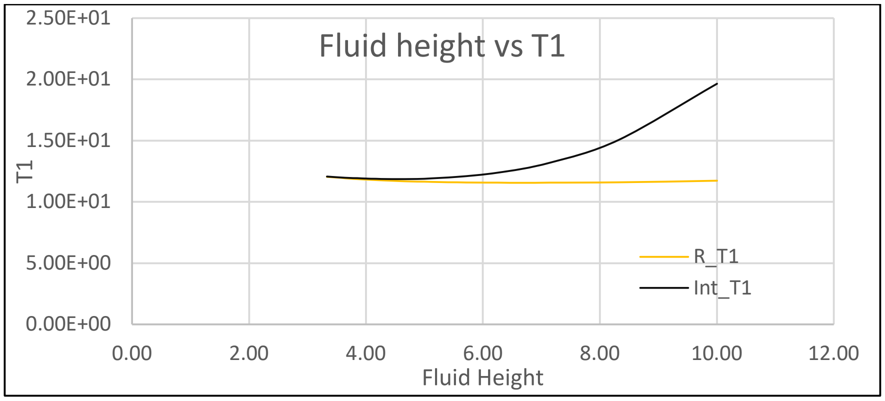

Fig.4.7 First convective time period for different fluid height

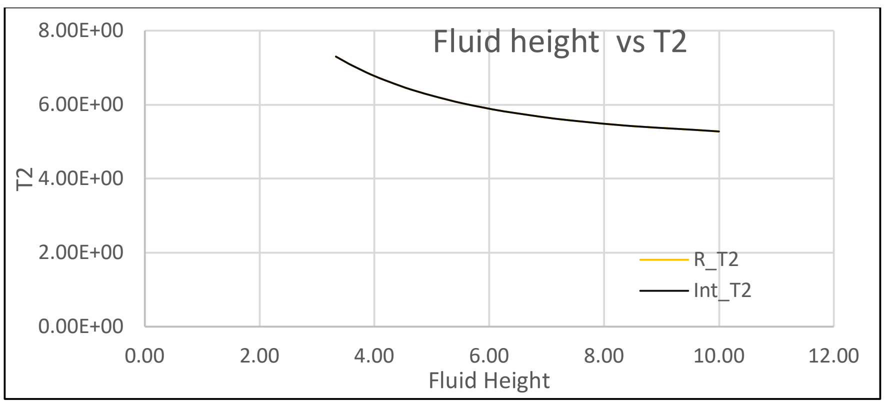

Fig.4.8 Second convective time period for different fluid height

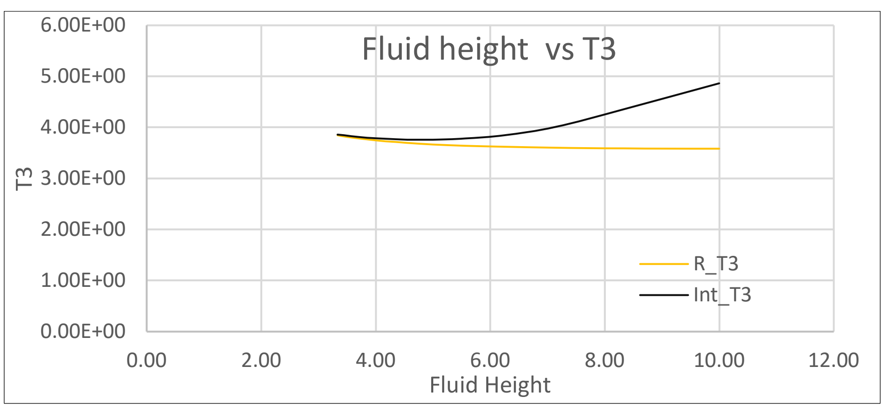

Fig.4.9 Third convective time period for different fluid height

It has been observed that the first convective time period (Fig. 4.7) and third convective time period (Fig. 4.9) of tank without baffle almost constant for all heights of tank. However, these time period for tanks with baffle increases with the increase of tank height and this is mainly due to the consideration of fluid-baffle interaction within the modeling. Beside this it has been found that for first and third mode time period of the tanks with and without baffle wall coincide each other for the tank of fluid height less 4.5m. For second mode, no variation is observed between Reservoir TP and Coupling TP.

b) Graphs for H/L vs Time period:

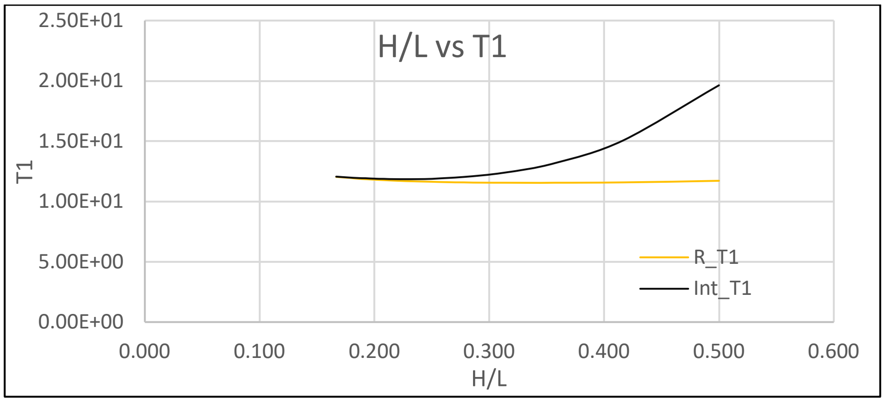

Fig.4.10 First convective time period for different *H/L* ratios

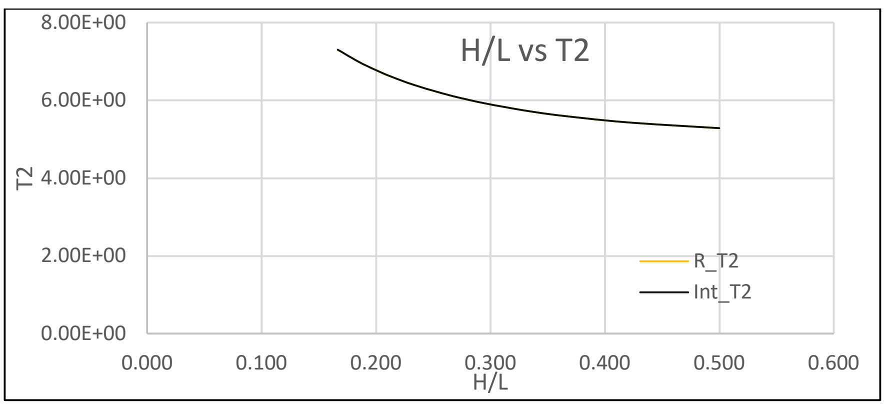

Fig.4.11 Second convective time period for different *H/L* ratios

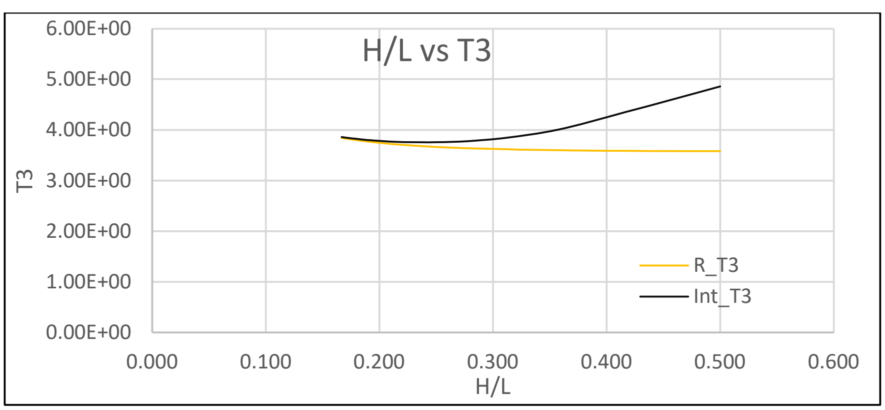

Fig.4.12 Third convective time period for different *H/L* ratios

It has been observed from Fig. 4.10-4.12 that T1 and T3 for tank with baffle at center increases with increase of *H/L* ratio, but the value of T2 decreases with increase in *H/L* ratio. The impact of baffle within the tanks is less significant for T1 and T3 when *H/L* ratio is lesser than 0.2 and there is no difference is observed between R_T and Int_T for second mode.

4.3.3 Changing Baffle position

Here the baffle has been positioned in different locations of tank with 20m length and 5m fluid height. The height and thickness of the baffle are considered as 4m and 100mm respectively. The variation in convective time periods for different baffle positions have been observed in graphical form.

a) Graphs for Baffle position vs Time period:

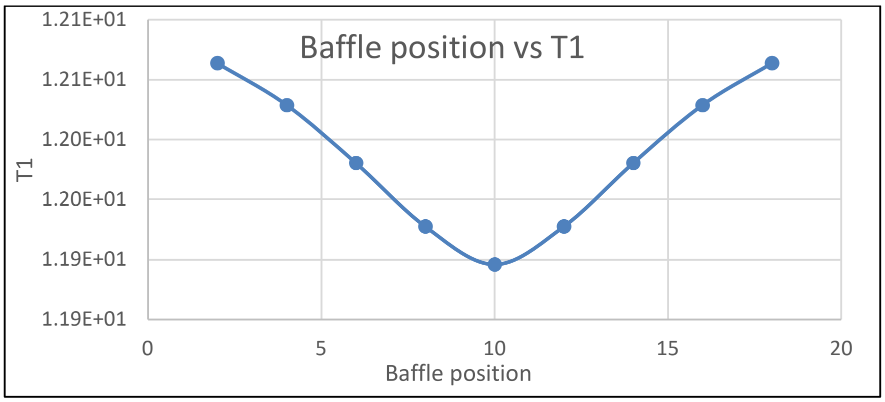

Fig.4.13 First convective time period for different position of baffle

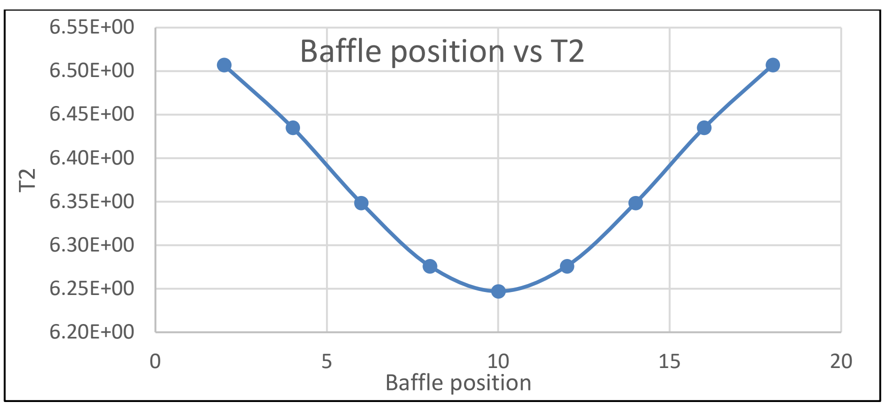

Fig.4.14 Second convective time period for different position of baffle

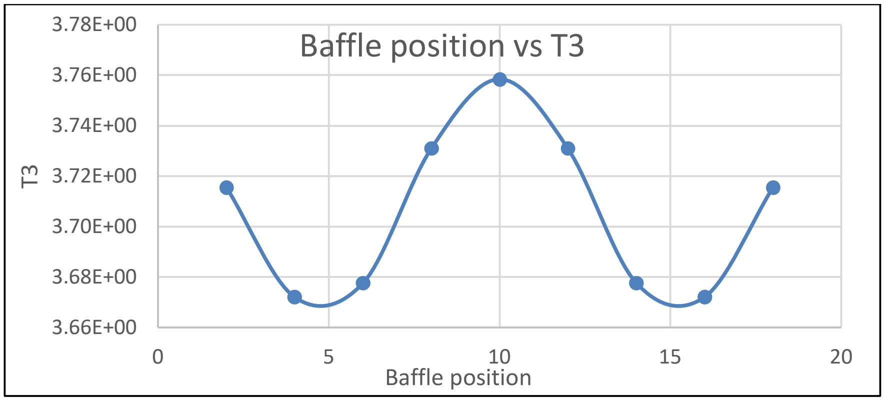

Fig.4.15 Third convective time period for different position of baffle

Here both first and second convective time period decreases with the increase of distance of baffle from tank wall when it is placed between the tank wall and midpoint of tank. In this case, the baffle divides the tank into two parts of different lengths and the portion of comparatively higher length predominate over the portion of comparatively lower length. From section 4.3.1 it is observed that the convective time period decreases with the decrease of tank length and this is the main reason of decreasing the first and second convective time period with the increase of distance of baffle from tank wall. It has been further observed that the baffle position upto $1/4^{th}$ length of tank for third convective time period decreases after that it is increasing upto the middle of the tank and gains the maximum value when it is places at the middle of the tank.

4.3.4 Changing Baffle height

Here the geometry of tank and baffle are considered as follows: Length= 20m, Fluid height= 5m, Thickness of baffle= 100mm and the baffle is kept at middle of tank. The graphs are plotted for convective time periods with the different baffle height.

a) <u>Graphs for Baffle height vs Time period:</u>

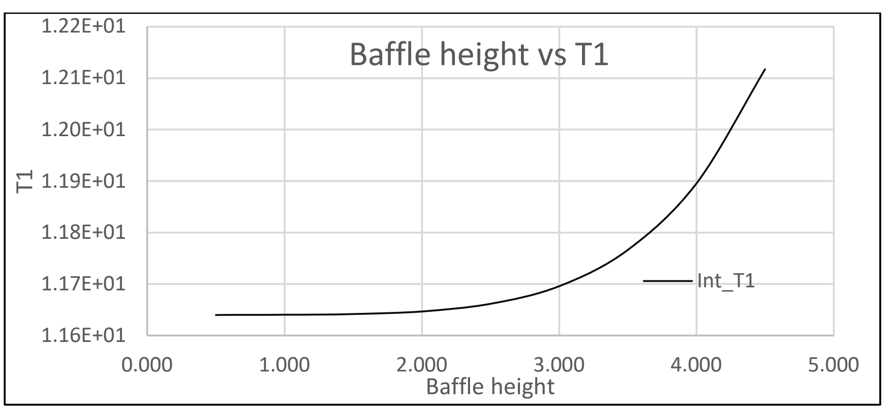

Fig.4.16 First convective time period for different height of baffle

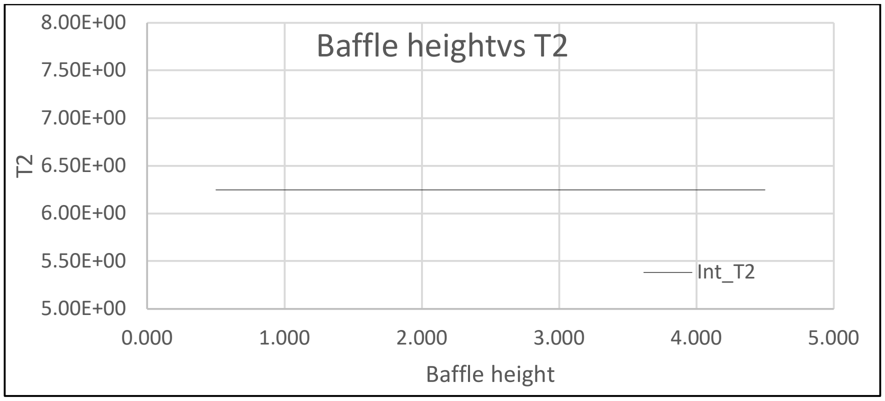

Fig.4.17 Second convective time period for different height of baffle

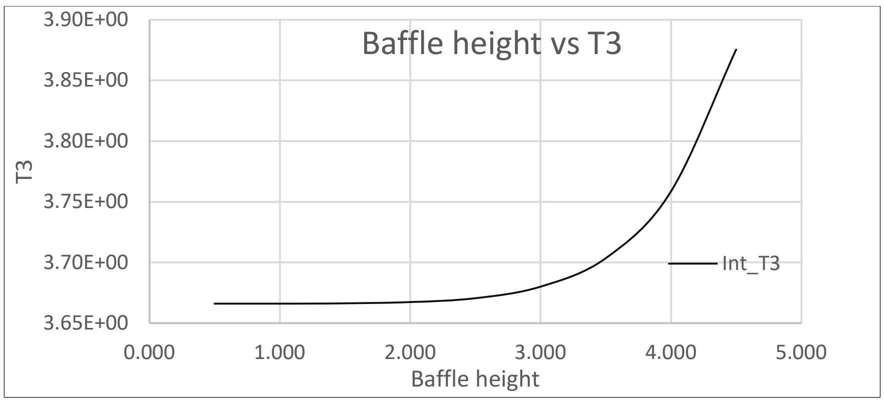

Fig.4.18 Third convective time period for different height of baffle

Here first and third convective time period increase with the increase of baffle height. However, for second convective time period no variation is observed.

4.3.5 Changing Baffle Thickness

Here, Length of tank= 20m, Fluid height=5m and Height of baffle = 4m. Baffle has been kept at the middle of tank. The graphs are plotted for convective time periods with the different baffle thickness.

a) Graphs for Baffle Thickness vs Time period:

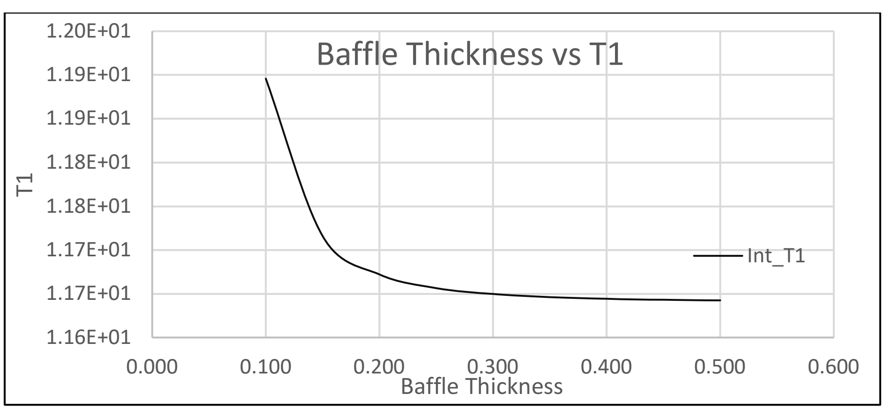

Fig.4.19 First convective time period for different baffle thickness

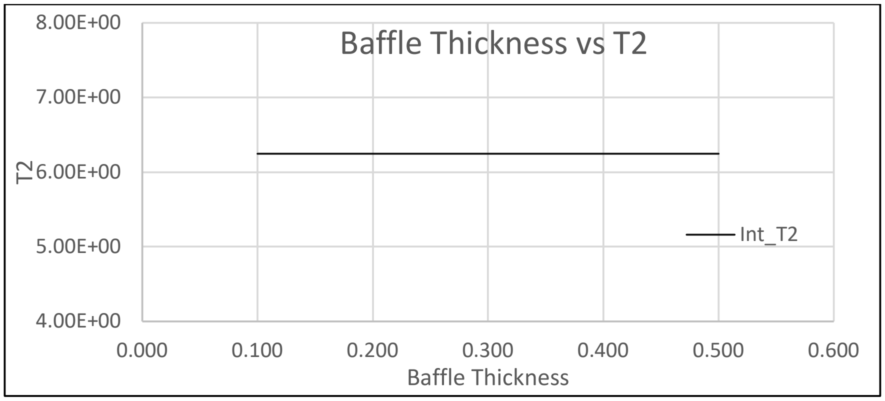

Fig.4.20 Second convective time period for different baffle thickness

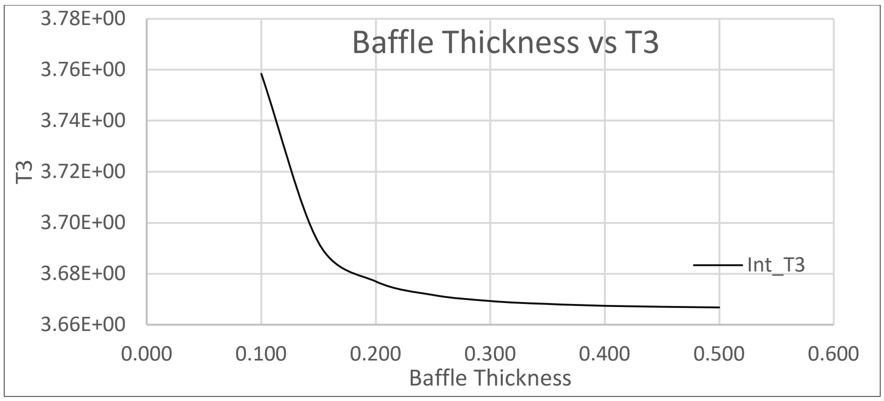

Fig.4.21 Third convective time period for different baffle thickness

Here for First and Third mode convective time period decreases with the increase of Baffle thickness. It has been observed that below Baffle thickness of 0.4m or more precisely it can be noted that near Baffle thickness (t)/ Baffle height (l') ratio below 0.1 the difference between tank with and without baffle are almost insignificant. However, for second mode convective time period has not changed with baffle thickness.

CHAPTER-5
CONCLUSION

The convective time period of rectangular water tank with baffle within tanks is determined considering baffle-fluid interaction. The liquid within the tank is considered to be linearly compressible. Pressure and displacement based finite element method are used to simulate the liquid in tank and baffle wall respectively. Based on the present study the following conclusions may be drawn.

a) The convective time period of tank increases with the increase in the length of tank. This time period of tank with baffle is slightly greater than to those of tank without baffle. However, for comparatively narrow tank, the third convective time period and for large tank, the first convective time period of tank with and without baffle are almost same.

b) The height of the fluid within the tank is also an important parameter for free vibration analysis of rectangular tank with elastic baffle. In this case, the convective time period increases with the increase of fluid height for first and third time period but decreases for second time period.

c) The height of baffle also influences the convective time period of tank. The convective time periods for first and third mode increase with the increase of baffle height. It means the free vibration responses increase with the increase of flexibility of baffle wall. But very little effect of baffle height has been observed for second convective time period which can be neglected.

d) The convective time period decreases with the increase of the distance between the tank wall and baffle for first two convective time period. These convective time periods gain the highest value when it is near to the tank wall and it has lowest value when it is placed near the midpoint of tank. But the third convective time period decreases upto the $1/4^{th}$ distance from tank wall, after that the time period increases upto the midpoint of the tank and gains the maximum value at the midpoint of tank.

e) The convective time period of tank decreases with the increase of baffle thickness for first and third convective time period because the higher thickness of baffle reduces the flexibility of baffle hence reduces the effect of elastic baffle within tanks. However, very little variation has been observed for second time period that can be neglected.

5.1 Future Scope of Work

The present work is an investigation of convective time period of rectangular water tank with elastic baffle within it. There are certain other aspects that may be considered for further research:

- The present study is limited to the free vibration analysis of tank considering vertical baffle. The study may be extended for horizontal baffle
- The responses of rectangular tank with elastic baffle may be determined against sinusoidal and earthquake excitations.
- The present problem may be extended to 3-dimensional form with or without baffle.
- The analysis may also be performed for cylindrical and other types of tanks.
- Non-linear wave theory may be used to simulate the water or other fluid motion within the tank

REFFERENCE

Doğangün, A. and Livaoğlu, R.(2008) "A comparative study of the seismic analysis of rectangular tanks according to the codes of USA, European Community, New Zealand and Turkey", The 14TH World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China

Kotrasová, Kamila, Leoveanu, Ioan-Sorin and Kormaníková, Eva (2013) "A Comparative study of the seismic analysis of rectangular tanks according to EC8 and IS1893", Buletinul AGIR nr. 3/2013 ● iulie-septembrie

Yuan, Renmin., Wu. Xuping., Luo, Tao., Liu. Huizhi. and Sun, Jianning. (2011) "A review of water tank modeling of the convective atmospheric boundary layer", R. Yuan et al. / J. Wind Eng. Ind. Aerodyn. 99 (2011) 1099–1114

Katsuhisa, Fujita (1981) "A seismic response analysis of a cylindrical liquid storage tank including the effect of sloshing", Bulletin of the JSME, Vol. 24, No. 195, September 1981

Katsuhisa, Fujita (1982) "A seismic response analysis of a cylindrical liquid storage tank including the effect of sloshing (2nd Report, Analysis Based on Energy Method)", Bulletin of the JSME, Vol. 25, No. 204, June 1982

Sharma, Vinod and Biag, Aamir Mirza(2019) "A study of hydrodynamic behavior of liquid in overhead tank as per IS 1893-Part II (2014)", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 8 Issue 09, September-2019

Prajapati, Keyur Y., Patel, Dr. H. S. and Darji, Prof. A. R. (2014) "Analysis of hybrid staging systems for elevated storage reservoir", PARIPEX - INDIAN JOURNAL OF RESEARCH, ISSN - 2250-1991, Volume: 3 Issue: 6, June 2014

Kianoush, M.R., Tso, W.K., and Hamidi, M. "Behavior of concrete liquid structures subjected to seismic loading"

Waghmare, M.V., Madhekar, S.N. and Matsagar, Vasant(2015) "Behavior of elevated water storage tanks under seismic events", V. Matsagar (ed.), Advances in Structural Engineering, Springer India 2015

Bachir, Meziani and Ouerdia, Ourrad (2014) "Capillary effect on the sloshing of a fluid in a rectangular tank submitted to sinusoidal vertical dynamical excitation", www.sciencedirect.com/science/journal/10016058, 2014,26(2):326-338 Journal of Hydrodynamics

Hibberd, M.F. and Sawford, B.L.(1992), "Design criteria for water tank models of dispersion in the planetary convective boundary layer", Boundary-Layer Meteorology 67: 97-118, 1994

Drosos, G.C., Dimas, A.A. and Karabalis, D.L.(2008) "Discrete models for seismic analysis of liquid storage tanks of arbitrary shape and fill height", Journal of Pressure Vessel Technology, Transactions of the ASME · November 2008, Vol. 130 / 041801-1

Joseph, Asha and Joseph, Glory(2016) "Dynamic behavior and seismic response of ground supported cylindrical water tanks", The Institution of Engineers (India) 2018

Hadj-Djelloul, Nasser Dine, Djermane, Mohammed, Sharari, Noor and Merabti, Soufiane(2020) “Dynamic behavior of elevated water tanks under seismic excitation”, International Journal of Innovative Technology and Exploring Engineering (IJITEE),ISSN: 2278-3075, Volume-9 Issue-9, July 2020

Aregawi, Birhane and Kassahun, Abdulaziz(2017) “Dynamic response of ground supported rectangular water tanks to earthquake excitation”, Momona Ethiopian Journal of Science (MEJS), V9(1):66-75, 2017, CNCS, Mekelle University, ISSN:2220-184X

Helou, Amin H.(1985) “Dynamics of internal waves in cylindrical tank”, Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. Ill, No. 2, March, 1985, ASCE, ISSN 0733-950X/85/0002-0453/$01.00. Paper No. 19622

Meng, Xun, Li, Xuehong, Xu, Xiuli, Zhang, Jiandong, Zhou, Wenling and Zhou, Ding(2018) “Earthquake response of cylindrical storage tanks on an elastic soil”, Journal of Vibration Engineering & Technologies

Hadj-Djelloul, N. and Djermane, M.(2019) “Effect of geometric imperfection on the dynamic of elevated water tanks”, Civil Engineering Journal, Vol. 6, No. 1, January, 2020

Jung, Jae Hwan, Yoon, Hyun Sik and Lee, Chang Yeol(2015) “Effect of natural frequency modes on sloshing phenomenon in a rectangular tank”, Int. J. Nav. Archit. Ocean Eng. (2015) 7:580~594

Jung, J.H., Yoon, H.S., Lee, C.Y. and Shin, S.C.(2012) “Effect of the vertical baffle height on the liquid sloshing in a three-dimensional rectangular tank”, J.H. Jung et al. / Ocean Engineering 44 (2012) 79–89

Jin, Xin, Tang, Jinbo, Tang, Xiaochun, Mi, Shuo, Wu, Jiaxin, Liu, Mingming and Huang, Zongliu(2020) “Effect of viscosity on sloshing in a rectangular tank with intermediate liquid depth”, Experimental Thermal and Fluid Science 118 (2020) 110148

Zhao, Chunfeng, Chen, Jianyun, Xu, Qiang, Wang, Jingfeng and Wang, Bo(2015) “Investigation on sloshing and vibration mitigation of water storage tank of AP1000”, C. Zhao et al. / Annals of Nuclear Energy 90 (2016) 331–342

Hejazi, Fatemeh Sadat Akhavan and Mohammadi, Mohammad Khan(2019) “Investigation on sloshing response of water rectangular tanks under horizontal and vertical near fault seismic excitations”, Soil Dynamics and Earthquake Engineering 116 (2019) 637–653

Jonker, Harmen J. J. and Jiménez, Maria A.(2014) “Laboratory experiments on convective entrainment using a saline water tank”, Boundary-Layer Meteorol (2014) 151:479–500

Kotrasová, Kamila and Kormaníková(2017) “Liquid storage cylindrical tank - earthquake analysis”, MATEC Web of Conferences 125, 04009 (2017)

Liu, Wing Kam and Lam, Dennis(1983) “Nonlinear analysis of liquid-filled tank”, J. Eng. Mech. 1983.109:1344-1357.

Cox, E.A., Gleeson, J.P. and Mortell, M.P.(2005) “Nonlinear sloshing and passage through resonance in a shallow water tank”, Z. angew. Math. Phys. 56 (2005) 645–680 0044-2275/05/040645-36

Ikeda, T. and Nakagawa, N.(1996) “Non-Linear vibrations of a structure caused by water sloshing in a rectangular tank”, Journal of Sound and Vibration (1997) 201(1), 23-41

Norbert, Jendželovský and Ľubomír, Baláž(2014) “Numerical modeling of cylindrical tank and compare with experiment”, Applied Mechanics and Materials Vol 617 (2014) pp 148-151

Shrigondekar, Anand. H and Padhye, Rajesh D(2016) “Performance of RC elevated water tank for different bracing patterns under the effect of earthquake excitation”, IJIRST –International Journal for Innovative Research in Science & Technology| Volume 2 | Issue 11 | April 2016, ISSN (online): 2349-6010

Fabbrocino, Giovanni, Iervolino, Iunio, Orlando, Francesca and Salzano, Ernesto(2005) “Quantitative risk analysis of oil storage facilities in seismic areas”, G. Fabbrocino et al. / Journal of Hazardous Materials A123 (2005) 61–69

Muller, Oscar and Rubinstein, Marcelo(1992) “Reliability-Based design of RC water tank structures under seismic action”, EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS, VOL. 21,665478 (1992)

Helou, Sameer H.(2014) “Seismic induced forces on rigid water storage tanks”, Asian Journal of Engineering and Technology (ISSN: 2321 – 2462) Volume 02 – Issue 04, August 2014

Omidinasab, F. and Shakib, H.(2011) “Seismic response evaluation of the rc elevated water tank with fluid-structure interaction and earthquake ensemble”, KSCE Journal of Civil Engineering (2012) 16(3):366-376, Vol. 16, No. 3 / March 2012

Visuvasam, J., Simon, J., Packiaraj, J. S., Agarwal, R., Goyal, L. and Dhingra. V.(2017) “Seismic response of elevated rectangular water tanks considering soil structure interaction”, IOP Conf. Series: Materials Science and Engineering 263 (2017) 032036

Malhotra, P.K., Velestos, A.S. and Tang, H.T.(1993) “Seismic response of unanchored liquid storage tanks”, SMiRT-12 I K. Kussmaul (Editor), 1993 Elsevier Science Publishers B.V. All rights reserved

Malhotra, Praveen K., Wenk, Thomas and Wieland, Martin(2000) “Simple procedure for seismic analysis of liquid-storage tanks”, Structural Engineering International 3/2000

Vathi, Maria and Karamanos, Spyros A.(2015) “Simplified model for the seismic performance of unanchored liquid storage tanks”, Proceedings of the ASME 2015 Pressure Vessels & Piping Division Conference, PVP2015, July 19-23, 2015, Boston, Massachusetts, USA

Livaoğlu, R. and Doğangün, A.(2006) “Simplified seismic analysis procedures for elevated tanks considering fluid–structure–soil interaction”, R. Livaogˇlu, A. Dogˇangu¨ n / Journal of Fluids and Structures 22 (2006) 421–439

Dumitrache, C.L., Deleanu, D. and Scurtu. C.(2019) “Sloshing effect, design and optimization of water ballast tank”, 5th International Scientific Conference SEA-CONF 2019

Patel, Chirag N., Vaghela, Shashi N. and Patel, H.S.(2012) “Sloshing response of elevated water tank over alternate column proportionality”, IJAET/Vol.III/ Issue IV/Oct.-Dec., 2012/60-63

Kotrasova, Kamila and Kormanikova, Eva(2017) “The study of seismic response on accelerated contained fluid”, Hindawi, Advances in Mathematical Physics, Volume 2017, Article ID 1492035