



**APPLICATION OF BASE ISOLATION SYSTEMS IN SEISMIC DESIGN OF STEEL
WATER STORAGE TANKS**

by

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ABSTRACT

This study examines the seismic behaviour of a modular steel water storage tank equipped with a base isolation system, focusing on the friction pendulum system (FPS) as the primary isolation mechanism. Analytical models were developed using the lumped mass analogy technique, where the masses are referred to as convective, impulsive, and base masses. Numerical simulations were performed using Abaqus software, considering fluid-structure interaction, to simulate the dynamic behaviour of an isolated tank under seismic excitation. A comparative analysis was undertaken between isolated and non-isolated tanks and those incorporating an FPS to assess the system's efficiency. Moreover, the study was conducted to measure the effects of key system parameters on the base isolation of liquid storage tanks. Key parameters considered in this study include the tank's aspect ratio, isolation period, and friction coefficient. The objective was to assess the performance of a tank supported by friction pendulum bearings (FPS). The application of base isolation in steel water storage tanks can produce different results, influenced by factors such as isolation system design, tank properties, seismic intensity, and overall structural stability. To achieve the desired results, conducting a comprehensive engineering analysis and considering design elements were crucial. The approach involved the application of simulation-based analysis to investigate how base isolation affected the seismic response of tanks during an earthquake. The research established the efficiency of the isolation system in alleviating fluid-induced forces by attaining potential stability, less hydrodynamic pressure, wall buckling risk reduction, better control of water behaviour, decrease and stable bearing shear impact in isolated tanks compared to non-isolated tanks.

Keywords: Friction pendulum system, elevated water tank, finite element method, base isolation, fluid structure-interaction, hydrodynamic pressure.

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DEDICATION

"اللهم انفعنا بما علمتنا وعلمنا بما ينفعنا الحمد لله على فضله وكرمه"

“O God, benefit us from that which you have taught us and teach us that which benefits us. Praise be to God for His grace and generosity.”

- Firstly, this thesis is dedicated to my beloved wife, whose constant support, patience, and reassurance have been a pillar of strength throughout the entire journey.
- To my father, for his support and unwavering encouragement despite the adversity he has had to endure during the current war in our country. I am constantly inspired by his resilience and motivated by his love.
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TABLE OF CONTENTS

Declaration	iii
Abstract	iv
Acknowledgements	v
Dedication	vi
Table of contents	vii
List of figures	ix
List of tables.....	xi
Glossary.....	xii
CHAPTER ONE: INTRODUCTION AND BACKGROUND	1
1. Introduction	1
1.1 Background	1
1.2 Research Problem.....	3
1.3 Research Questions	4
1.4 Aim, Objectives, and Outcomes.....	4
1.5 Significance	4
1.6 Delineation	4
1.7 Research Methodology.....	5
1.8 Research Design.....	5
1.9 Organisation of Dissertation.....	5
1.10 Chapter Summary.....	6
CHAPTER TWO: LITERATURE REVIEW.....	8
2.1 Application of Base Isolation	8
2.1.1 Introduction	8
2.2 Previous Research Studies.....	10
2.3 Technique of Fluid Structure Interaction in Storage Water Tanks	19
2.3.1 Arbitrary Lagrangian Eulerian (ALE) method	19
2.3.2 Acoustic method.....	19
2.3.3 Coupled Eulerian-Lagrangian (CEL) method.....	19
2.4 Seismic Load in Water Storage Tanks.....	20
2.4.1 Elevated Water Tanks.....	20
2.4.2 Response Spectrum Curve.....	21
2.5 Base Shear and Overturning Moment	Error! Bookmark not defined.
2.6 Chapter Summary.....	22
CHAPTER THREE: DEVELOPING FPS MODEL, FSI TECHNIQUE, AND INPUT.....	24
3.1 Introduction	24
3.2 Principle of FPS	25
3.2.1 Function of FPS.....	25
3.2.2 Methods for a model friction pendulum system	26
3.3 Bi-Directional Plasticity Model.....	27
3.4 Verification of Model Benchmark of Analysis	28
3.5 Isolator Stiffness of FPS.....	28
3.6 Non-Sliding Situation.....	28
3.7 Sliding Situation.....	29
3.8 Fluid Structure Interaction.....	29
3.8.1 Boundary Conditions.....	31
3.9 Seismic Input.....	32
3.10 Chapter Summary.....	34
CHAPTER FOUR: VERIFICATION OF THE PROPOSED MODEL FOR FRICTION PENDULUM SYSTEM (FPS).....	35
4.1 Structure Modelling.....	35
4.2 Soil Structure Interaction Effect.....	36

4.2.1	Time history response.....	36
4.3	Finite Element Modelling Technique	36
4.4	Chapter Summary	42
CHAPTER FIVE: FEM ANALYSIS, SIMULATION AND MODELLING STRATEGY OF ELEVATED STEEL WATER STORAGE TANKS CONSIDERING FRICTION PENDULUM SYSTEM		43
5.1	Introduction	43
5.2	Finite Element Modelling of Elevated Steel Water Storage Tanks	43
5.2.1	Structural layout, element types, and material properties	43
5.2.2	Hoop stress of the isolated tank	46
5.2.3	Meshing generation and element discretisation	50
5.3	Results and Discussion	51
5.3.1	Seismic displacement analysis.....	51
5.3.2	Shell stress analysis	52
5.3.3	Water interaction	54
5.3.4	Base shear analysis.....	57
5.4	Chapter Summary	58
CHAPTER SIX: SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS		56
6.1	Introduction	56
6.2	Evaluation of the Research Aim, Objectives, and Outcomes	60
6.2.1	Develop and validate a finite element model of elevated water tanks equipped with base isolation under earthquake motion.....	60
6.2.2	Conduct analysis of seismic response loads with and without FPS of the "SBS ST05" to evaluate the effectiveness of water motion under earthquake excitation.....	61
6.2.3	Analyses of the impact of sliding bearings on the seismic performance of steel water tanks	62
6.3	Conclusion.....	63
6.4	Contribution of this Research	64
6.5	Recommendations for Future Research.....	64
APPENDICES		71
Appendix A: Finite Element Model Report		71
Appendix A1: Introduction		71
Appendix A2: Meshing Elements.....		72
Appendix A3: Summary		72

LIST OF FIGURES

Figure 1.1: Support frame collapse of elevated steel water reservoir, 1933 Long Beach (adapted from NZSEE, 2009).....	2
Figure 1.2: Damaged support to elevated concrete water reservoir, 2001 Bruj (adapted from NZSEE, 2009)	2
Figure 1.3: Rigid and flexible masses model - Adapted from Pourbehi et al. (2023).....	3
Figure 1.4: Flowchart diagram illustrating the research process of the thesis	7
Figure 2.1: Seismic isolated structure vs. conventional earthquake-resistant structure	8
Figure 2.2: Cross section of Laminated Rubber Bearing (LRB), rectangular and cylindrical shapes	9
Figure 2.3: Cross section of Friction Pendulum System (FPS), open and installed - Adapted from Robertson (2010).....	10
Figure 2.4: (a-c) Elephant’s foot buckling, (d-f) Diamond shape buckling - Adapted from Brunesi and Nascimbene (2024)	19
Figure 2.5: Masses of elevated tank - Adapted from NZSEE (2009).....	20
Figure 2.6: Cross section two mass model - Adapted from NZSEE (2009).....	21
Figure 2.7: Seismic zones of South Africa - Adapted from 10160-4:2017 (2017).....	22
Figure 2.8: Spectrum curve - Adapted from 10160-4:2017 (2017).....	22
Figure 3.1: Cross section of FPS and force displacement curve - Adapted from Meral (2021).....	24
Figure 3.2: FPS force displacement - Adapted from Lousidis (2015).....	25
Figure 3.3: Dynamic friction and spring model.....	26
Figure 3.4: Elastic & hysteretic resisting force component - Adapted from Mosqueda et al. (2004)....	27
Figure 3.5: Typical FSI problem	31
Figure 3.6: Experiment test for water storage tanks using a shaking table - Adapted from Alembagheri (2011).....	33
Figure 3.7: ETA20e03 signal	34
Figure 4.1: Isolated structure with SSI - Krishnamoorthy & Anita (2016)	35
Figure 4.2: Structure model with Kelvin and spring element via Abaqus	37
Figure 4.3: Spring element	38
Figure 4.4: Simplified soil and foundation mesh.....	38
Figure 4.5: Simplified structure mesh	39
Figure 4.6: Displacement graph over time for rigid soil.....	40
Figure 4.7: Displacement output from Abaqus over time.....	40
Figure 4.8: Base shear value over the time.....	41
Figure 4.9: Base shear over time Abaqus	41
Figure 4.10: Displacement vs Base shear curve of FPS isolator	42
Figure 5.1: Shell element and wind girt.....	44
Figure 5.2: Elevated steel structure and steel plate.....	44
Figure 5.3: Wind girt connected to steel plate.....	45
Figure 5.4: Concrete foundation.....	45
Figure 5.5: Gravity and hydrostatic pressure lead to applied	47
Figure 5.6: Boundary condition and displacement force for a non-isolated model	48
Figure 5.7: Boundary condition and displacement force for an isolated model	48
Figure 5.8: ET signal for 7 seconds - Estekanchi and Alembagheri (2012)	49
Figure 5.9: Comparison of spectrum response curve for SANS10160-4 and ET signal	49
Figure 5.10: FPS isolator defined as a spring element.....	50
Figure 5.11: Tank shell and water elements	50
Figure 5.12: Comparison of tank displacement over time	52
Figure 5.13: Maximum hoop stress of the shell non-isolated tank	53
Figure 5.14: Maximum hoop stress of the shell isolated tank	53

Figure 5.15: Shell stress over time	54
Figure 5.16: Hydro dynamic pressure of water for non-isolated tank	55
Figure 5.17: Hydrodynamic pressure of water for isolated tank.....	55
Figure 5.18: Comparison of impact of hydrodynamic pressure	56
Figure 5.19: Water sloshing over time	57
Figure 5.20: Base shear over time	58

LIST OF TABLES

Table 2.1: Summary of literature review.....	16
Table 2.2: Parameters of response spectra.....	22
Table 3.1: Characteristics of FPS.....	24
Table 4.1: Soil types and properties	35
Table 4.2: Material properties	36
Table 5.1: Tower elements dimensions	45
Table 5.2; Material parameters.....	46
Table 5.3: Instance table.....	51
Table 5.4: Outcomes of non-isolated and isolated tanks for variables	58

GLOSSARY

Acronyms

ALE
CEL
DVFPI
EM
EMB
ETM
FEA
FEM
FPB
FPS
HDRB
LNG
LRB
LRB
N-Z
PFS
PGA
R-FBI
SSI
VFPS
VOF

Definition

Arbitrary Lagrangian-Eulerian
Coupled Eulerian-Lagrangian
Double Variable Frictional Pendulum Isolator
Elastomeric
Elastomeric Bearing
Endurance Time method
Finite Element Analysis
Finite Element Method
Friction Pendulum Bearing
Frictional Pendulum System
High-Damping Rubber Bearings
Liquefied Natural Gas
Lead-Rubber Bearing
Laminated Rubber Bearings
Neoprene-Zinc
Pure-Friction System
Peak Ground Acceleration
Resilient Friction Base Isolation
Soil Structure Interaction
Variable Frictional Pendulum System
Volume of Fluid

CHAPTER ONE

INTRODUCTION AND BACKGROUND

1. Introduction

This chapter establishes the foundation of the research by presenting essential background information on seismic design and base isolation systems, particularly in the context of steel water storage tanks. It identifies the research problem, emphasising the vulnerability of such structures during seismic events and the limitations of conventional design approaches. This chapter presents the study's objectives and expected outcomes, focusing on improving the seismic performance of water tanks using advanced isolation strategies. It also summarises the research methodology, emphasising the analytical and modelling techniques employed to assess the efficiency of base isolation systems. This introduction sets the stage for the detailed exploration and analysis presented in the subsequent chapters.

1.1 Background

Steel storage tanks are essential components in numerous sectors, including water distribution, chemical processing, and nuclear energy facilities. Due to their critical function, they must be engineered to endure significant seismic forces. Their reliability and durability are essential for ensuring the continuous operation of industrial processes, maintaining water availability, and safeguarding nuclear power systems (Pourbehi et al., 2023).

Protecting liquid storage tanks from seismic hazards is a key concern in structural design. These tanks are often classified as lifeline structures due to their indispensable role in storing and supplying water for essential uses such as drinking, agriculture, and firefighting. Consequently, they must be designed, constructed, and maintained in accordance with established industry standards and guidelines to ensure their dependability and prevention of catastrophic failure (Rawat et al., 2015). Cylindrical liquid storage tanks respond to earthquakes in a manner distinct from conventional structures such as buildings and bridges. This is primarily due to the interaction between the tank structure and the contained liquid, which induces distinctive stress patterns not typically observed in conventional structures.

Liquid storage tanks are crucial structures in various industries, including nuclear power plants and other sectors related to public life. This specifies the strategic importance of supporting diverse processes and operations (Jadhav & Jangid, 2004). However, there have been multiple reports (NZSEE, 2009, (Malhotra, et al., 2000)) on large-scale damage to liquid storage tanks (Figures 1.1 and 1.2). These studies identified that the causes of tank failure are as follows:

- 1- Buckling of the tank wall.
- 2- Piping system failure.

3- Anchorage system uplift.



Figure 1.1: Support frame collapse of elevated steel water reservoir, 1933, Long Beach (Adapted from NZSEE, 2009)



Figure 1.2: Damaged support to elevated concrete water reservoir, 2001 Bruj (Adapted from NZSEE, 2009)

In recent decades, seismic isolation has gained recognition as an effective strategy for safeguarding liquid storage tanks against intense ground shaking. Steel tanks are widely utilized for storing water, petroleum products, and various chemicals, making their seismic performance a critical concern. These tanks must remain operational immediately after an earthquake, especially for emergency water supply (Soni et al., 2011). Furthermore, tanks containing highly flammable substances pose a significant risk in the event of structural failure, potentially leading to uncontrolled fires and severe environmental damage (Seleemah & El-Sharkawy, 2011).

Several methods are available to mitigate the damage to the water tank during a seismic event. One of the most effective approaches is the base isolation system, which involves placing a layer of isolating material between the tank and the foundation, decoupling the tank from the damaging effects of earthquake motion. Hence, the base isolation system helps to reduce the force acting on the tank during seismic events (Rawat et al., 2015). To analyse the seismic behaviour of an isolated tank-liquid system, the structure is typically modelled using three lumped masses: convective, impulsive, and base masses (Figure 1.3). The effectiveness of different isolation systems can be evaluated through analytical seismic response analyses of these models. Furthermore, an analysis study will provide quantification of the effects of the significant parameterisation system of base isolation for the liquid storage tanks. Therefore, the base isolation effect of earthquakes will be lessened in storage tanks (Bagheri & Farajian, 2016).

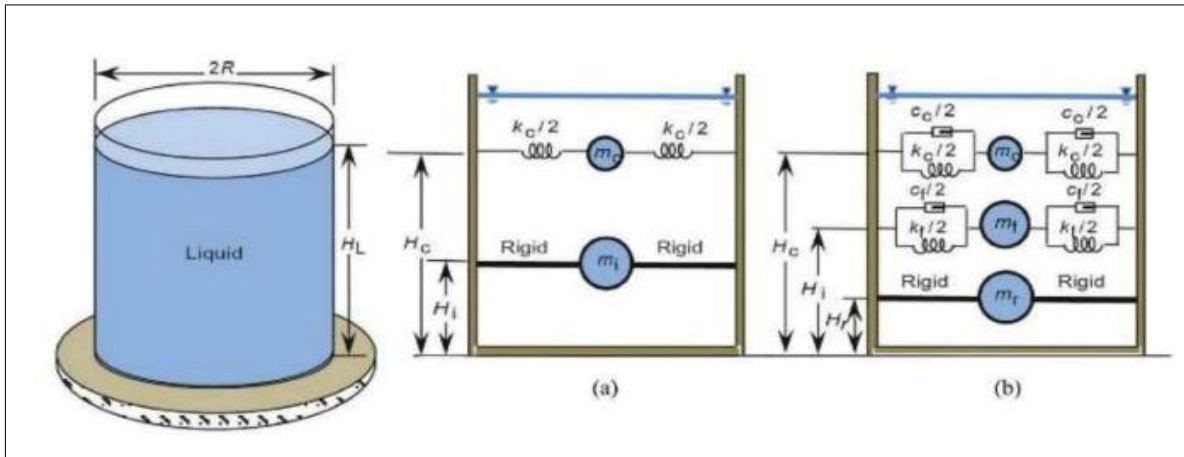


Figure 1.3: Rigid and flexible mass model
(Adapted from Pourbehi et al. (2023))

Previous studies have employed sliding bearings to isolate liquid storage tanks, with analyses performed under bi-directional seismic ground motions. Several researchers compared various isolation systems for liquid storage tanks, including lead-rubber bearing (LRB), pure-friction system (PFS), frictional pendulum system (FPS), resilient friction base isolator (R-FBI), and the Electric de France system (Bagheri & Farajian, 2016). Comparing the two forms of isolation systems, the studies pointed out that sliding forms can better respond to seismic forces than elastomeric bearings (EMB). Various base isolation systems have proved that FPS is more effective than the other systems. The researchers further observed the seismic performance of liquid storage tanks isolated by FPS under unidirectional excitation and showed that the isolation system effectively reduces the response of the structure (Bagheri & Farajian, 2016).

1.2 Research problem

The interaction between the contained fluid and the supporting structure is a key factor influencing the seismic response of liquid storage tanks. During ground shaking, energy from the earthquake is transmitted through the tank structure to the contained fluid, resulting in complex dynamic behaviour. This interaction introduces an added mass effect, which causes the liquid to slosh (Seleemah & El-Sharkawy, 2011).

Common problems associated with steel water storage tanks during earthquakes include:

- **Buckling:** Steel water tanks are highly susceptible to buckling when exposed to horizontal forces, such as those produced by an earthquake. This can cause the tank to collapse or deform and lead to catastrophic failure.
- **Collapse:** Water inside the tank can slosh around during an earthquake and create additional stresses on the tank structure. This can cause cracking, deformation, or even rupture of the tank.

1.3 Research questions

1. How can seismic behaviour in elevated water tanks with friction pendulum systems be predicted?
2. How does the base isolation system affect an elevated water tank during an earthquake?

1.4 Aim, objectives, and outcomes

Base isolation systems offer significant benefits in structural design by reducing seismic demands on critical components. For steel water storage tanks, the primary objective of base isolation is to decouple the structure from ground motion, effectively separating vertical and horizontal load paths to enhance stability. This approach mitigates forces and stresses transmitted to the tank, thereby lowering the likelihood of structural failure and excessive liquid sloshing. The technique employs isolators or damping devices that absorb seismic energy and limit force transfer from the foundation to the tank.

The main objectives of base isolation for steel water storage tanks are:

1. To develop and validate a finite element model for predicting the seismic behaviour of elevated steel water storage tanks equipped with FPS base isolation under earthquake ground motion.
2. To conduct a detailed analysis of the "SBS ST05" elevated water storage tank, both with and without FPS base isolation, to provide design recommendations for enhancing seismic resistance and to evaluate the effectiveness of water motion under earthquake-induced ground excitation.
3. To analyse the impact of sliding bearings FPS on the seismic performance of steel water storage tanks.

These systems ensure safer and more resilient structures, as well as protecting both occupants and assets.

1.5 Significance

This study adopts a simulation-based analytical methodology to investigate the impact of base isolation on the seismic response of elevated steel water storage tanks. By utilising finite element modelling techniques, the study aims to replicate realistic earthquake loading conditions and assess the dynamic behaviour of tanks both with and without base isolation systems, specifically the FPS.

1.6 Delineation

This research utilises simulation-based isolation analysis to evaluate the seismic performance of flexible water storage tanks with and without base isolation, and to investigate tank interaction with earthquake ground motion. Abaqus software is used to model and simulate the tank structure along with its base isolation system. However, certain factors were deliberately excluded from the scope of this research to maintain focus and manage complexity. Notably, wind loads and their influence on the dynamic behaviour of the tank were not considered. Additionally, thermal effects, soil-structure interaction, and nonlinear material behaviour were beyond the scope of this study. These exclusions were made to concentrate the analysis on seismic performance and the role of base isolation systems.

1.7 Research methodology

This research employed a qualitative case study approach to evaluate the effectiveness of base isolation in the seismic design of steel water storage tanks. Finite element modelling (FEM) was utilised to quantify the effect of isolation on the seismic response of the tanks under earthquake loading. The study incorporated both primary and secondary data sources. Primary data were obtained from industry-supplied design drawings, while secondary data were gathered through an extensive review of relevant literature and technical reports. Abaqus software is employed to analyse data and simulate the tank and its base isolation system. In essence, the study evaluated tank performance during simulated earthquakes and compared results with literature findings on various isolation systems. It measured the seismic response of base isolation and liquid interaction by FPS during the earthquake to compare the liquid interaction and base isolation response at different times and vibrations.

This investigation seeks to determine the key factors that influence the effectiveness of base isolation systems. By comparing the behaviour of tanks equipped with base isolation to those without, the study evaluates their structural performance and the dynamics of liquid movement within. Particular attention is given to elevated steel water storage tanks that incorporate base isolation in their design.

1.8 Research design

In earthquake-prone regions, the seismic design of steel water storage tanks is critical to ensuring the safety and reliability of water delivery systems. Base isolation systems enhance seismic performance by mitigating the impact of ground motion on both the tank structure and its contents.

A comprehensive finite element (FE) analysis was carried out using Abaqus to construct detailed three-dimensional models of steel water tanks, both with and without base isolation. These models were exposed to a range of seismic inputs, including displacement, acceleration, and stress, to assess their structural response under earthquake conditions. The outcomes of the simulations were utilised to identify the most effective design parameters for implementing base isolation systems.

1.9 Organisation of the dissertation

Chapter one provides a general introduction to the background, aims, outcomes, and significance. The background provides detailed information on the research context, specifically highlighting the gap or problem in the tank's seismic response during the earthquake. The chapter also presents the appropriate research aim and objectives required in addressing the identified problem.

Chapter two presents a detailed literature review covering the data and information of previous research. The chapter also presents information on research approaches employed by the different investigations. The relevance of these approaches was evaluated to have a holistic understanding of the research.

Chapter three discusses the characterisation of the FPS modelling approach, including FSI, and the selection of seismic input for dynamic analysis. The application of FPS is discussed in relation to its features and findings in the seismic base isolation technique. Applicable mathematical equations for modelling FPS, along with those required to define and determine the boundary conditions for FSI. Other areas discussed include the performance evaluation of a structure (seismic tank) and failure assessment based on increasing acceleration.

Chapter four validates the proposed model for FPS using FEM to determine the structure's performance level against earthquake ground motion effects. Other relevant areas include soil structure interaction effects, finite element modelling techniques, and time history responses.

Chapter five presents the results and discussion of FEM analysis, simulation and modelling outcomes for elevated steel water storage tanks using FPS. The chapter also discusses the importance of FSI in the assessment of the tank's response under seismic events. The adoption of a finite element modelling framework for elevated water tanks involves evaluating the hydrodynamic interaction and structural response under seismic loads.

Chapter six presents the conclusion and recommendations for future research. The findings derived through the analysis of the study's problem are elucidated in this chapter in accordance with the study's objectives to strengthen the purpose of the research. Another section of the chapter covers the contribution to the knowledge base of this research field.

1.10 Chapter summary

This chapter introduces the background, research problem, aims, objectives, and expected outcomes of the study. A flowchart (Figure 1.4) illustrates how the research was conducted.

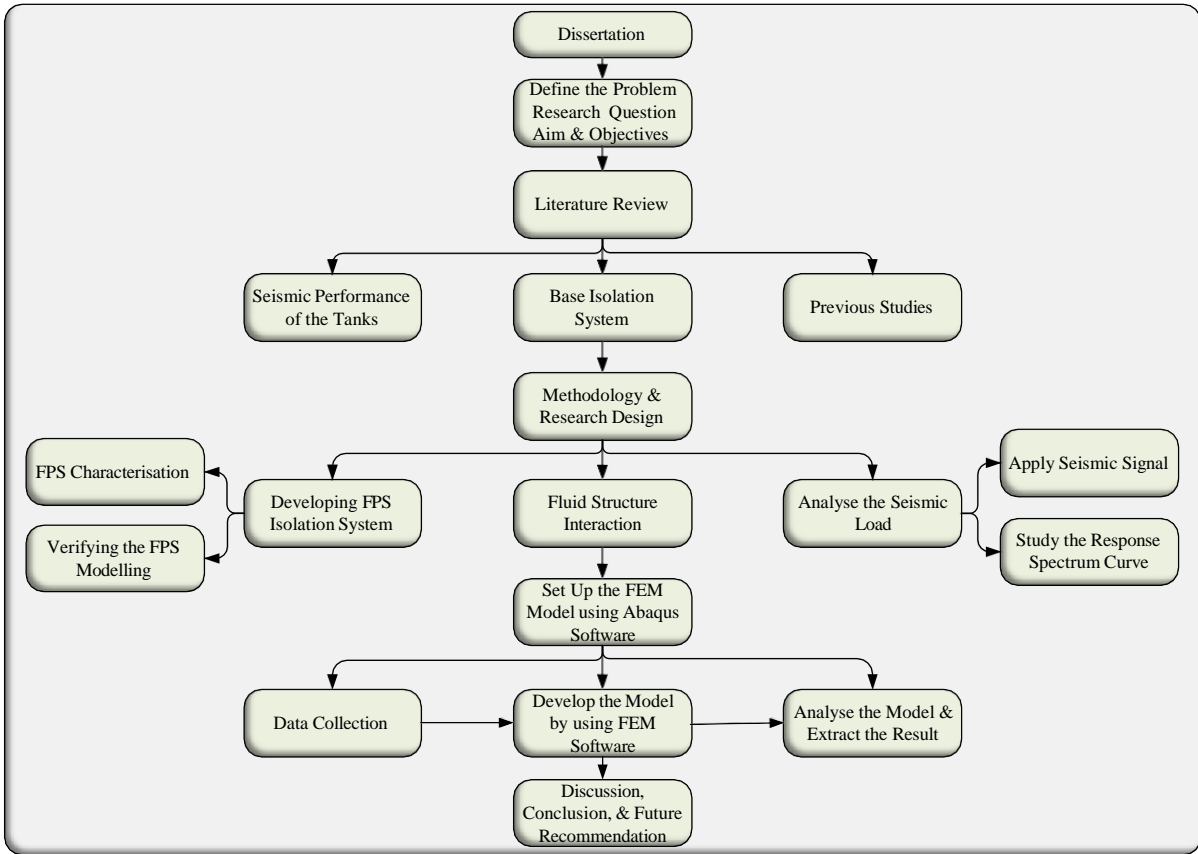


Figure 1.4: Flowchart diagram illustrating the research process of the thesis

CHAPTER TWO

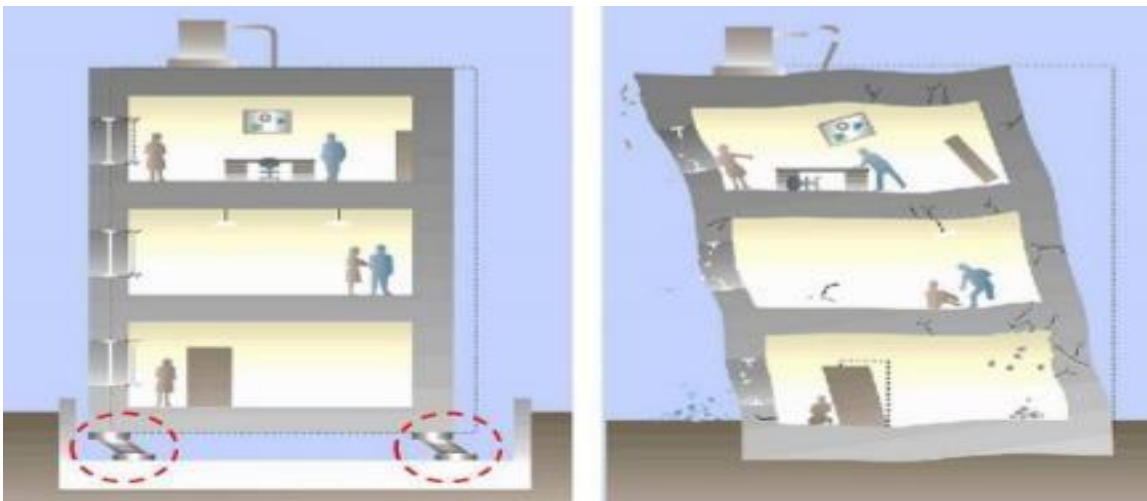
LITERATURE REVIEW

2.1 Application of base isolation

2.1.1 Introduction

Traditionally, the design of earthquake-resistant structures focused on making them sufficiently stiff and rigorous to withstand seismic forces. However, this approach can be costly, as it requires the structure to absorb all lateral loads. Base isolation, by contrast, offers a more efficient and cost-effective solution by reducing the transmission of seismic energy to the structure (Manarbek, 2013).

Base isolation is a fundamental principle in earthquake engineering that involves decoupling a structure from its foundation. In essence, this technique minimises or prevents structural damage during seismic events by allowing controlled movement between the ground and the superstructure (Halkude et al., 2018). The base isolation technique is designed to reduce the influence of earthquake responses on the structure, whereby the base and foundation are separated. Base isolation has recently gained popularity as a prominent tool for earthquake-resistant structures. The concept of base isolation has evolved over more than a century and has recently gained widespread recognition as a reliable strategy for enhancing seismic resilience (Jain et al., 2017). This technique has been successfully implemented in numerous structures, safeguarding them against the devastating effects of earthquakes.



**Figure 2.1: Seismic isolated structure vs. conventional earthquake-resistant structure
(Adapted from Nakamura & Okada (2019))**

The inherent rigidity and flexibility of base isolation significantly influence the seismic response of structures. Earthquake-induced acceleration and displacements vary across a spectrum of periods from zero to infinity. By employing base isolation, the transfer of motion from the ground to the building is reduced, resulting in controlled displacements. This approach effectively mitigates the impact of amplified acceleration, enhancing the structure's resilience and safeguarding against potential damage during seismic events. Acknowledging the dynamic behaviour of structures and adopting base isolation techniques enables a more reliable and robust seismic design, leading to safer and more resilient buildings that can withstand the varying forces of earthquakes across different periods. Seismic isolation involves placing specialised devices between the foundation and superstructure (Figure 2.1). These devices exhibit low lateral stiffness, increasing the structure's period of vibration, high vertical stiffness, and substantial damping to dissipate seismic energy.

Isolation systems are typically divided into two main types: elastomeric bearing (EMB) systems and sliding mechanisms. EMB units are valued for the flexible nature of elastomeric materials, which allow them to absorb deformations under operational loads while retaining long-term durability. Common examples of EMB devices include natural rubber bearings, lead-rubber bearings, and high-damping natural rubber bearings Figure 2.2.

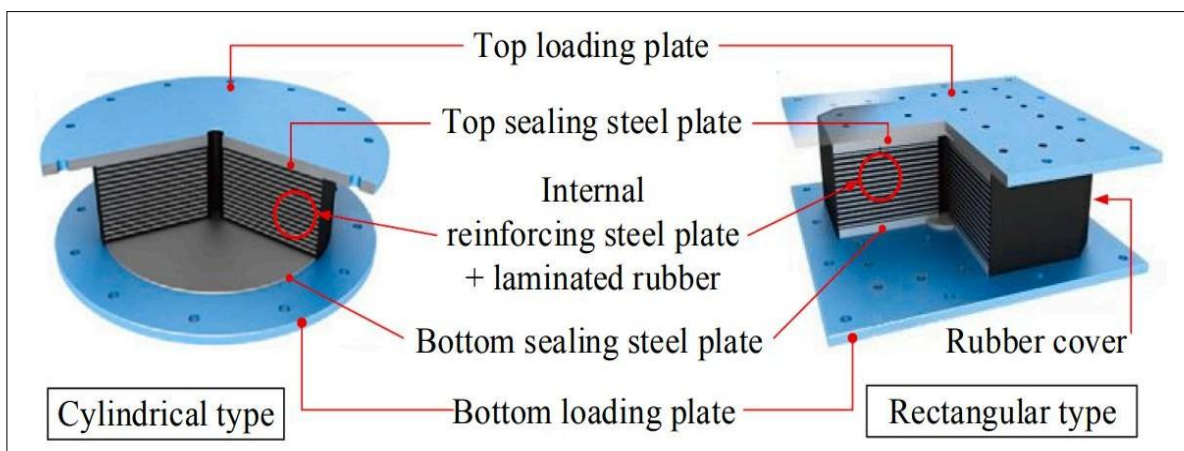


Figure 2.2: Cross section of laminated rubber bearing (LRB), rectangular and cylindrical shapes (Adapted from Nguyen & Guizani (2021))

Sliding isolation devices are highly regarded for their effectiveness in seismic isolation, especially in severe earthquake scenarios. They excel in reducing superstructure acceleration and are insensitive to earthquake frequency, making them versatile for mitigating seismic effects. They are also used widely in buildings and bridges. Moreover, these systems offer advantages over traditional rubber bearings by providing effective isolation across a broad frequency spectrum. The frictional force at the base, proportional to the structure's mass, aligns with its center of mass and resistance, minimising torsional effects in asymmetric buildings Figure 2.3 (Kunde & Jangid, 2003).



Figure 2.3: Cross section of friction pendulum system (FPS), open and installed (Adapted from Robertson (2010))

2.2 Previous research

Liquid storage tanks are critical components of infrastructure, particularly in industrial and nuclear facilities. Unlike typical structures, their weight fluctuates due to varying liquid levels, and they may contain substances such as liquefied natural gas (LNG) or corrosive chemicals. Catastrophic failures during seismic events (e.g., the Northridge earthquake in 1994 and others) have highlighted vulnerabilities, including tank wall buckling, piping system failures, and anchorage uplift. These failures can disrupt infrastructure, cause fires, or lead to environmental contamination. Hence, safeguarding fluid storage tanks against seismic events is imperative (Panchal & Soni, 2014).

Seleemah & El-Sharkawy (2011) examined the dynamic behaviour of cylindrical ground-supported liquid storage tanks fitted with base isolation, considering both broad and slender geometries. Their research explored three distinct isolation systems, alongside the response of conventional, non-isolated tanks. Through systematic analytical methods, the study assessed critical tank responses influenced by factors such as the aspect ratio, isolation period, and the friction coefficient associated with the FPS system. The findings demonstrated that base isolation significantly mitigates seismic-induced tank responses. Most significantly, percentage reductions between 50 – 90% of base shear and responses to impulsive displacements were observed. Convective displacement, however, registers 20 – 70% higher than fixed base tanks, underlining the necessity of increased height above the liquid surface. Furthermore, the study underscored the heightened effectiveness of base isolation for slender tanks compared to their broader counterparts. Therefore, this research significantly advances seismic design strategies for cylindrical liquid storage ground tanks, enhancing their overall resilience and reinforcing the importance of tailored approaches to different tank configurations.

Vimal et al. (2020) conducted a study that focused on the assessment of the seismic behaviour of elevated water tanks under varying conditions and highlighted the importance of seismic response. The importance of elevated water tanks in seismic design became particularly apparent when assessing their behaviour in both empty and full states. Four distinct elevated tank configurations, each with varying parameters, were analysed under seismic conditions using base isolation methods. Although empty tanks may seem less critical from a structural design perspective, the study highlighted their heightened vulnerability to seismic forces. In contrast, filled tanks can be effectively protected through the application of base isolation. The study identified a clear relationship between the storage volume of elevated water tanks and the resulting base shear and base moment during seismic activity. Tanks without contents are particularly vulnerable due to their shorter natural vibration periods, unless base isolation is employed. Notably, the rate at which maximum base shear is reduced in empty tanks is twice that observed in half-filled tanks. These findings underscore the crucial role of base isolation in enhancing the seismic safety of empty elevated tanks. By diminishing the impact of earthquake forces, base isolation proves to be a highly efficient approach for improving structural resilience.

Nimbekar et al. (2021) conducted a study that evaluated the seismic performance of staging systems for elevated water tanks using lead rubber bearing isolation. The study emphasised the urgency of safeguarding well-designed concrete structures against severe damage as a result of the vulnerability induced by the recent earthquakes. Utilising SAP2000 software, seismic forces on elevated water tanks in Zone IV are analysed according to the "Code of India [IS1893(Part1)2002]". The results from the equivalent static analysis demonstrated a significant reduction in base shear for isolated tanks compared to non-isolated tanks in both X and Y directions.

Another researcher, Bagheri & Farajian (2018), performed a study on the seismic behaviour of steel liquid storage tanks, explicitly focusing on tanks base-isolated by friction pendulum system (FPS) bearings. The study focused on two parameters: the effect of peak ground acceleration (PGA) and the Pulse-Like Nature of the earthquake motion, to evaluate how effectively FPS reduces seismic responses. The study also employed various ground motions with distinct characteristics to assess the responses of cylindrical liquid storage tanks. The study revealed that under far-field ground motions, isolation significantly reduces responses compared to near-fault ground motions, particularly evident in tanks of varying aspect ratios. These factors have a minimal influence on sloshing displacement. However, impulsive displacement, overturning moment, and structural base shear tend to diminish with extended isolation periods or lower friction coefficients. The study highlighted that isolation periods of about 3 seconds diminished peak responses. Findings showed that analysing the aspect ratios of a range of tanks corroborates the primary outcomes obtained from both broad and slender tank configurations. Ultimately, this investigation offers valuable insights into optimising seismic design strategies for steel

liquid storage tanks using FPS base isolation to enhance their seismic resilience and advance engineering practices in the field.

Kim & Lee (1995) evaluated the seismic performance of various base-isolated liquid storage tank configurations by analysing the influence of isolator stiffness and tank geometry. Their research adopted a thorough experimental methodology, incorporating pseudo-dynamic testing on cylindrical tanks fitted with base isolators and subjected to simulated seismic loads. This approach, combined with a substructuring technique, enabled a detailed assessment of the tanks' seismic response. The finding demonstrated a notable reduction in base shear force due to the presence of base isolation, particularly when the system's dominant frequency matched the effective frequency range of the isolation mechanism.

Shrimali & Jangid (2003) performed a study utilising linear EMB and tested for absolute earthquake motion to evaluate the earthquake responses of isolated high-liquid storage steel tanks. The study focused on two distinct tank isolation arrangements. One is located at the lower end of the tower, and the other at the upper end, which is made of steel. The steel tower's mass was equally distributed between its top and bottom. The research yielded valuable insights into the response of the two tanks, i.e., slender and broad tanks. By obtaining their responses, however, the study conducted a parametric analysis to gauge the impact of critical system parameters on the effectiveness of seismic isolation. In addition, comparative evaluations were made between the earthquake responses of isolated tanks and their non-isolated counterparts. The findings unveiled a reduction in base shear, primarily influenced by impulsive forces and rigid mass dynamics. The study also underscored the substantial reduction in steel tower drift when subjected to seismic loads.

Panchal & Jangid (2008) discussed an extensive analysis of the seismic behaviour of the liquid storage tanks utilising the variable frictional pendulum system (VFPS) as isolation. The study focused on subjecting these isolated tanks to six distinct near-fault ground motions. A close examination of changes in base shear, sloshing displacement, impulsive displacement, and isolator displacement was conducted on the dynamic behaviour of the isolated tanks. A pivotal aspect of this inquiry was a comparative analysis between tanks isolated with VFPS and traditional FPS.

A group of researchers (Soni et al., 2011) provided an insightful exploration into the behaviour of liquid storage tanks, both slender and broad, when isolated by the innovative double variable frequency pendulum isolator (DVFPI). This isolator introduces a dynamic dimension with unequal geometry and friction coefficients on its upper and lower sliding surfaces. The research encompasses four distinct design cases of DVFPI, each characterised by variations in isolator geometry and friction coefficients. The criterion in performance optimisation is a minimisation criterion of the number of responses and

energy quantities. Fundamental parameters such as initial period, friction coefficients, frequency variation factors at the sliding surfaces, and the aspect ratio of the tank have been intensively considered. The outcomes emphasised that optimising DVFP performance involves specific design strategies. For instance, a slender tank benefits from a high initial stiffness on the upper sliding surface relative to the lower one, along with equal friction coefficients. In contrast, a broad tank should have equal initial stiffness and friction coefficients on both sliding surfaces.

The seismic performance of liquid storage tanks was analysed using a sliding isolation system that incorporated two horizontal directions to accurately replicate earthquake motion (Shrimali & Jangid, 2002). A central aspect of the study involved modelling the continuous liquid as three distinct lumped masses, i.e., convective, impulsive, and rigid, each assigned specific stiffness values based on the properties of the tank wall and the liquid. The parametric investigation aimed to explore how key system variables influence overall effectiveness. A marked reduction in base shear and impulsive displacement further demonstrated the efficiency of the sliding isolation system. Additionally, the study found that the protective capability of isolation systems increases proportionally with the flexibility of the sliding mechanism, offering valuable insights into advanced seismic design strategies.

Malhotra (1997) investigated the extraordinary effects of the isolation technique on the liquid contents' inherent and force (sloshing) motions. This technique entails providing the wall of the tank with a layer of horizontally flexible bearings so that it is independent of the base plate. In contrast, the base plate remains grounded, or rather, the base plate is used and stays connected to the ground. There are two different steel tanks: one comparatively wide and the other comparatively narrow, where the isolation is explored in all its implications. The studies reveal a significant decrease in hydrodynamic base shears, overturning moments, and axial compressive stresses acting on the tank walls without affecting the vertical motion of the liquid.

Rawat et al. (2015) carried out a comprehensive investigation that explored the dynamics of ground-supported, flexible base-isolated cylindrical tanks under unidirectional earthquake ground motions using 3-D finite element (FE) analysis. The study introduced a novel approach that systematically evaluates the impulsive and convective (sloshing) components affecting the tank seismic response. Two distinct base isolation systems—elastomeric bearing (EMB) and sliding systems—were analysed in detail. The results indicated that the impulsive component of base shear experienced a significantly greater reduction compared to the convective component. Interestingly, the study found that neither isolation system had a substantial effect on sloshing displacement, suggesting that both techniques are effective in maintaining stable liquid dynamics within the tank during seismic events.

Bagheri & Farajian (2016) applied a comprehensive model to analyse the behaviour of an isolated tank-liquid system consisting of three distinct lumped masses (convective mass, impulsive mass, and base mass). The seismic performance of a cylindrical liquid storage tank equipped with an FPS under near-fault ground motion was studied. The fluid–structure interaction was effectively represented by modelling the liquid masses and connecting them to the tank wall through an arrangement of springs and dampers. Specific insights were derived from the analysis presented in the study. It was found that the application of a FPS leads to a substantial reduction in several response parameters of base-isolated tanks when compared to equivalent fixed-base configurations.

Jadhav & Jangid (2004) initiated an investigation into the seismic response of isolated liquid storage tanks, with the primary aim of assessing and comparing the efficacy of various isolation systems. During the investigation, a detailed parametric analysis was conducted on the impact of crucial system parameters on the performance of the seismic isolation for these tanks. Some aspects considered include the aspect ratio of the tank and the period of the isolation systems used. All three employed base isolation systems can substantially curtail the earthquake-induced forces acting on the liquid storage tanks. Among these systems, the N-Z (Neoprene-Zinc) isolation system proves to be the most efficient and superior to the lead rubber bearing (LRB) and FPS bearing. Furthermore, the study supports the efficacy of the formulated approximate analysis method in predicting the response of base-isolated liquid storage tanks subject to seismic forces.

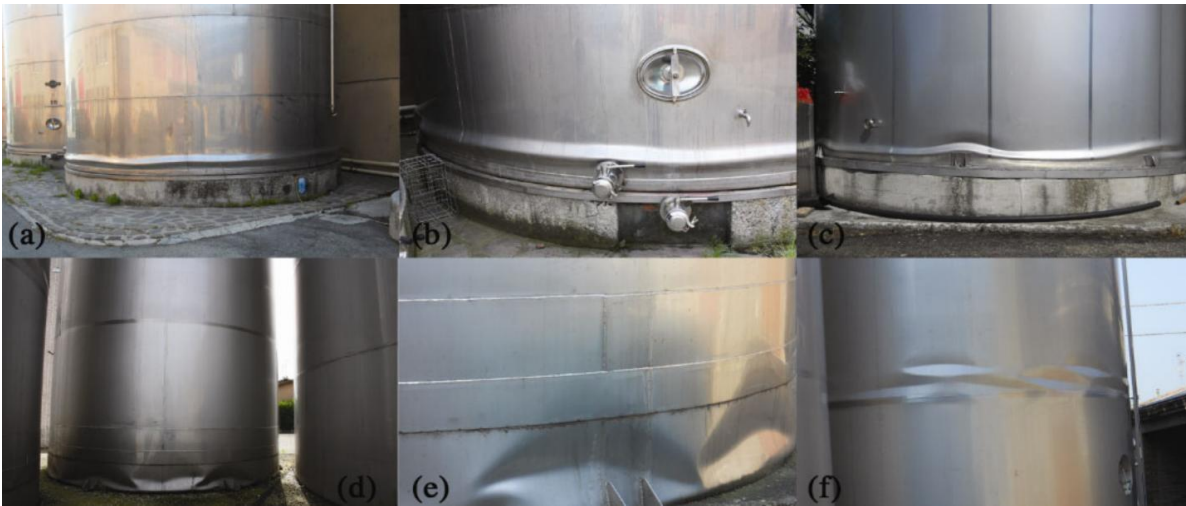
Wang et al. (2001) researched the application of seismic base isolation to improve the capability of liquid-filled storage tanks to resist earthquakes. The study focused more on the sliding type FPS or FPS bearings than EMB. These are chosen due to their unique characteristic of maintaining unchanged dynamic properties for FPS-isolated tanks, regardless of the storage level. The research explored the potential of FPS isolation as a robust strategy to fortify liquid storage tanks against seismic forces. Additionally, the hydrodynamic pressure increases with H/R during an earthquake, and seismic isolation can effectively reduce the impulsive dynamic pressure while barely affecting the convective dynamic pressure.

Halkude et al. (2018) investigated three distinct base isolation methods for elevated water tanks, such as EMB, LRB, and FPS. The study, which encompasses tanks of varying capacities in whole, partial, and empty conditions, focused on the seismic behaviour of the tanks with and without base isolation. The LRB system was the most effective in controlling seismic response. EMB and FPS also substantially improved performance over non-isolated tanks. The study underscored the benefits of employing base isolation to curtail the transmission of seismic effects to the superstructures of elevated water tanks.

Ren et al. (2023) studied the behaviour and response of an elevated water tank under seismic excitation. The study used FE software to analyse multi-scale responses by applying model analysis, response spectrum, and time history analysis. It also modelled the liquid contents using techniques like adding two mass approaches and a simplified spring mass mechanical model. The effect of the fluid-structure interaction (FSI) was investigated, along with the influence of tank geometry (height and thickness), aspect ratio, liquid fill level, and soil condition on natural frequencies and seismic response parameters. Furthermore, the performance of FPB as a base isolation to mitigate seismic forces was quantified as a result of the ground motions. The outcomes showed that the addition of FPS to the tank base increases convective and significantly decreases impulse displacement and base shear. Therefore, the effect of soil-structure interaction (SSI) can be clarified by comparing underground and above-ground tanks and soil types.

Tsipianitis & Tsompanakis (2022) investigated the beneficial impact of an isolated water tank via a single friction pendulum bearing (FPB), wherein a supplemental linear damper was added to reduce seismic vulnerability. Four different percentages of damper have been applied for a squat and slender tank concerning isolator displacement (5%, 10%, 20%, and 30%) for near-fault ground motions. The joystick model was used to simulate liquid storage tank response, and the fragility outcomes produced raise the damping performance and lower displacement at high PGA levels.

These literature studies established the effectiveness of base isolation for water tanks, including the enhancement of the seismic performance of tanks. The researchers demonstrated that the isolated tank reduced the shear force and acceleration response, while also improving tank integrity compared to a non-isolated tank. The understanding of these studies indicated that the base isolation of water tanks improved resilience, decreased water losses, and ensured safe water supplies. This resulted in a decrease in hydrodynamic forces acting on the tank wall, thereby reducing the likelihood of damage such as outward buckling of the lower shell courses. This is often referred to as 'elephant's foot' buckling (Figure 2.4).



**Figure 2.4: (a-c) Elephant's foot buckling, (d-f) Diamond shape buckling
(Adapted from Brunesi and Nascimbene (2024))**

Krishnamoorthy and Anita (2016) investigated the impact of SSI on the seismic response of a structure isolated with FPS. The researcher assumed a rigid foundation, neglecting the influence of supporting soil flexibility. A computational model was formulated employing the FE method to conduct the seismic analysis. The FEM model was employed to analyse a structural response under three different soil conditions, examining their influence on seismic performance. The isolation system (FPS) is represented using a fictitious spring model that incorporates two distinct phases: sliding and non-sliding. This modelling technique enabled a more precise depiction of the dynamic behaviour of isolated systems under varying seismic ground motions and soil conditions.

A brief review of research studies conducted on base isolation for tanks is discussed below (Table 2.1):

Table 2.1: Summary of literature review

S/N	Author	Title	Task Type	Isolation system	Summary of finding
1	Seleemah & El-Sharkawy (2011)	Seismic response of base-isolated liquid storage ground tanks.	Broad and cylindrical ground tank	FPS	The authors examined how the tank's aspect ratio, isolation period, and the FPS influence critical response parameters. Their findings revealed a substantial reduction—ranging from 50% to 90%—in base shear and impulsive displacement for base-isolated tanks. In contrast, convective displacement was found to be between 20% and 70% higher than that observed in fixed-base tanks.
2	Vimal et al. (2020)	Experimental investigation on elevated water tanks with base isolation-response spectrum approach.	Elevated tank	—	The researchers examined the seismic behaviour of both filled and empty elevated water tanks. Four configurations were considered: base-isolated, fixed-base, and other isolation systems. The findings indicated that base isolation significantly reduced base shear, however, roof displacement was greater compared to the fixed-base configuration. Furthermore, the maximum base shear observed in the empty tank was approximately twice that recorded for the filled tank.
3	Nimbekar et al. (2021)	Seismic response control of elevated water tank using base isolation: A review.	Elevated tank	LRB	The researchers have utilised SAP2000 software to analyse the seismic performance of elevated water tanks. The results show a reduction of base shear for isolated tanks compared to non-isolated tanks.
4	Bagheri & Farajian (2018)	The effects of input earthquake characteristics on the nonlinear dynamic behaviour of FPS-isolated liquid storage tanks.	Cylindrical	FPS	This research concentrated on the seismic behaviour of steel liquid storage tanks supported by bases isolated through a FPS. The results indicated that base isolation significantly reduces structural responses under far-field ground motions when compared to near-fault seismic events.
5	Kim & Lee (1995)	Pseudo dynamic test for the evaluation of the seismic performance of base-isolated liquid storage tanks.	Cylindrical	LRB	Using the pseudo-dynamic testing method, the study investigated the seismic response of a tank isolated with a LRB system. The results indicated a significant reduction in base shear forces, particularly when the dominant frequency of the structure coincided with the effective operational range of the isolation system.
6	Shrimali & Jangid (2003)	Earthquake response of isolated elevated liquid storage steel tanks.	Elevated tank	—	This research investigated the seismic response of an elevated water tank incorporating linear elastomeric base isolation. A parametric analysis was performed to compare the performance of isolated and fixed-base configurations. The findings revealed that the isolated system experienced a significant reduction in base shear compared to the fixed-base counterpart.

Table 2.1 continues.

7	Panchal & Jangid (2008)	Variable friction pendulum system for seismic isolation of liquid storage tanks.	Cylindrical	VFPS	The authors investigated the seismic response of steel liquid tanks and applied a VFPS. The study focused on subjecting these isolated tanks to six distinct near-fault ground motions. It is observed that the response of a tank isolated with VFPS pulses matches well only if the period of isolation reaches the highest value.
8	Soni et al. (2011)	Double variable frequency pendulum isolator for seismic isolation of liquid storage tanks.	Broad and cylindrical ground tank	DVFPS	The study examined four distinct design configurations of the DVFPI, each defined by differences in isolator geometry and friction coefficients. The primary aim was to enhance performance by applying a criterion focused on minimising structural responses and energy demands. The results underscored that achieving optimal DVFPI performance requires targeted design strategies.
9	Shrimali & Jangid (2002)	Seismic response of liquid storage tanks isolated by sliding bearings.	Slender and broad Tank	Sliding system	The study placed emphasis on a detailed representation of the continuous liquid by dividing it into three lumped masses: convective, impulsive, and rigid. It was concluded that the effectiveness of isolation systems in safeguarding tanks is directly linked to the increased flexibility offered by sliding isolation mechanisms.
10	Malhotra (1997)	New method for seismic isolation of liquid-storage tanks.	Cylindrical	—	The researcher investigated the seismic isolation of a ground-supported tank by detaching the wall from the base plate and connecting it to a flexible membrane. The study concluded that this configuration resulted in a significant reduction in both hydrodynamic base shear and overturning moment.
11	Rawat et al. (2015).	Seismic analysis of base-isolated cylindrical liquid storage tank using coupled acoustic-structural interaction.	Cylindrical	Elastomeric bearing and sliding system	This study focused on the discrete evaluation of the impulsive and convective (sloshing) components affecting the tank. The results also reveal a higher impulsive component of base shear compared to the convective accumulation.
12	Bagheri & Farajian (2016)	Seismic response of base isolated liquid storage tanks under near fault ground motions.	Cylindrical	FPS	This research investigated the base-isolated cylindrical tank by FPS under near-fault ground motion. Findings revealed that the friction pendulum system yields substantial reductions in several response characteristics of the base-isolated tank compared to the equivalent fixed-base tank.

Table 2.1 continues.

13	Jadhav & Jangid, (2004)	Response of base-isolated liquid storage tanks.	Broad tank	LRB, N-Z, FPS	The study investigated the seismic response of liquid storage tanks isolated using three different systems: LRB, N-Z, and FPS. These systems were tested under absolute earthquake ground motion. Findings revealed that the effectiveness of the tanks was reduced. However, the N-Z system demonstrated better performance compared to LRB and FPS systems.
14	Wang et al. (2001)	Seismic isolation of rigid cylindrical tanks using friction pendulum bearings.	Rigid cylindrical	FPS	This study investigated the seismic performance of liquid storage tanks using sliding-type FPS rather than elastomeric bearing systems. The FPS isolators maintained consistent dynamic characteristics across varying storage levels. The research focused on evaluating the effectiveness of FPS-based isolation in enhancing the earthquake resilience of liquid storage tanks.
15	Halkude et al. (2018)	Parametric study of base isolation system for elevated water tank.	Elevated	EMB, LRB, FPS	The researchers studied the effects of isolation systems on the elevated tanks with three different loadings. According to the findings, the researchers found that the LRB is most efficient in controlling the seismic response.
16	Ren et al. (2023)	Seismic response of elevated steel tanks equipped with the seesaw system.	Elevated tank	FPS	The primary focus of this study was the behaviour and response of raised water tanks under seismic force. The paper analysed the response spectrum and time history using the FE method. It also studied soil interaction and investigated sloshing by isolating the water tank base with FPS, i.e., it provided a numerical approach for analysing and understanding elevated water tanks' seismic and FSI.
17	Tsipianitis & Tsompanakis (2022)	Improving the seismic performance of base-isolated liquid storage tanks with supplemental linear viscous dampers.	—	FPS	These two researchers investigated an isolated water tank that uses a single friction pendulum by adding a viscous damper. They applied various damping levels and findings revealed that the damping levels (5 and 10 %) were most effective in reducing acceleration submitted to the tank, while another level (20 and 30%) showed increased acceleration for the superstructure.
18	Krishnamoorthy & Anita (2016)	Soil–structure interaction analysis of a FPS-isolated structure using finite element model.	—	FPS	This paper investigated the SSI effects on a structure isolated with an FPS under 3 different soil conditions. Findings indicated that soft soil exhibits higher displacement and base shear compared to other soils. The effects of SSI are more significant in structure, with a longer isolation period. Additionally, a higher coefficient of FPS reduces sliding displacement but might increase base shear.

2.3 Technique of fluid structure interaction in storage water tanks

2.3.1 Arbitrary Lagrangian Eulerian (ALE) method

ALE adaptive mesh is a hyper-analysis technique available in Abaqus. It enables a high-quality meshing throughout the analysis process and is more flexible when large deformation and fluid flow problems occur by making the mesh move independently of the material. ALE has features to handle complex problems, such as sloshing in water tanks and interaction between fluid and structure, thus improving the accuracy of meshing results (SYSTEMS, 2024).

2.3.2 Acoustic method

The acoustic method is one of the techniques used in Abaqus FEA to simulate the propagation of low-amplitude pressure waves through fluid media such as water and air. In FSI scenarios, acoustic elements are employed to model wave transmission and its interaction with structural boundaries. However, acoustic elements are not suitable for capturing large fluid deformations, such as sloshing or significant water motion, due to their inherent limitation in representing only low-amplitude wave phenomena (SYSTEMS, 2024).

2.3.3 Coupled Eulerian-Lagrangian (CEL) method

The CEL method is a technique used in analysing complex interactions between fluid and structural boundaries. CEL allows contact between Lagrangian and Eulerian bodies in the same model, enabling the fluid domain to interact with the solid domain. This allows the Lagrangian mesh to interact with Eulerian material, making the sloshing effect visible. CEL used in Abaqus has a formula called volume of fluid (VOF) to capture the interface between fluid and structure.

2.4 Seismic load in water storage tanks

Estekanchi and Alembagheri (2012) introduced a novel time history-based method known as the endurance time (ET) for evaluating the seismic response of steel liquid storage tanks. The ET method applies intensifying dynamic excitation as the loading function, allowing structural responses to be monitored progressively as the intensity increases.

2.4.1 Elevated water tanks

The spring-mass analogy will be employed to determine the hydrodynamic forces caused by an earthquake on a tank with flexible walls. The mass of the elevated water tank can be identified in two mass modes, which are convective and impulsive Figure 2.5. The flexibility of the tower, including the tank shell, might be neglected (NZSEE, 2009). The hydrodynamic pressures can be analysed considering the tank as rigid, including tower mass and impulsive mass Figure 2.6.

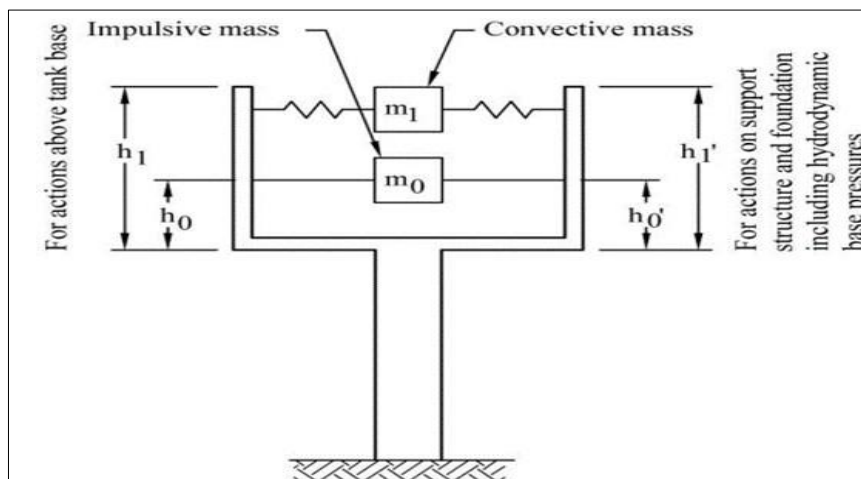
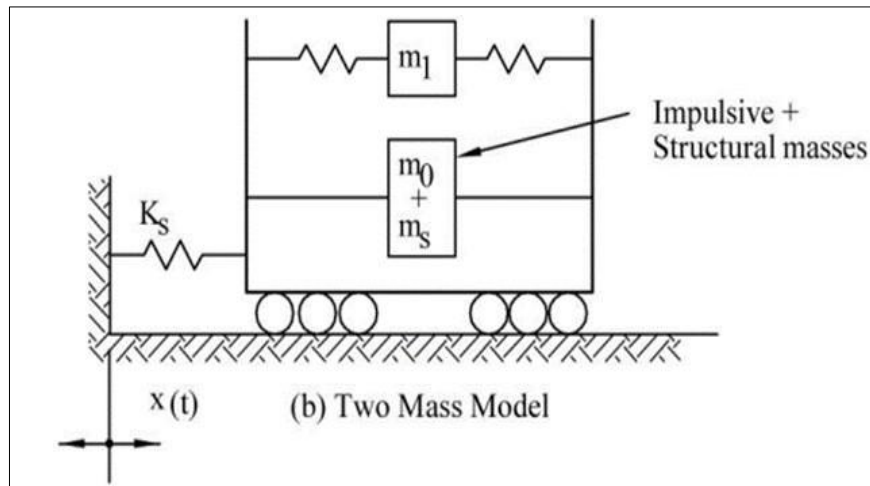


Figure 2.5: Masses of an elevated tank
(Adapted from NZSEE (2009))



**Figure 2.6: Cross section two mass model
(Adapted from NZSEE (2009))**

Standard structural dynamics and response spectrum techniques are employed to estimate the seismic response of elevated water tanks. For the convective (sloshing) component of the liquid mass, a damping ratio of 0.5% is typically recommended to account for energy dissipation during seismic excitation. The analysis adopts a two-mass model: the impulsive mass, which includes the tank and supporting tower and behaves like a pendulum with associated stiffness, and the convective mass, which is assumed to be rigidly connected to the ground. Based on the identified parameters, one can easily determine the convective mass springs' stiffness and identify the impulsive mass attached to the ground accordingly (NZSEE, 2009).

2.4.2 Response spectrum curve

To obtain response spectrum curves, there are two parameters involved, which are site location and ground type Figure 2.7.

2.5 Base shear and overturning moment

To evaluate base shear, it is necessary to determine the maximum shear stresses within the tank shell by applying the total seismic load at the base. This method can also be used to calculate the peak axial stresses in the shell. For a precise evaluation of the total overturning moment acting on the tank's foundation or supporting structure, the base moment generated by hydrodynamic impulsive and convective pressures must be included. The total overturning moment is the sum of the moments and pressures acting on both tank walls and base. (NZSEE, 2009).

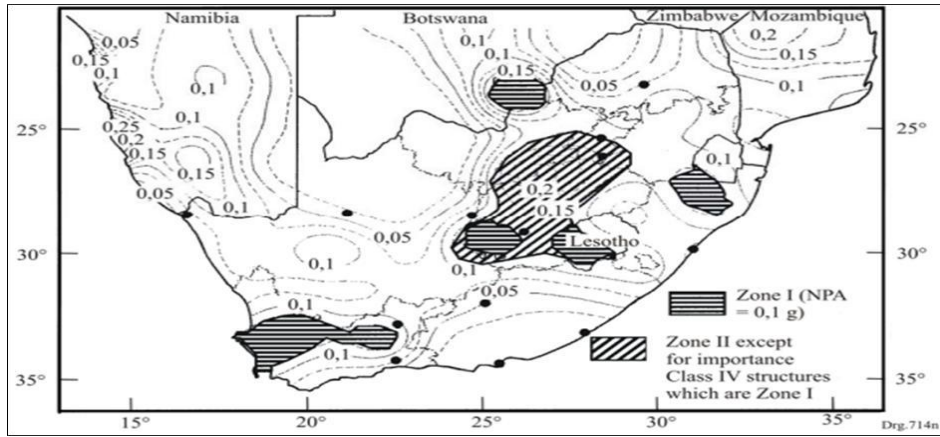


Figure 2.7: Seismic zones of South Africa
 (Adapted from 10160-4:2017 (2017))

Table 2.2: Parameters of response spectra

Subsoil class	S	TB	TC	TD
1	1.00	0.15	0.4	2.0
2	1.20	0.15	0.5	2.0
3	1.15	0.20	0.6	2.0
4	1.35	0.20	0.8	2.0

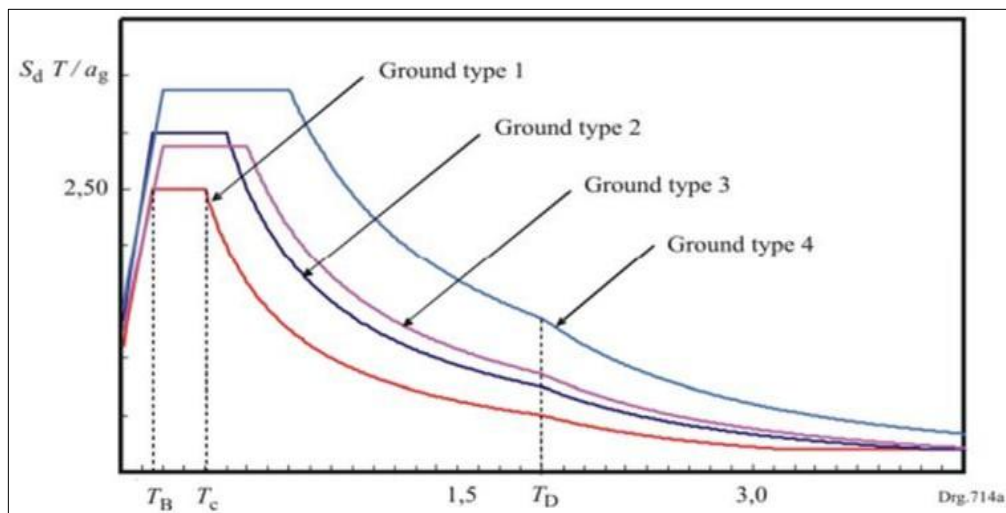


Figure 2.8: Spectrum curve
 (Adapted from 10160-4:2017 (2017))

2.6 Chapter Summary

The studies demonstrated that base isolation significantly enhances the seismic performance of water storage tanks. The findings reveal that isolated tanks experience reduced shear forces and acceleration

responses, while also maintaining greater structural integrity compared to non-isolated tanks. The research concludes that implementing base isolation improves the overall resilience of water tanks, minimises water losses, and contributes to the reliability of safe water supply systems during and after seismic events.

CHAPTER THREE

DEVELOPING A FINITE ELEMENT MODEL OF FPS, AND FSI STRATEGY

3.1 Introduction

In recent years, alongside multilayer elastomeric bearings (EMB), a new class of isolators known as the frictional pendulum system (FPS) has emerged Figure 3.1. This system has gained widespread use in base isolation applications for water storage structures due to its affordability, remarkable fundamental period, and robust characteristics as presented in Table 3.1 (Petti et al., 2013). FPS bearings utilise a spherical sliding surface to create a pendulum mechanism, where the fundamental period is determined by the radius of curvature of the sliding surface. Unlike EMB, FPS dynamic response is influenced by friction behaviour, with the vertical component of ground motion playing a crucial role due to its effect on the normal force acting on the isolator.

Table 3.1: Characteristics of a frictional pendulum system (FPS)

Aspect	Description
High rigidity	FPS maintains stability even under wind loads and minor seismic forces.
Vertical load capacity	These bearings can handle substantial vertical loads.
Stability	FPS remains stable during ground motion events.

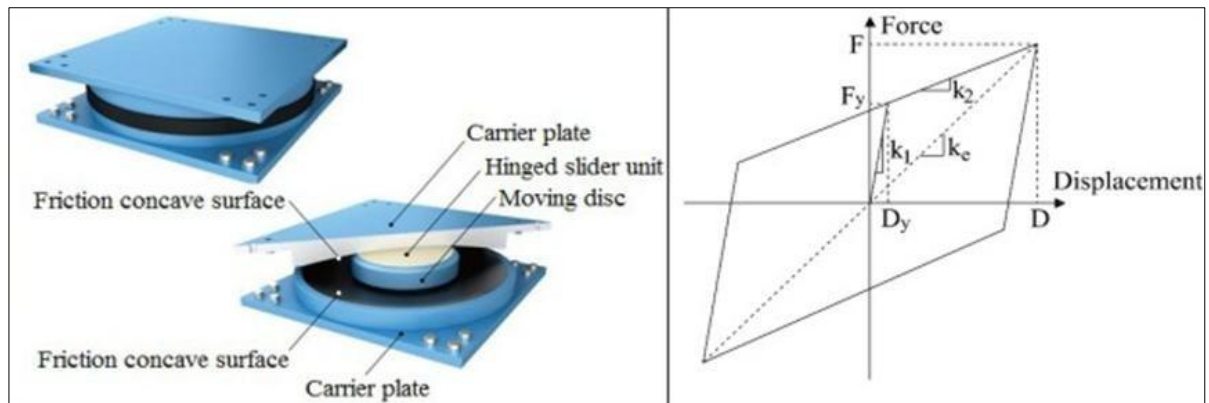


Figure 3.1: Cross-section of a frictional pendulum system and force displacement curve.
(Adapted from Meral (2021))

In the present context, the FPS features a slider that moves along a concave spherical surface during seismic activity, offering effective isolation for structures. The surface is coated with Teflon to ensure low friction (approximately 3%), which enables smooth sliding during an earthquake. Following seismic excitation, the slider naturally returns to its original position due to gravitational forces acting

on the curved base. This mechanism restores the structure to its position while minimising residual displacement as a system (Kerileng & Dundu, 2017).

3.2 Principle of FPS

The FPS bearing functions as a protective mechanism, more like a fuse, by activating when the shear force rises higher than the static friction. It comprises a sliding surface and an articulated slider coated with a high-pressure bearing material. When FPS supports a structure, it moves in pendulous movements when there is movement, following the sliding motion of the slider along the concave spherical surface. An important feature of the FPS is its uniform functionality regardless of the orientation of the concave surface (Lousidis, 2015).

3.2.1 Function of FPS

FPS demonstrates excellent re-centring capabilities through pendulum motions constituted by a swivel slider bearing. This device can move along this sliding surface whose radius (R) corresponds to the effective pendulum length. Typically, the structure's mass operates at the centre of the isolation system when a lateral force is directly applied to the weight (W), Figure 3.2.

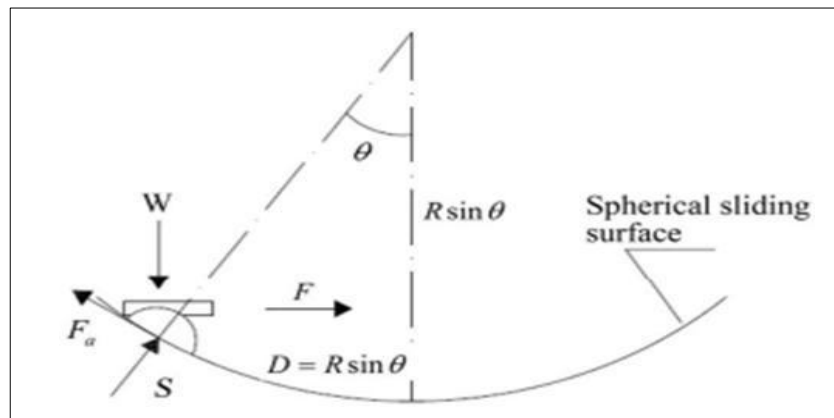


Figure 3.2: Frictional pendulum system force displacement
(Adapted from Lousidis (2015))

One of the attributes of FPS is the fundamental period of the bearing T_R , which can be found in the following equation 1:

$$T_R = 2\pi \sqrt{R/g} \quad (1)$$

Where:

T_R = Fundamental period of vibration

R = Radius of sliding surface

g = Acceleration of gravity

3.2.2 Methods to model a friction pendulum system (FPS)

Modelling FPS helps to comprehend the physical and dynamic behaviour of the system. Some of the methods described:

- Equivalent linear with viscous damping,
- Bilinear using spring elements, and
- Dynamic friction modelling combined with spring elements, Figure 3.3.

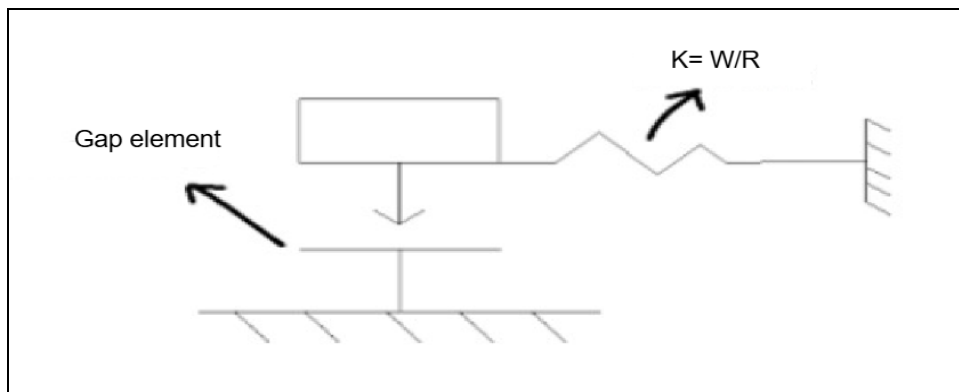


Figure 3.3: Dynamic friction and spring model

Force displacement, as seen in Figure 3.2, is stopped by a stopper that can be derived from the equation 2:

$$K = W/R \quad (2)$$

Where:

W = Weight of mass

R = Radius

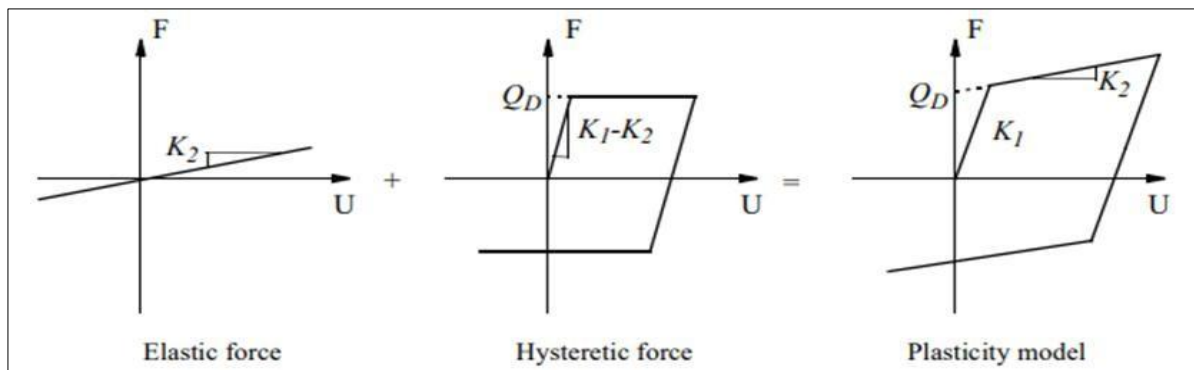
The gap is modelled as a spring with friction between the base and the foundation. The bottom of the spring is linked to the foundation, while the top is linked to the superstructure (Dargush, n.d.).

3.3 Bi-directional plasticity model

A simplified non-linear model represents rigid-plastic behaviour, capturing the characteristics of FPS. For numerical computation, the behaviour is often modelled using a rate-independent plasticity framework with a bi-directional restoring force given by equation 3.

$$F = K_2 U + F_P \quad (3)$$

The post-yield hardening stiffness and hysteretic force are key components in modelling the behaviour of the FPS. In the plasticity model, the total resisting force is contributed to the elastic and hysteretic components, as the model is shown schematically in Figure 3.4.



**Figure 3.4: Elastic and hysteretic resisting force component
(Adapted from Mosqueda et al. (2004))**

The model simulates the restoring force of a pendulum using orthogonal elastic springs characterised by stiffness W/R . The hysteretic force is modelled as elastic-perfectly plastic with initial stiffness and yield force Q_D .

Strength can be derived using the following approaches:

- Hysteretic force with significant elastic stiffness,
- Interaction force, and
- Allowing the modelling of the friction force.

The deformation based on the thickness of the slider is typically in the order of 0.01 (Scheller & Constantinou, 1999). An estimation for the plasticity model parameter K_1 can be obtained through the division of the yield force Q_D by the yield displacement U_Y is given by equation 4:

$$K_I = \frac{Q_D}{U_Y} = \frac{\mu W}{U_Y} \quad (4)$$

However, variations within a range of values as big as two orders of magnitude greater than that will not affect the resistance force Q_D .

3.4 Verification of the model benchmark of analysis

The modelling strategy adopted in this study aims to validate the proposed methodology by comparing it with the research conducted by Krishnamoorthy and Anita (2016), titled "Soil–structure interaction analysis of an FPS-isolated structure using finite element model". The validation of the methodology will substantiate the accuracy and reliability of the model by verifying and comparing the findings obtained from the benchmark study using Abaqus software. This approach considers the capability of Abaqus to generate specific material properties required for the analysis.

3.5 Isolator stiffness of FPS

The restoring force F_r of the FPS related to the sliding displacement is given by equation 5:

$$F_r = m\omega_r^2 x = k_r x \quad (5)$$

Where:

m = Mass

ω = The isolator frequency given by $\sqrt{g/R}$

R = The radius of curvature

g = The acceleration of gravity.

The isolator stiffness is equal to $m g/R$

3.6 Non-sliding situation

This condition is the opposite of the sliding phase, where the frictional force is lower than the resistance force F_s . To simulate the superstructure, foundation, and soil as one element, the stiffness value applied will be higher than the friction spring k_b (connection between superstructure and foundation). The motion equation can be found from equation 6:

$$M(\ddot{u}) + C(\dot{u}) + K(u) = F(t) \quad (6)$$

The isolator stiffness responsible for managing the restoring force depends on the FPS radius of curvature. It also plays a significant role in modelling sliding and non-sliding behaviour during seismic analysis.

3.7 Sliding situation

This condition occurs when the frictional force exceeds the frictional resistance F_s . The stiffness of the frictional spring is set to zero to allow sliding between the superstructure and the foundation, while the frictional force is used $F_x = F_s$. The dynamic behaviour of the structure given by equation 7:

$$M(\ddot{u}) + C(\dot{u}) + K(u) = F(t) + F_b \quad (7)$$

Where:

M = Mass

C = Damping

K = Stiffness

u = Acceleration and velocity

t = The load vector

Where F_b is derived from equations 8 and 9 by:

$$F_b = -k_r u_r - F_S \operatorname{sgn}(\dot{u}_r) \text{ Superstructure interaction} \quad (8)$$

$$F_b = k_r u_r + F_S \operatorname{sgn}(\dot{u}_r) \text{ Foundation interaction} \quad (9)$$

3.8 Fluid structure interaction

A simple definition of fluid structure interaction (FSI) states that FSI is the interplay of movable structure with an internal or external fluid (Thiriat, 2013). FSI is described as the interplay between a fluid flow and a deformable or rigid body that has been exposed to either internal or external flow (Andersson, 2011). FSI was also described as the cause of free surface fluctuation and hydrodynamic pressure loads that can trigger unforeseen variability or performance failure of the structures (Thiriat, 2013). Understanding the above definitions led to the development of different assumptions required to create a model that illustrates fluid behaviour, wherein analytical and numerical methods were purported for the investigation of the FSI.

The analytical method is proposed for FSI that involves storage tanks, while the numerical method is proposed for FSI problem involving any kind of geometry. The FSI numerical method involves a two-way linkage between finite-element code Abaqus and finite-volume code FlowVision (Aksenov, 2004; Thiriat, 2013; Pourbehi, 2019). Considering the above methods, fluid basic equations were formulated

from functions, such as Ω (fluid domain), \underline{u} (velocity field), ρ (density), and p (hydrodynamic pressure). These functions depend on space and time. The fluid flow observes the continuity equation and Euler's equation (Thiriat, 2013).

The continuity equation denotes the conservation of mass as given in equation 10:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \underline{u}) = 0 \quad (10)$$

And Euler's equation denotes the conservation of momentum as given in equation 11:

$$\rho \left(\frac{\partial \underline{u}}{\partial t} + \frac{1}{2} \underline{\text{grad}}(\underline{u}^2) + \underline{\text{rot}}(\underline{u}) \wedge \underline{u} \right) = \underline{f} + \underline{\text{div}}(\underline{\sigma}_c) \quad (11)$$

In the last equation 11, \underline{f} denotes body forces acting on the fluid (e.g. gravity force), and $\underline{\sigma}_c$ denotes stress

tensor (Thiriat, 2013). In this case, the flow of the fluid is considered incompressible, that is, fluid with a low flow velocity (Thiriat, 2013). Thus, density ρ is constant and homogeneous, and it is obtained from the continuity equation (Thiriat, 2013) see equation 12.

$$\text{div}(\underline{u}) = 0 \quad (12)$$

The property of incompressibility and irrotationality of the fluid flow produced the equation stated below, which represents the velocity potential as shown in equation 13.

$$\Delta \phi = 0 \quad (13)$$

The fluid and structure interaction modelling, as presented by Pourbehi (2019) and Zienkiewicz (2005), demonstrated that hydrodynamic pressure is generated more than hydrostatic pressure in the tank during the motions of a small amplitude. The Helmholtz equation governs the above statement as a result of the property of compressibility of the fluid flow (Thiriat, 2013; Pourbehi, 2019), see equation 14.

$$\phi = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 0 \quad (14)$$

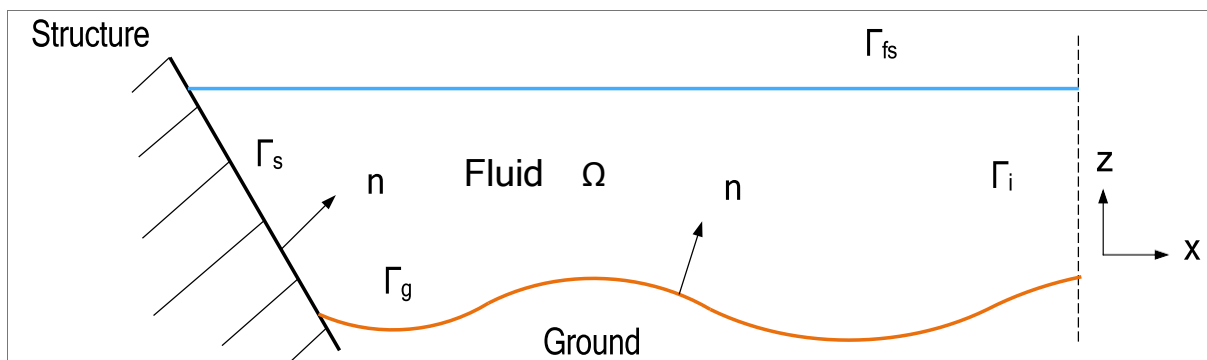
The above equation is recognised as the wave equation, which describes the propagation of pressure within the fluid and corresponds to the velocity of sound, c , in the fluid, and t as the time. This approach

is similar to the approach used for the fluid and structure interaction in a dam (Pourbehi, 2019). Considering the numerical simulation of the fluid and structure interaction in a tank, parameters such as temperature distribution, reaction kinetics, humidity impact, and 3D confining stresses were identified (Pourbehi, 2019). Based on the small displacement of fluid within the tank, the value of the pressure can be computed to determine solutions for the FSI problems by understanding and integrating the velocity potential functions to produce the equation stated below for the total pressure, that is, the sum of hydrodynamic pressure and hydrostatic pressure (Thiriati, 2013), as given by equation 15.

$$p = -\rho \frac{\partial \phi}{\partial t} \quad (15)$$

3.8.1 Boundary conditions

All the equations stated above explain the behaviour of the fluid within the tank as a process towards expressing the boundary conditions in understanding FSI problems. Thiriati (2013) presented a simple illustration of the FSI problem in a diagram Figure 3.5.



**Figure 3.5: Typical FSI problem
(Adapted from Thiriati (2013))**

The diagram depicts four boundary conditions and parameters that are applicable in the modelling of FSI pertaining to a seismic occurrence as a process for the evaluation of the response of the structure. These four boundary conditions are identified as:

Γ_s = interface between structure and fluid

Γ_{fs} = free surface

Γ_g = interface between ground and fluid

Γ_i = imaginary boundary to model an “infinite” domain of water.

The essential properties in the modelling of the FSI are also identified below:

- Fluid density, ρ ;
- Sound velocity in the fluid, c ;
- Ground density, ρ_g ;
- Sound velocity in the ground, c_g ;
- Velocity of the ground, v_g .

The existence of the four boundary conditions enables the understanding of solving the FSI problems, starting with the conception of the interface between structure and fluid, Γ_s wherein normal velocity will be equal as a result of considering a fluid and a solid particle (Thiriat, 2013). This is expressed in two cases, for instance, the first case is a rigid structure wherein the velocity of the structure's particles at the FSI, \underline{v} is equal to the ground velocity, \underline{v}_g . The second case considers a deformable structure, wherein the velocity \underline{v}_s due to structural deformation, it will be added to the ground velocity, \underline{v}_g . In this case, the velocity \underline{v}_s due to the structure deformation is unknown, and a coupled system is produced (Thiriat, 2013).

The free surface Γ_{sf} condition is another boundary condition wherein gravity waves are considered. According to Thiriat (2013), this specific condition influences the study of waves and surface fluctuation by determining the waves' height to prevent slosh. In the interface between fluid and ground Γ_g condition, observation specifies that, considering a rigid groundwater surface, the condition remains the same, unlike in the interface between structure and fluid. The last of the four boundary conditions is infinite boundary Γ_i condition which involves propagation modelling of waves from Γ_s towards the other side of a big tank to prevent wave reflection (Thiriat, 2013). Andersson (2011) also provided a clear understanding of the boundaries in FSI by stating that particle velocity is coupled to the rigid or flexible structure in solid-particle boundaries.

3.9 Seismic input

This section addresses challenges related to fluid-structure interaction (FSI), which require multiple dynamic analyses with various seismic signals to account for a wide frequency range. The endurance time (ET) method represents a seven-seismic signal developed by Estekanchi and Alembagheri (2012), to evaluate the complex effects of earthquakes on structures such as thin-wall tanks.

Figure 3.6 represents a conceptual shaking table test scenario in which three water storage tanks, with unknown resistance and dynamic characteristics, were subjected to testing. The main objective of this

test was to determine the seismic performance of the tanks. Each tank was exposed to a randomly generated acceleration signal to evaluate its dynamic response.

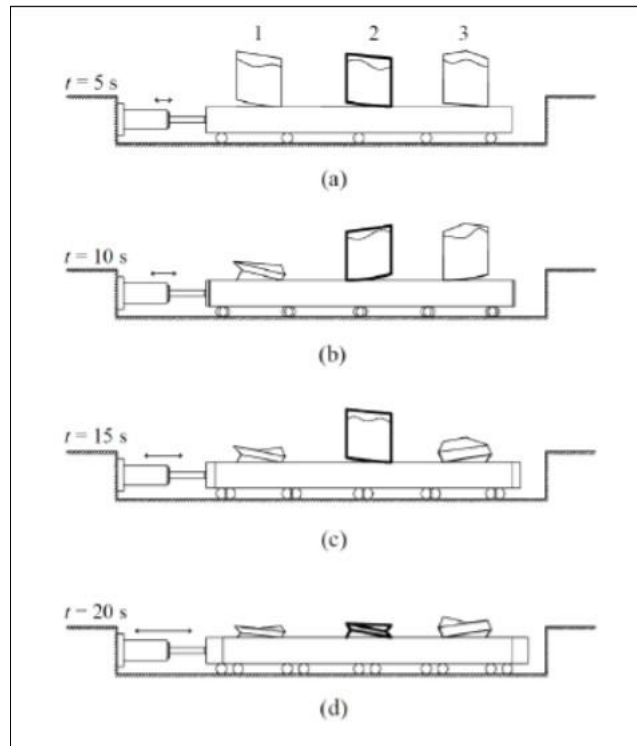
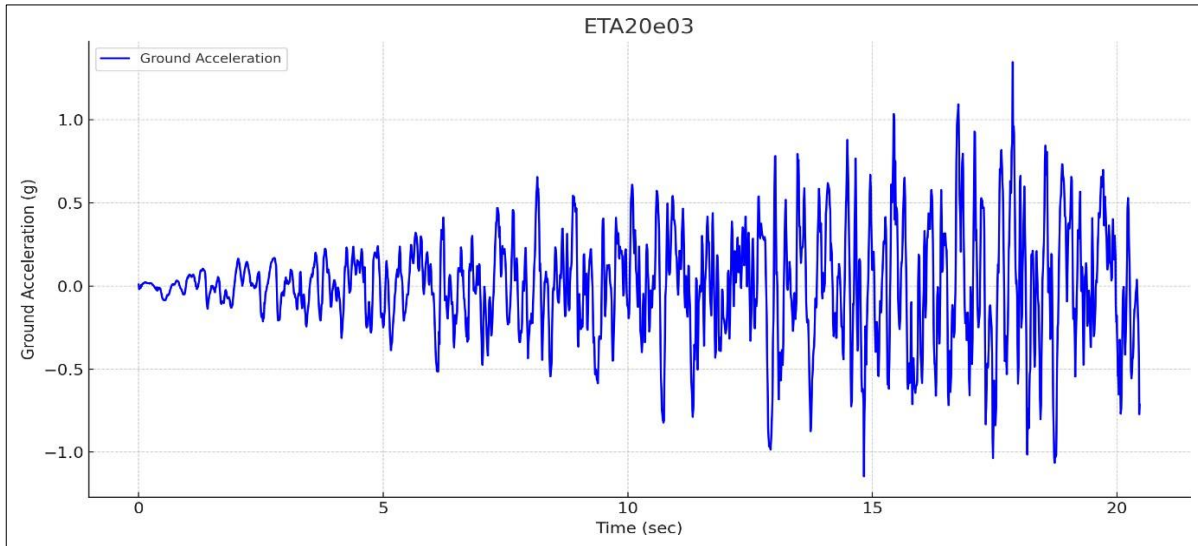


Figure 3.6: Experiment test for water storage tanks using a shaking table (Adapted from Alembagheri (2011))

As shown in Figure 3.6, after 5 seconds, all tanks are stable with no failure. Then the acceleration was increased to 10 seconds further to observe the failure in tank 1. The acceleration increased further to 15 seconds, and it was observed that tank 3 had collapsed. At 20 seconds, tank 2 failed. Based on the output of the test, noticeably tank 2 performed better than tanks 1 and 3 in terms of seismic resistance.

The ET method was utilised to evaluate the structural performance under seismic loading. In this approach, the structure was subjected to artificially generated acceleration signals of increasing in intensity, while observing the resulting forces and displacement were monitored. The ET signal developed by the author is displayed in Figure 3.7.



**Figure 3.7: ETA20e03 signal
(Estekanchi and Alembagheri (2012))**

3.10 Chapter summary

This chapter presents the characterisation of the FPS modelling technique, fluid–structure interaction (FSI), and the selection of seismic input for dynamic analysis. The FPS, a widely used seismic base isolation system, is favoured for its high rigidity, vertical load-bearing capacity, stability, and re-centring capability. These features are enabled by a spherical sliding surface that facilitates pendulum motion, with the system’s dynamic behaviour governed by the radius of curvature, gravitational forces, and ground motion. The modelling approaches discussed include equivalent linear, bi-linear, and dynamic friction-spring models.

FSI involves both analytical and numerical methods that focus on key parameters such as hydrodynamic pressure and fluid velocity. Boundary conditions play a critical role in FSI problems, as they define the interfaces between the fluid and the structure, the free surface, and the interaction with the ground.

Finally, this chapter introduces the seismic input methodology used for dynamic analysis. The ET method, developed by Estekanchi and Alembagheri (2012), is applied using multiple seismic intensity levels to evaluate structural performance. Artificial acceleration signals simulate a shaking table experiment involving three water tanks, with failure assessed based on increasing acceleration levels. This chapter lays the groundwork for the subsequent validation of FPS and the analysis of dynamic responses under seismic loading.

CHAPTER FOUR

VERIFICATION OF THE PROPOSED MODEL FOR FRICTION PENDULUM SYSTEM (FPS)

This chapter describes the validation of the friction pendulum system (FPS) model using a benchmark study titled "Soil–structure interaction analysis of an FPS-isolated structure using finite element model" by (Krishnamoorthy & Anita, 2016). The validation is conducted through numerical simulation using Abaqus software.

4.1 Structure modelling

The numerical model presents a five-story frame structure used to examine the influence of soil structure interaction (SSI) on the seismic response of the structure isolated by FPS. Krishnamoorthy and Anita (2016) modelled the FPS-isolated structure using the finite element method (FEM) as shown in Figure 4.1. The structure with a fixed base exhibits a fundamental period of 0.5 seconds. The FPS is defined by a friction coefficient of 0.05 and a curvature radius of 1 metre, resulting in an isolation period of approximately 2.0 seconds.

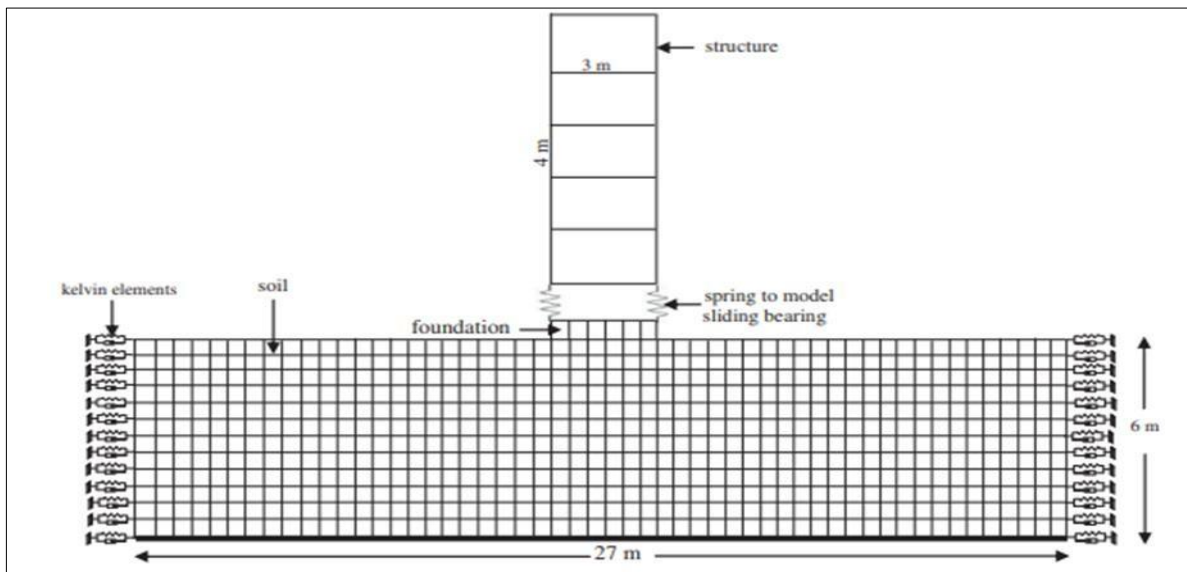


Figure 4.1: Isolated structure with SSI
(Adopted from Krishnamoorthy and Anita (2016))

Table 4.1: Soil types and properties

	(kN/m^2)	μ	$\Lambda(kN/m^3)$	ζ (%)
Soil	500000	0.3	20	0.05

A single soil type with varying stiffness properties was considered to investigate soil flexibility and SSI effects as given in Table 4.1. The geometry of the structure and material properties, including modulus of elasticity, mass, damping ratio, and beam and column sizes, were all specified in Table 4.2.

Table 4.2: Material properties

Material properties	Superstructure	Foundation
Modulus of elasticity	$2.2 \times 10^7 \text{ kN/m}^2$	$2.2 \times 10^7 \text{ kN/m}^2$
Mass	$5.0 \text{ kNsec}^2/\text{m}^2$	$2.4 \text{ kNsec}^2/\text{m}^2$
Damping %	5%	5%
Beam dimension	0.45 m \times 0.45 m	-
Column dimension	0.45 m \times 0.60 m	-
Poison's ratio	-	0.15

Spring friction represents the interface gap between the base of the structure and its foundation, with stiffness parameters varying from high (non-sliding) to zero (sliding), thereby simulating a range of contact scenarios. To emulate an infinite soil domain, Kelvin elements are positioned along the lateral boundaries of the soil model. The FEM is employed to investigate the influence of soil–structure interaction on the seismic performance of an isolated building subjected to earthquake loading.

4.2 Soil structure interaction effect

This section investigates the impact of the FPS on the time history response of base shear and displacement in the isolated structure under seismic ground motions, considering the influence of SSI.

4.2.1 Time history response

The time history response analysis utilised the El Centro earthquake record to demonstrate the effect of soil structure interaction over time. The author identified that the soil exhibited near-rigid base behaviour in terms of base shear and displacement responses during earthquake events. However, SSI significantly affects sliding displacement and base shear responses depending on the soil type and earthquake motion characteristics (Krishnamoorthy & Anita, 2016).

4.3 Finite element modelling technique

The FEM is a computational approach employed to address complex engineering challenges by dividing the domain into smaller subdomains known as elements. These elements are interconnected at specific locations referred to as nodes. Abaqus FE is a powerful and widely adopted software tool for such analyses, owing to its capability to manage intricate geometries and diverse material behaviours. Within Abaqus, the model is discretised into individual elements, each possessing distinct shapes and roles. The number of nodes associated with an element determines the degree of the interpolation polynomial.

Elements are typically classified into three categories: one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D).

An isolated structure was modelled using Abaqus FEA as a 2D system. The soil was assumed to be rigid, and Kelvin elements are attached to the foundation. The model is displayed in Figure 4.2.

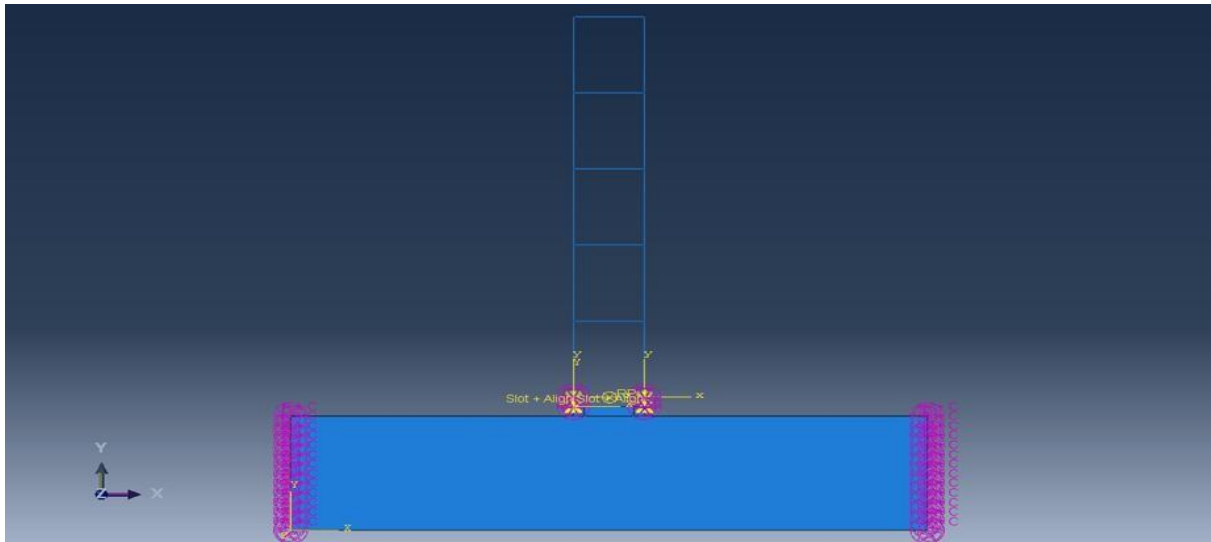


Figure 4.2: Structure model with Kelvin and spring element via Abaqus

Figure 4.3 illustrates the foundation decoupled from the structure base using FPS. In Abaqus, the FPS is modelled as a spring-friction element defined using the 'slot + align' connector feature. This element bridges the interface by linking the bottom part to the foundation and the top part to the structure base, allowing relative sliding motion during seismic excitation.



Figure 4.3: Spring element

The foundation was meshed using CPE4R elements Figure 4.4, a 4-node bilinear plane strain quadrilateral with reduced integration and hourglass control. These elements are widely recommended for their efficiency and accuracy (SYSTEMS, 2024). B23, a 2-node cubic beam in a plane, was used for the structure.

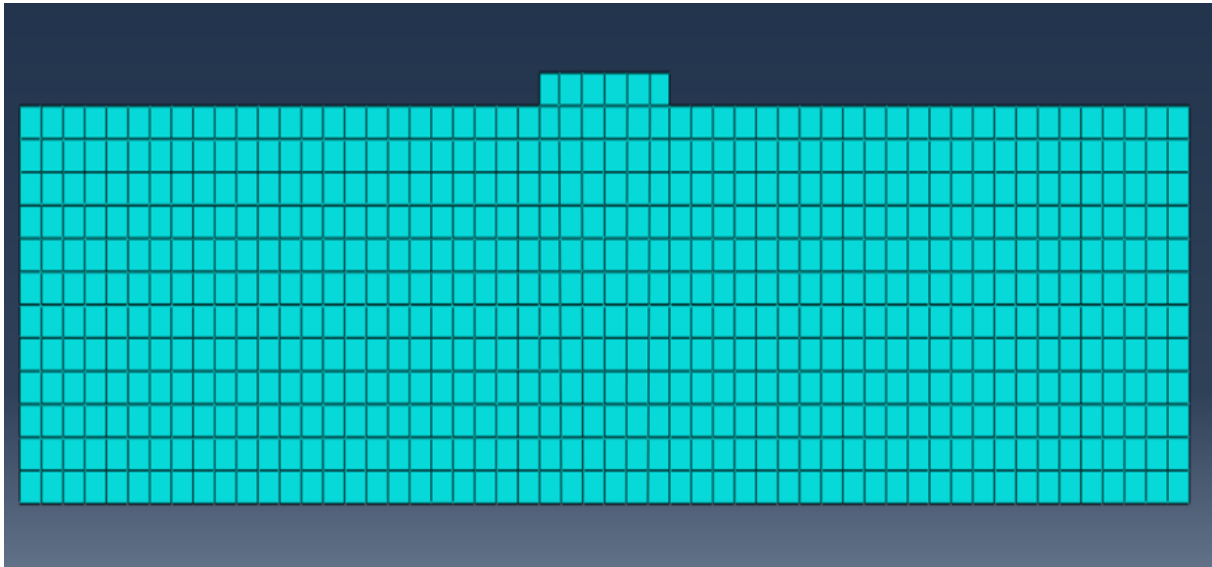


Figure 4.4: Simplified soil and foundation mesh

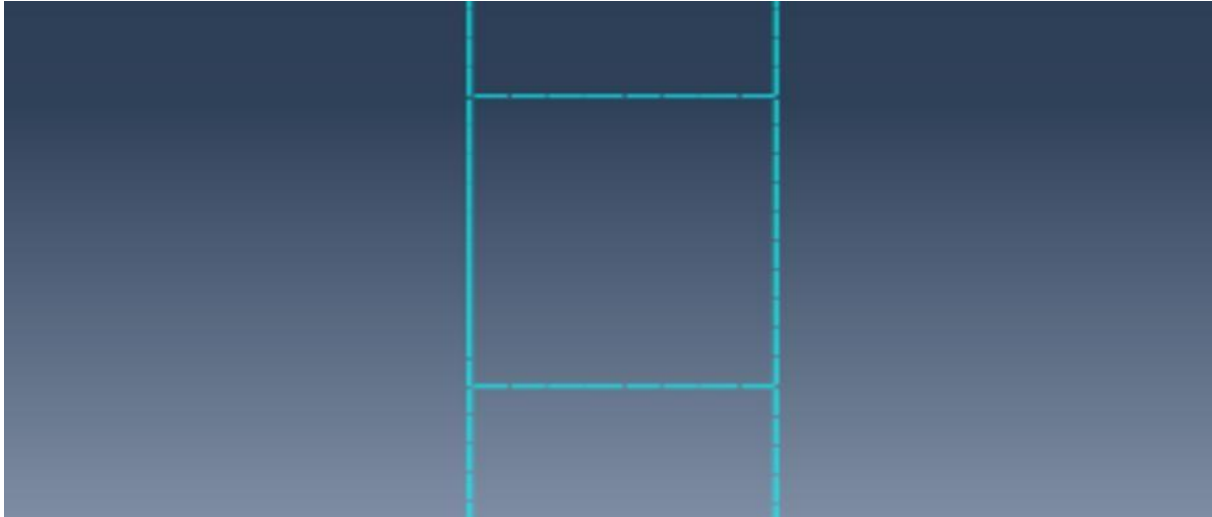


Figure 4.5: Simplified structure mesh

The following analysis of the model developed using Abaqus illustrates the stress and displacement of the structure isolated with and without FPS. The results were generated using FEA. A comparative time history analysis was conducted to evaluate base shear and displacement responses under the El Centro earthquake ground motion. This comparison was used to study the effect of FPS isolation with soil–structure interaction (SSI) relative to a rigid base condition.

Figure 4.6 and Figure 4.7 illustrate the time history of displacement over 20 seconds. The output results from the Abaqus software display a similar behaviour pattern compared to the experimental research results. Both graphs indicate that the displacement fluctuates strongly up to 8 seconds. After 10 seconds, the pattern indicates stabilisation. Overall, the validation model converges toward similar displacement values and exhibits the same dynamic response.

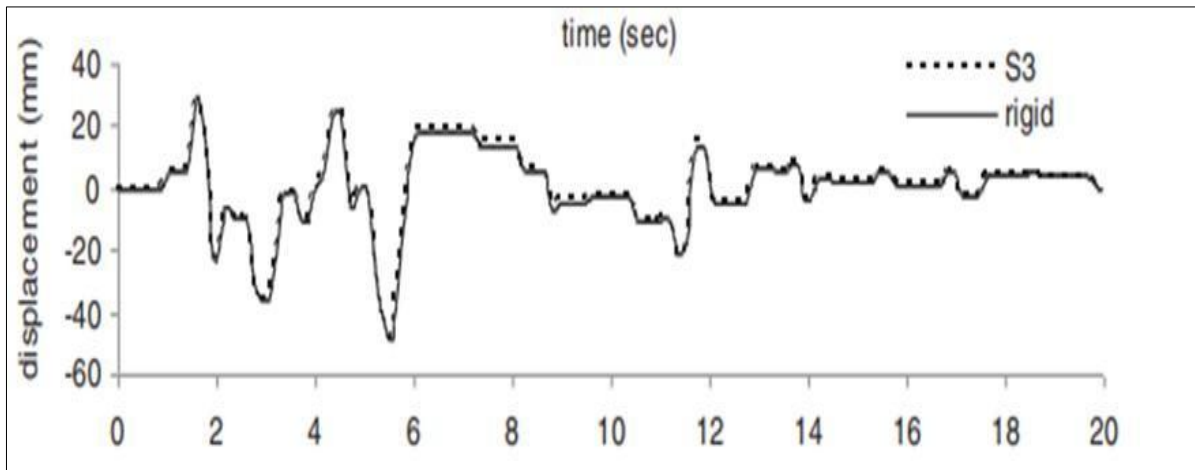


Figure 4.6: Displacement graph over time for rigid soil

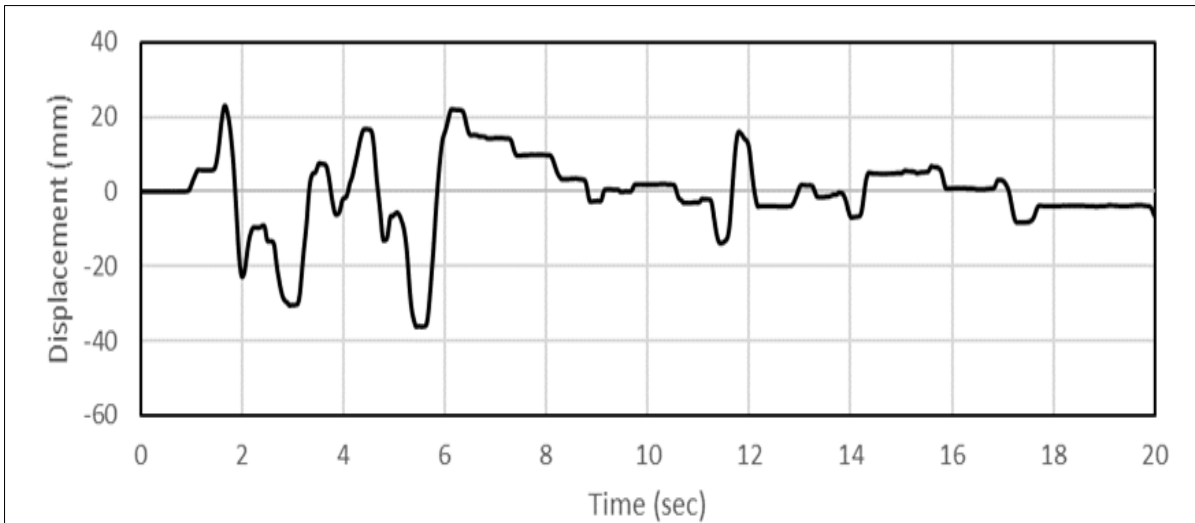


Figure 4.7: Displacement output from Abaqus over time

Figure 4.8 and Figure 4.9 present a comparison of base shear responses between the experimental study and the Abaqus simulation for model validation. Over 20 seconds, the amplitude ranges roughly from 50 kN to -40 kN. During the first 5 seconds, the range value of the response patterns is indistinguishable. Moreover, the Abaqus results show similar values, with no serious amplitude reduction over time.

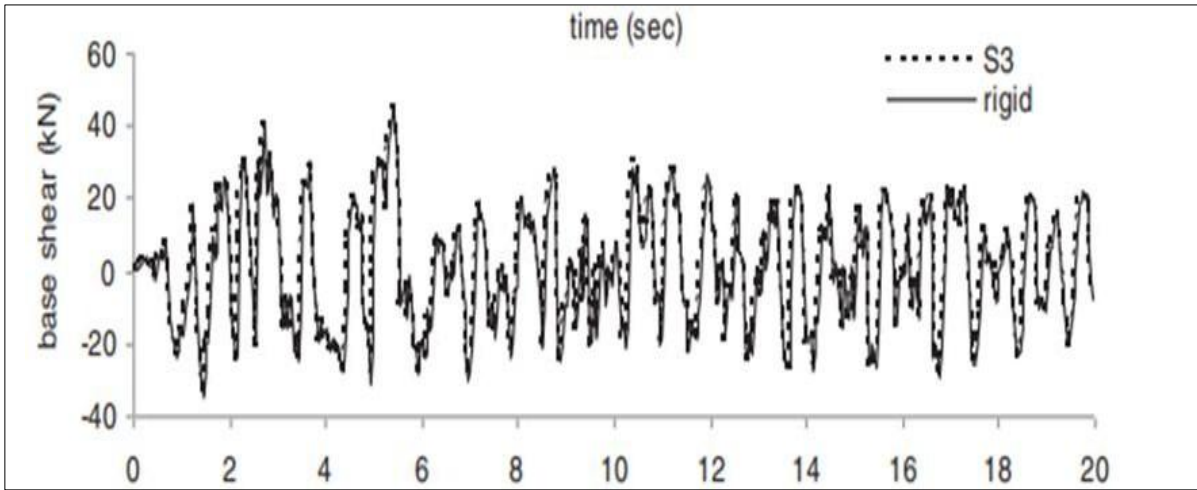


Figure 4.8: Base shear value over the time

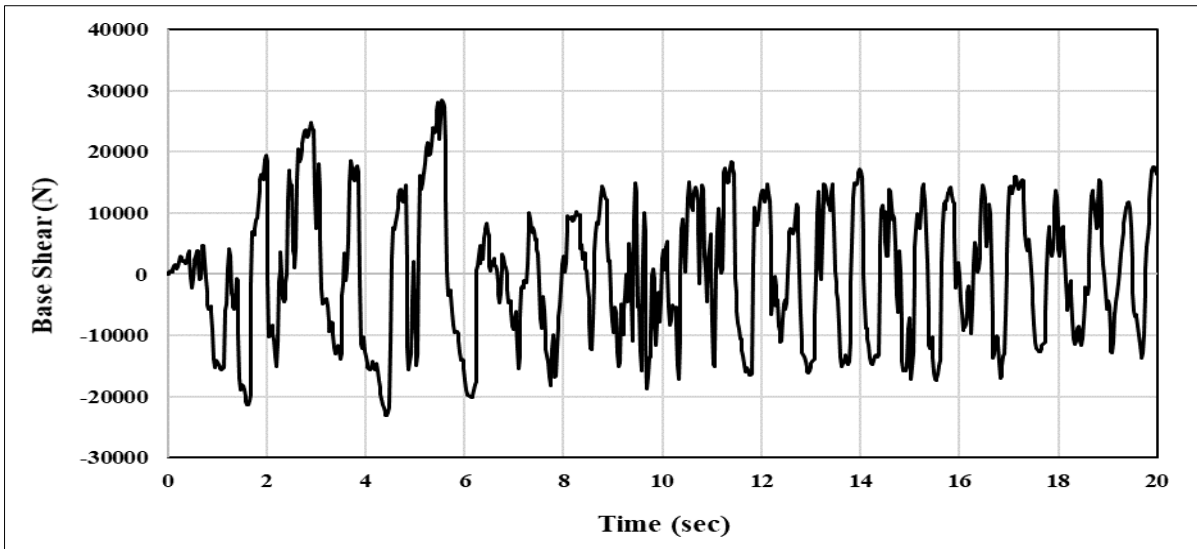


Figure 4.9: Base shear over time Abaqus

The hysteresis curve associated with the FPS demonstrates its capacity to dissipate energy throughout the loading cycle induced by seismic activity. This graph illustrates the correlation between the restoring force and the corresponding displacement, as shown in Figure 4.10.

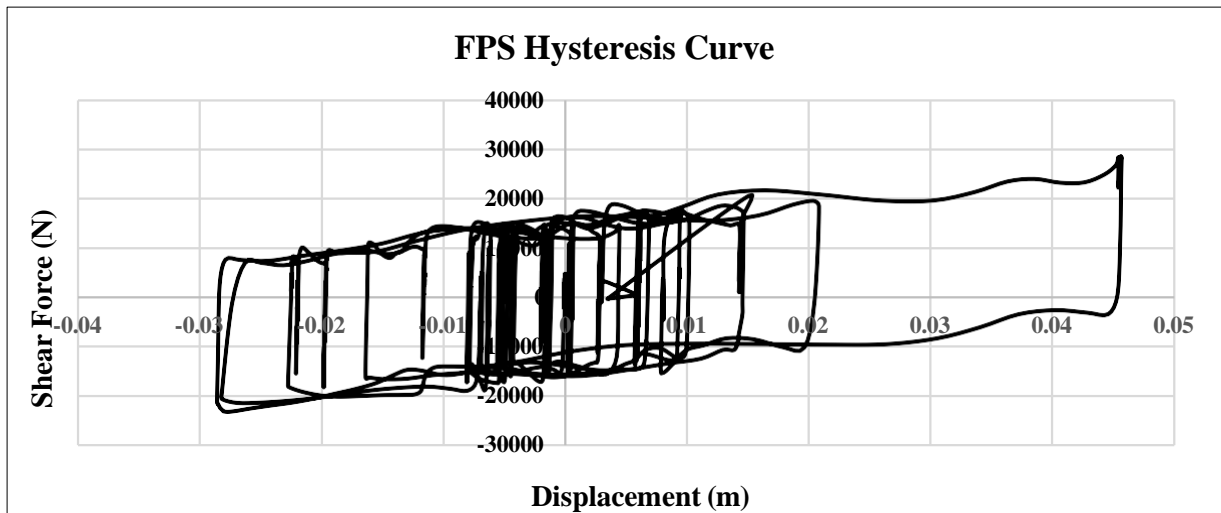


Figure 4.10: Displacement vs Base shear curve of FPS isolator

4.4 Chapter Summary

The preceding section describes the validation of FPS, which can potentially enhance structural performance during earthquake occurrence. This chapter provided extensive information about FPS, including its benefits, working principle, modelling approach, and function behaviour.

Through time history response comparisons for the base shear and displacement, under the El Centro earthquake ground motion, the finite element model developed in Abaqus exhibits stability according to the experimental findings. For the base shear and displacement, the Abaqus model roughly matches experimental results for base shear and displacement on rigid soil, which simulates a fixed-base condition. The finite element modelling approach utilising Abaqus can accurately predict seismic response trends and reasonably match experimental results, particularly for the stiff base condition.

The findings highlight the effectiveness of FPS in mitigating seismic effects and demonstrate the model's ability to capture SSI behaviour. Minor discrepancies observed under extremely soft or flexible soil conditions suggest that further refinement of the FE model could improve accuracy in such cases.

CHAPTER FIVE

FEM ANALYSIS, MODELLING AND SIMULATION STRATEGY OF ELEVATED STEEL WATER STORAGE TANKS CONSIDERING FRICTION PENDULUM SYSTEM

5.1 Introduction

Steel water storage tanks are essential infrastructure used for portable water storage. This chapter focuses on an elevated steel water storage tank constructed and manufactured using Zinalume steel panels, supplied by SBS Tanks. The tank is a flexible cylindrical structure without a bottom plate and incorporates wind girders for lateral stability, along with a ring beam at the base to ensure structural integrity. Understanding FSI is essential for evaluating the tank's seismic response. This paper proposes a finite element modelling framework for elevated water tanks equipped with friction pendulum bearings. The theory and methods are outlined below. The applicability of these models was investigated and duly verified to ascertain the importance of the components, dynamic characteristics and seismic response in the context of overall structural systems. Two models were developed with and without base isolation to evaluate the hydrodynamic interaction and structural response under seismic load.

5.2 Finite element modelling of elevated steel water storage tanks

In this section, a finite element model of an elevated steel water tank is developed using Abaqus, with a focus on the selection of element types and material properties. The objective is to accurately simulate the structural and hydrodynamic behaviour of the tank under seismic loading conditions, both with and without base isolation.

5.2.1 Structural layout, element types, and material properties

The elevated steel water tank analysed in this research is a steel structure. The flexible tank is designed as a cylindrical shape using a shell element and supported by five wind girders and a ring beam at the base of the tank. The tank diameter is 3410 mm, and the height is 3176 mm. Figure 5.1. The water inside the tank created a solid element with a height of 3020 mm.

Each component of the model was developed as a 3D deformable, with dimensions 2000 x 2000 mm for the tower structure and a height of 15000 mm. The tower consists of pipe columns connected by bracing joints. Two main beams are placed on top of the columns, with secondary beams spanning across the main beams. The steel plate is designed and placed on top of the secondary beams to support the tank, as illustrated in Figure 5.2.

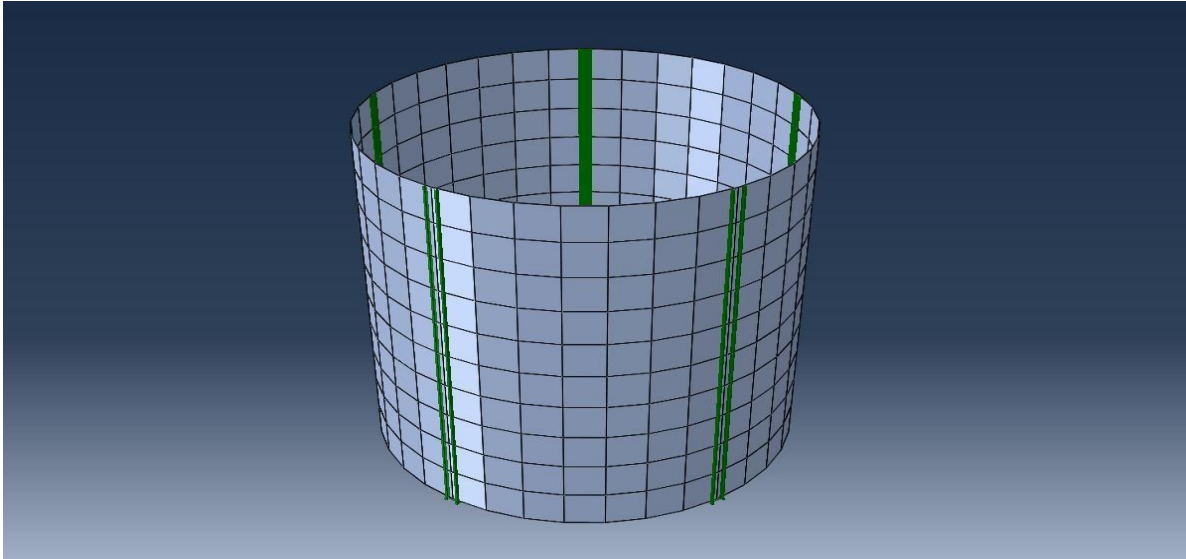


Figure 5.1: Shell element and wind girt

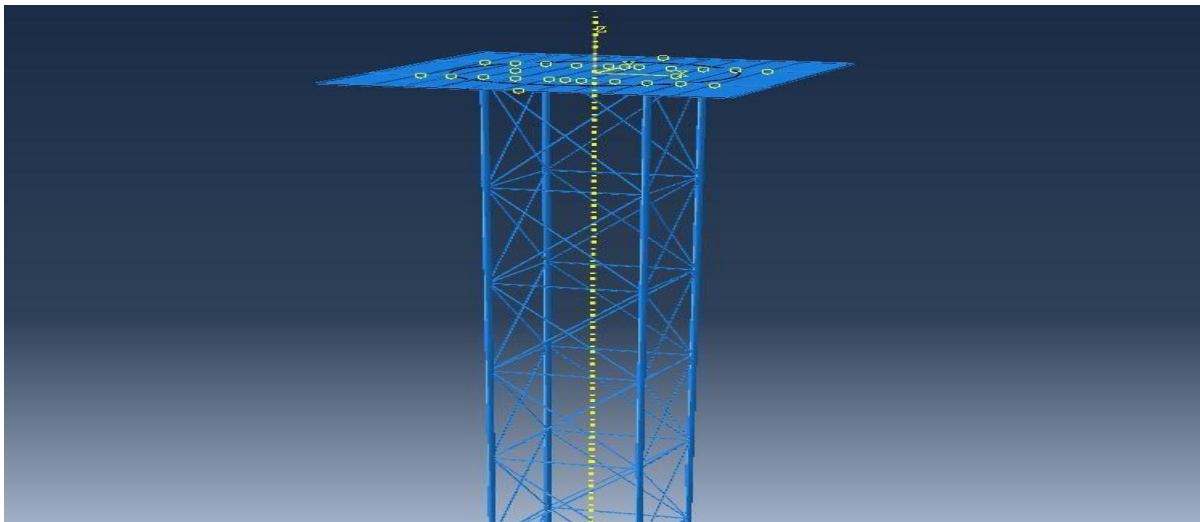


Figure 5.2: Elevated steel structure and steel plate

Figure 5.3 illustrates the wind girt connected to the steel plate, ensuring that the model behaves as a single structural unit. The columns, bracing, and beams are defined as planar wire and are appropriately oriented. Table 5.1 presents the cross-section shapes and dimensions of each structural component. The concrete foundation is modelled with an assumed height of 500 mm, and the thickness is 45 mm, as shown in Figure 5.4.

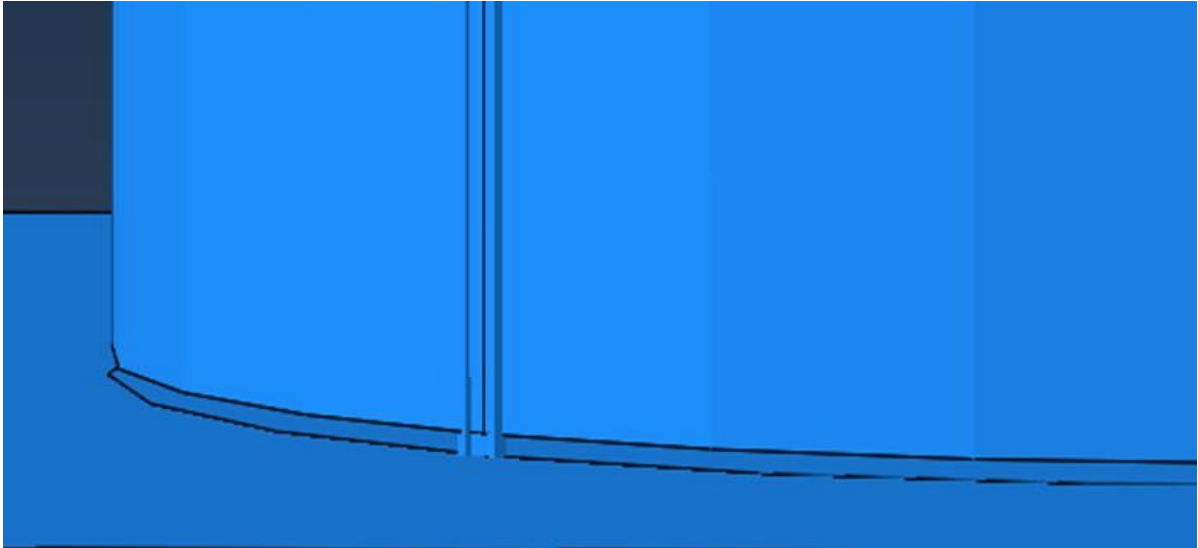


Figure 5.3: Wind girt connected to steel plate

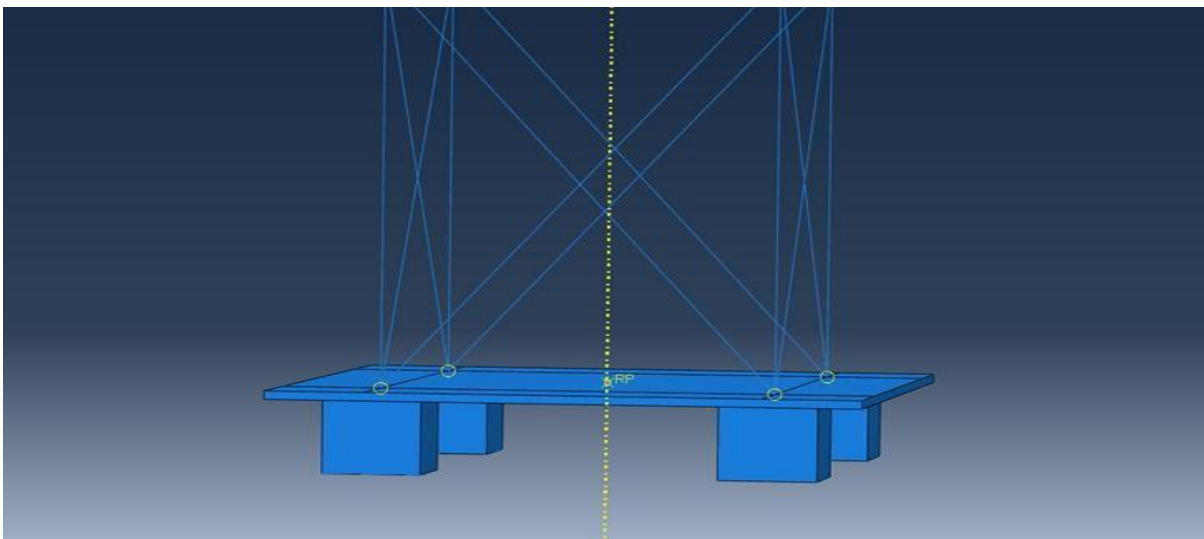


Figure 5.4: Concrete foundation

Table 5.1: Tower elements dimensions

Element	Section shape	Dimension (m)
Columns	Pipe	$R = 0.102 * t = 0.004$
Diagonal Bracing	L section	$0.04 * 0.003$
Horizontal Bracing	L section	$0.06 * 0.004$
Main Beam	I section	$0.14 * 0.037$
Secondary Beam	I section	$0.1 * 0.055$

Material properties are essential in finite element analysis, as they significantly affect the precision and dependability of the simulation outcomes. In this research, the model involves three main components: the tower structure, the tank, and the water. The tower structure and the tank consist of steel material. In contrast, the water consists of the acoustic domain, introducing FSI effects. The material properties are defined for the steel tank, water, and tower structures. Each component is characterised by parameters such as Young’s modulus, Poisson’s ratio, and mass density, as summarised in Table 5.2.

Table 5.2: Material parameters

Material properties	Tower structure (steel)	Tank	Water
Mass Density (kg/m ³)	7850	7850	1000
Young Modulus (GPa)	210	210	-
Poisson’s ratio	0.3	0.3	0.5
Bulk Modulus (GPa)	-	-	2.1

5.2.2 Hoop stress of the isolated tank

The connection between the structure and the tank was modelled as a tie constraint, which ensures these elements are seamlessly integrated without disconnections. The interaction between the model elements was defined as a general contact formulation, incorporating properties for both tangential behaviour and normal behaviour. Additionally, acoustic impedance was specified for the water domain to capture fluid–structure interaction effects accurately.

For the loading step, the model procedure was selected as a dynamic/explicit, with a gravity load applied to the entire model equal to 9.81 m/s². The hydrostatic pressure used in the model represents the interaction between the water and tank wall using the equation $p = \rho gh$ Figure 5.5. FSI refers to the interaction between the fluid and structure, where the fluid-induced force impacts the structure's integrity.

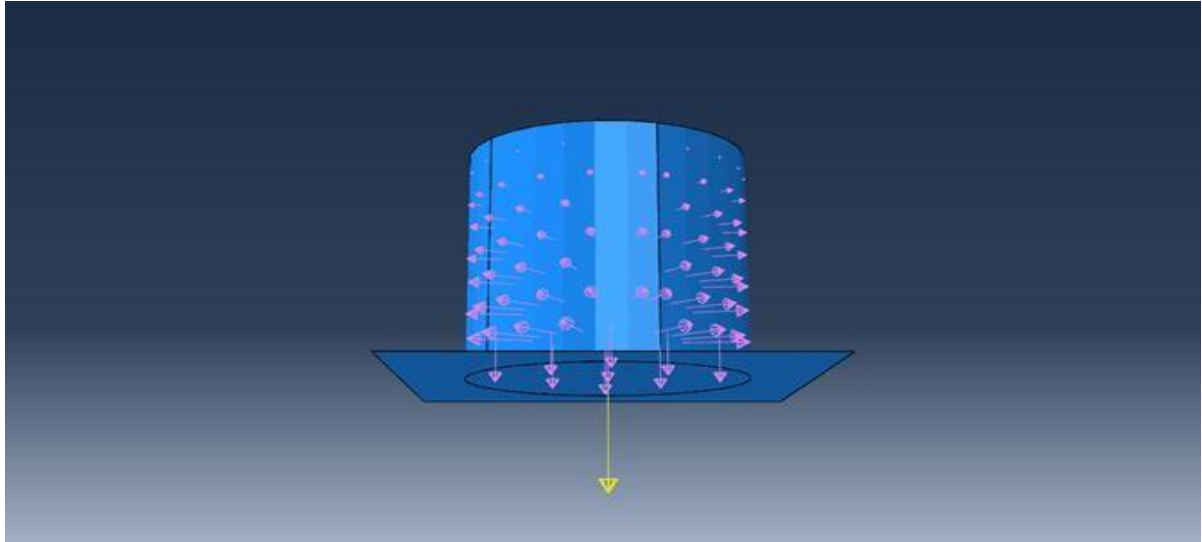


Figure 5.5: Gravity and hydrostatic pressure load to applied

Water is modelled as an acoustic element, considering that the speed of sound in water is set at 1450 m/s and a density of 1000kg/m^3 . The expression of Abaqus software's load and boundary conditions is how the model interacts with the environment. FEA features constraints that restrict the model's movement in specific directions, such as fixed movement or movement in other directions. Also, interaction conditions enable different model parts to interact as one element, such as friction, dynamic behaviour, and element contact.

In a non-isolated tank, the seismic load was imposed at the foundation of the tower. The seismic acceleration was defined to simulate ground motion during an earthquake, and the displacement function was specified at the footing of the tower structure. In the isolated tank model, the load was applied to the foundation by decoupling the base of the structure from the foundation. Boundary conditions were applied at the bottom of the foundation in both models, non-isolated and isolated, to constrain the model. Two types of boundary conditions were applied: displacement constraints to stabilise the model and control the degree of freedom, and horizontal acceleration to simulate seismic excitation as shown in Figure 5.6 and Figure 5.7.

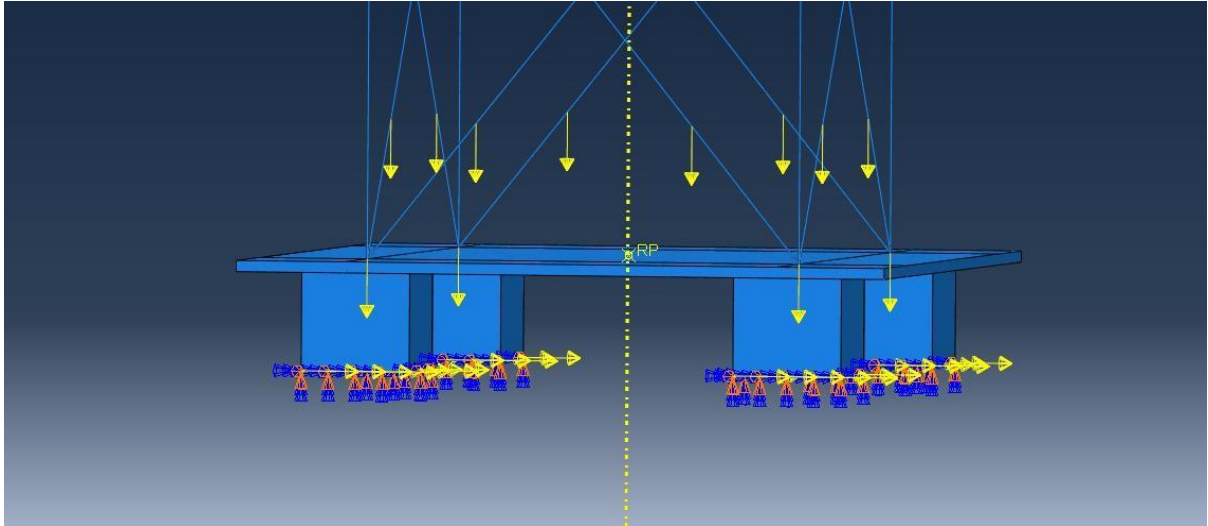


Figure 5.6: Boundary condition and displacement force for a non-isolated model

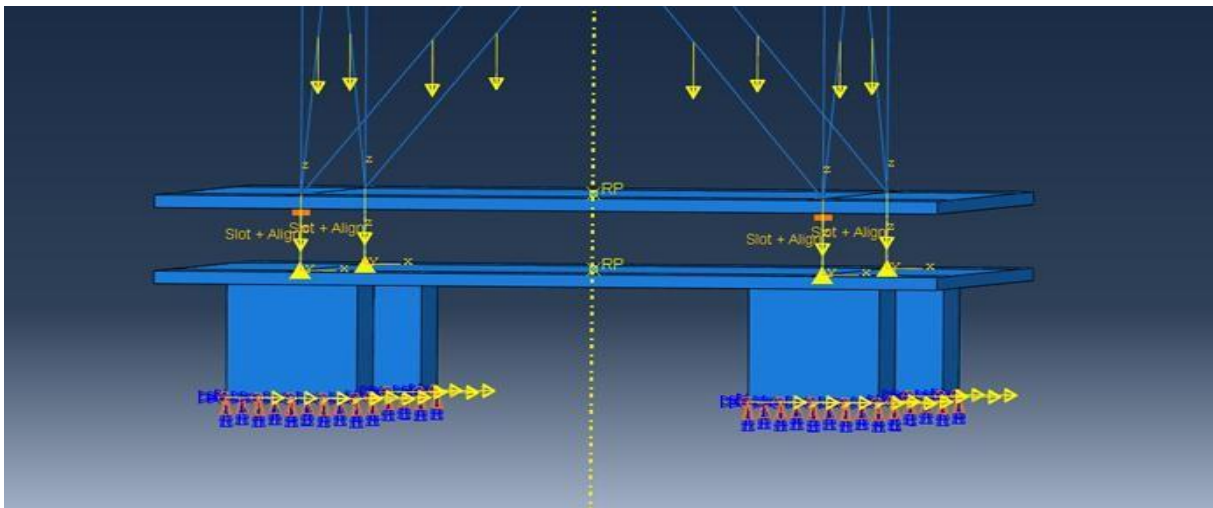
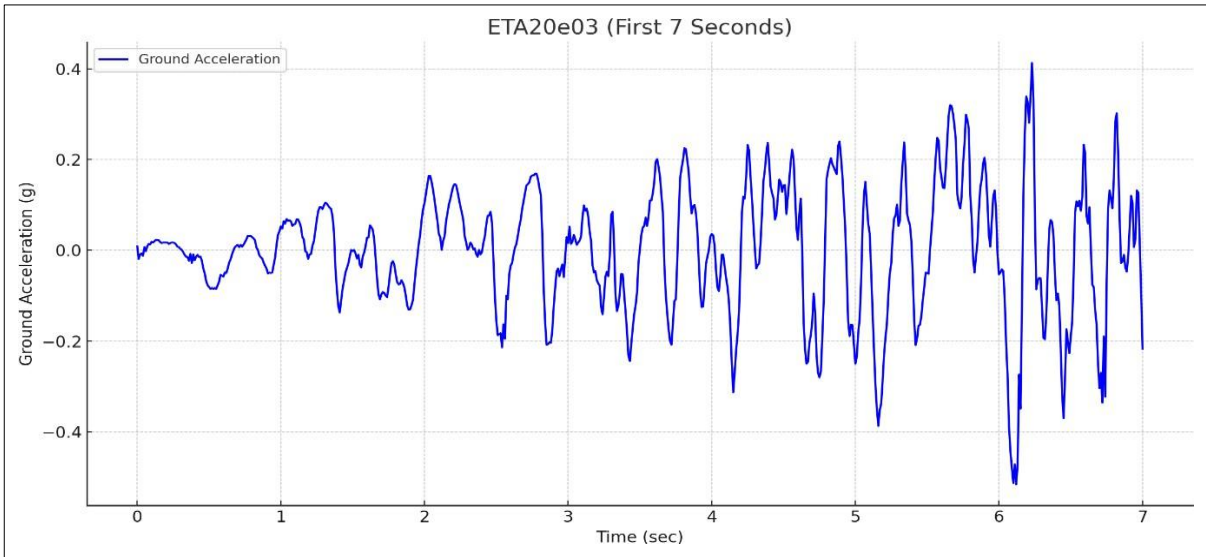


Figure 5.7: Boundary condition and displacement force for an isolated model

The ET method represents a set of seven seismic signals that has been developed by Estekanchi and Alembagheri (2012) to address the complexities associated with the impact of an earthquake on thin-walled tanks, such as those discussed in Chapter 3, section 3.9. This study focuses on time-history analysis over a duration of 7 seconds, using signals compatible with a peak ground acceleration (PGA) of 0.2g, to ensure the reliability and accuracy of the simulation results Figure 5.8. Figure 5.9 shows the spectrum response curve for ground type 3 based on SANS 10160-4: 2017 compared with the ET signal using SeismoSignal software.



**Figure 5.8: ET signal for 7 seconds
(Adopted from Estekanchi and Alembagheri (2012))**

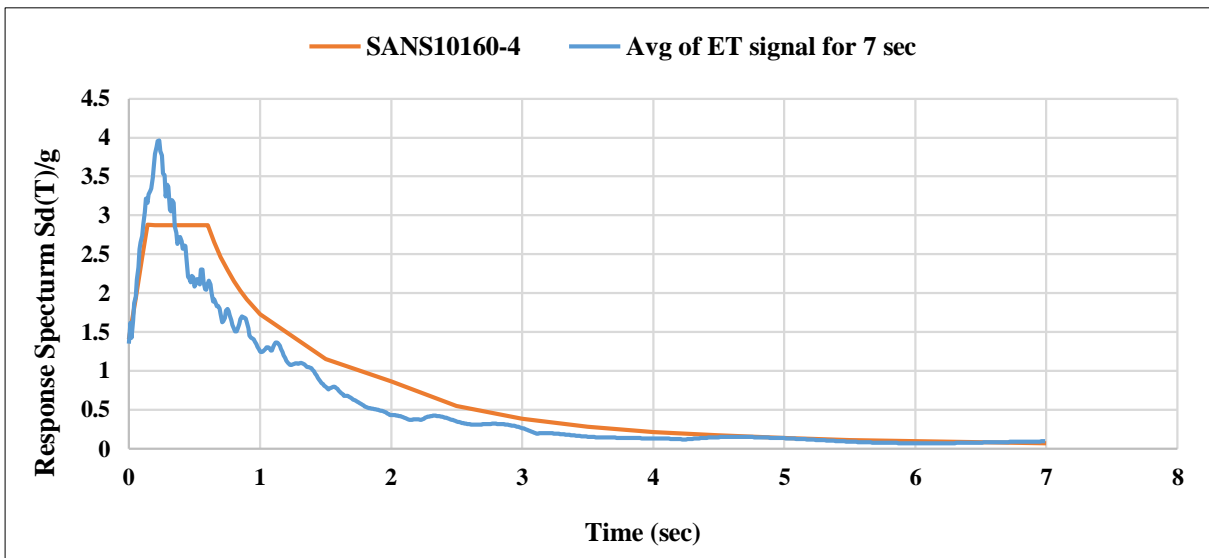


Figure 5.9: Comparison of spectrum response curve for SANS10160-4 and ET signal

The isolation system FPS is defined as a spring element connected between two elements Figure 5.10. In Abaqus, the wire (slot + align) connects two main elements by allowing movement along a specific direction, with the friction coefficient assumed to be 0.05, and the radius curvature is 500 mm. The spring behaviour simulates sliding with a defined isolator stiffness. In this model, the connection is established between the base of the tower columns and the top of the foundation. The spring element also accounts for damping and restoring forces.

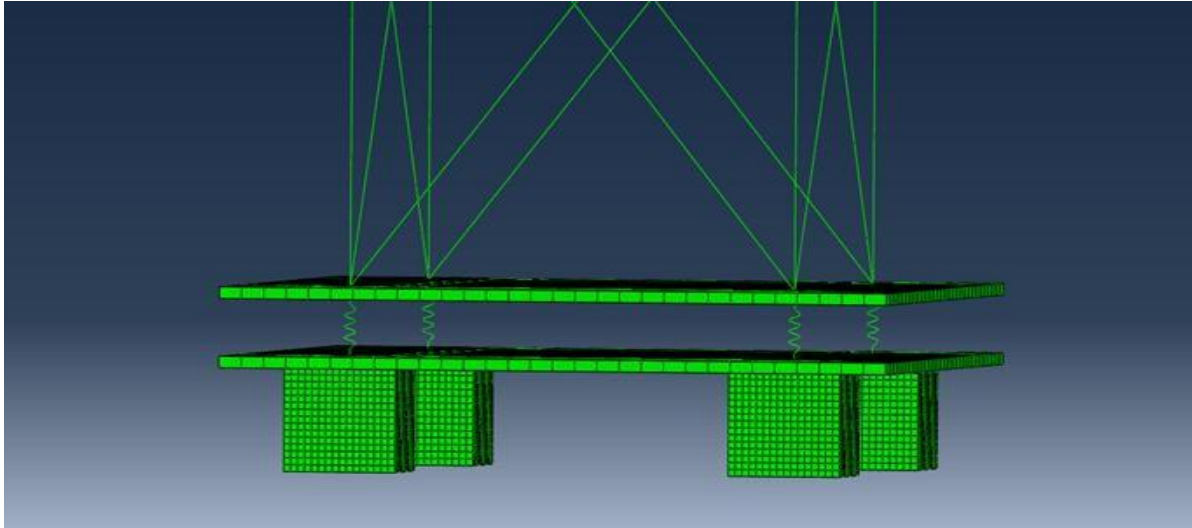


Figure 5.10: FPS isolator defined as a spring element

5.2.3 Meshing generation and element discretisation

Meshing is a significant step in finite element analysis, where the geometry is divided into smaller elements to improve the accuracy of the simulation. In Abaqus, the mesh is generated by discretising the model into nodes and elements. For this study, the mesh size for the shell elements is $0.3 * 0.3$ m, using the S4R element type. The acoustic domain representing water is meshed with a size of $0.2 * 0.2$ m, using the AC3D8R element type, which is an 8-node linear brick element. Figure 5.11 illustrates a finite element mesh for both the tank and water domain, and Table 5.3 below presents the element types used for each instance.

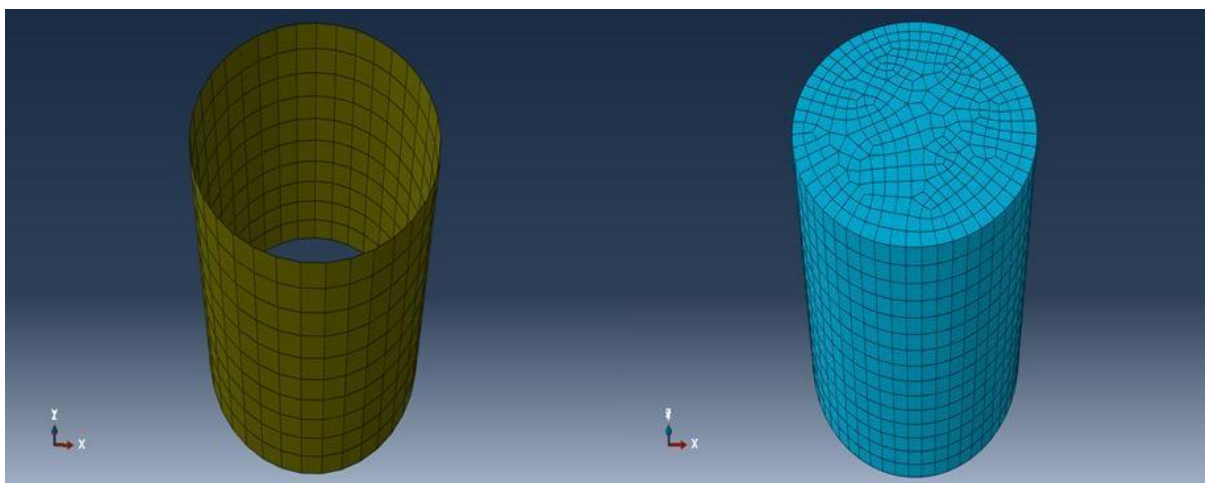


Figure 5.11: Tank shell and water elements

Table 5.3: Instance table

Instant name	Element type (# elements)
Main beam	B31
Ring beam	B31
Secondary beam	B31
Side beam	B31
Steel plate	S4R/S3R
Tank	S4R
Tower	B31
Water	AC3D8R
Wind girt	B31

5.3 Results and discussion

This part presents findings obtained from the analysis of the isolation system (FPS), involving two models of elevated water storage tanks with base isolation and one without base isolation using Abaqus software. The research aims to examine hoop stress distribution, displacement, base shear, and water behaviour inside the tank, and to evaluate the effectiveness of base isolation in mitigating seismic effects and improving the performance of water tanks.

5.3.1 Seismic displacement analysis

Displacement analysis is crucial for evaluating a structure's response to seismic activity, as it reveals how different components behave under earthquake-induced forces. This study examined the displacement of an elevated water tank, both with and without base isolation, to determine the effectiveness of the isolation system in minimising seismic-induced movement.

During seismic loading, horizontal displacement was observed in the non-isolated tank, primarily occurring at the top of the structure. The rigid connection to the ground restricts foundation movement, resulting in significant swaying at the tank's upper section. This displacement highlights the impact of seismic forces, which can compromise structural stability, potentially leading to collapse or overstressing the connection members of the tower. In contrast, the isolated tank exhibited a significant reduction in maximum displacement. The displacement at the top of the tower was significantly reduced due to the isolator, which decoupled the structure from ground motion and limited overall movement. This reduction highlighted the effectiveness of the isolation system in enhancing structural performance. The isolator absorbed the seismic force, thereby decreasing the risk of damage and improving the dynamic behaviour of the tank.

The comparison graph in Figure 5.12 represents the displacement of the tank over time for both models (non-isolated tank: displacement = -0.069 m, time = 6.65 secs;

for isolated tank: displacement = -0.026 m, time = 6.44 secs). Initially, both models start with smooth fluctuations until the first second. After that, the displacement starts increasing, but in the non-isolated model, the pattern moves erratically with greater amplitude than in the isolated model. The variation for the non-isolated model is larger than that of the isolated model over time. The isolated model maintains a more stable range. The isolation system (FPS) reduces displacement by damping the oscillations. This observation indicates that the displacement in the isolated tank is lower compared to the non-isolated tank, which demonstrates an improvement in resilience and performance.

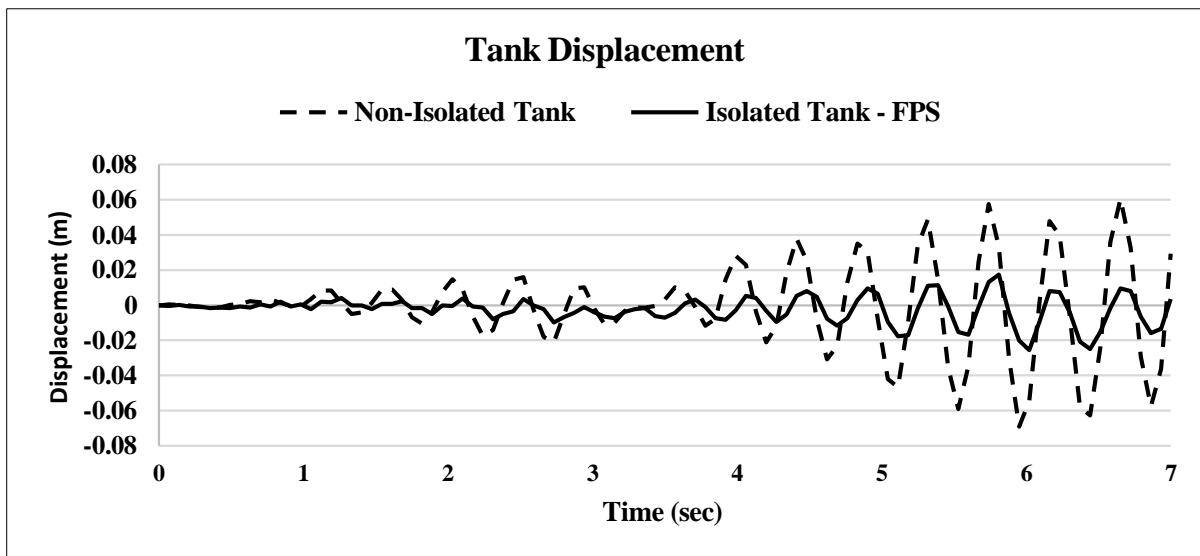


Figure 5.12: Comparison of tank displacement over time

5.3.2 Shell stress analysis

Understanding stress distribution in elevated steel water storage tanks is essential for evaluating their structural integrity under seismic loading. Hydrodynamic pressure increases proportionally with depth, resulting in peak stress concentrations at the bottom of the tank shell. This pressure exerts forces on the tank wall, leading to stresses such as circumferential (hoop) stress. Figure 5.13 and Figure 5.14 illustrate the maximum hoop stress exerted on the tank, and Figure 5.15 presents the temporal variation of shell stress throughout the seismic event. Analysis of the maximum hoop stress within the tank shell revealed a concentration of stress near the base in both isolated and non-isolated configurations. This high-stress zone at the bottom of the tank underscores a critical region in the stress distribution pattern under seismic loading conditions.

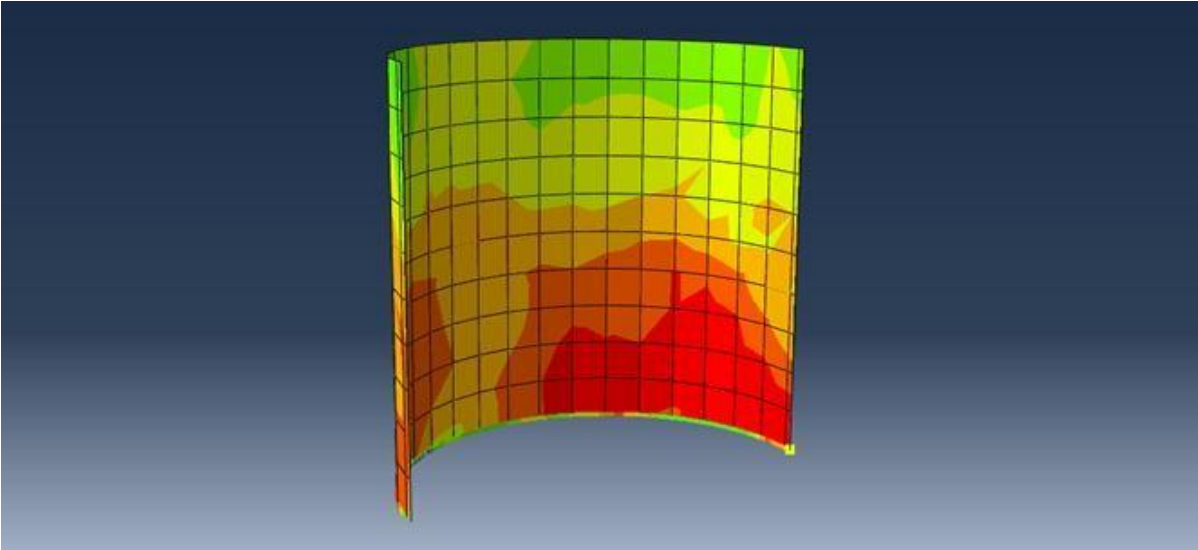


Figure 5.13: Maximum hoop stress of the shell of the non-isolated tank

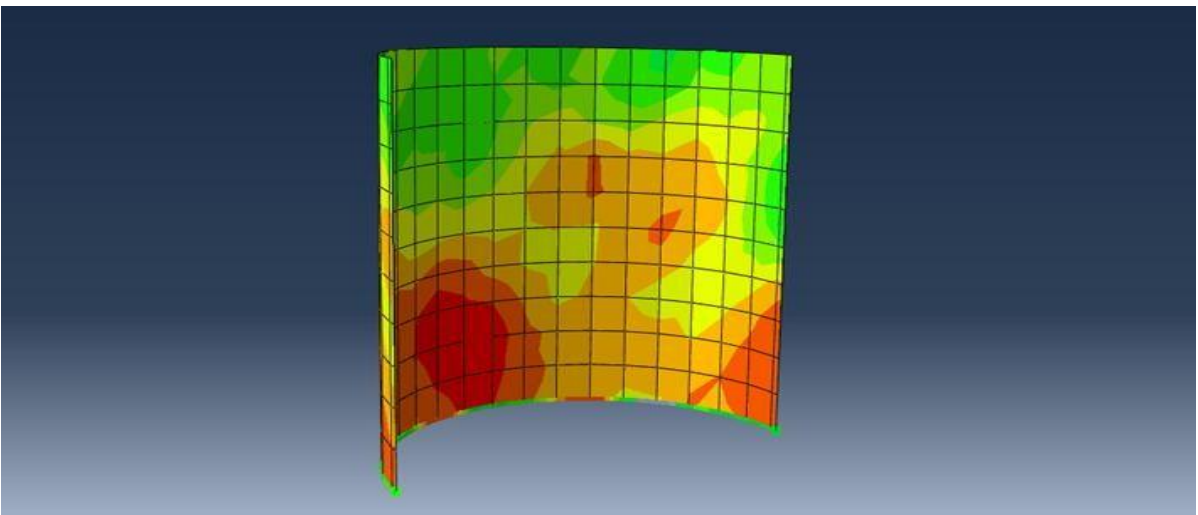


Figure 5.14: Maximum hoop stress of the shell of the isolated tank

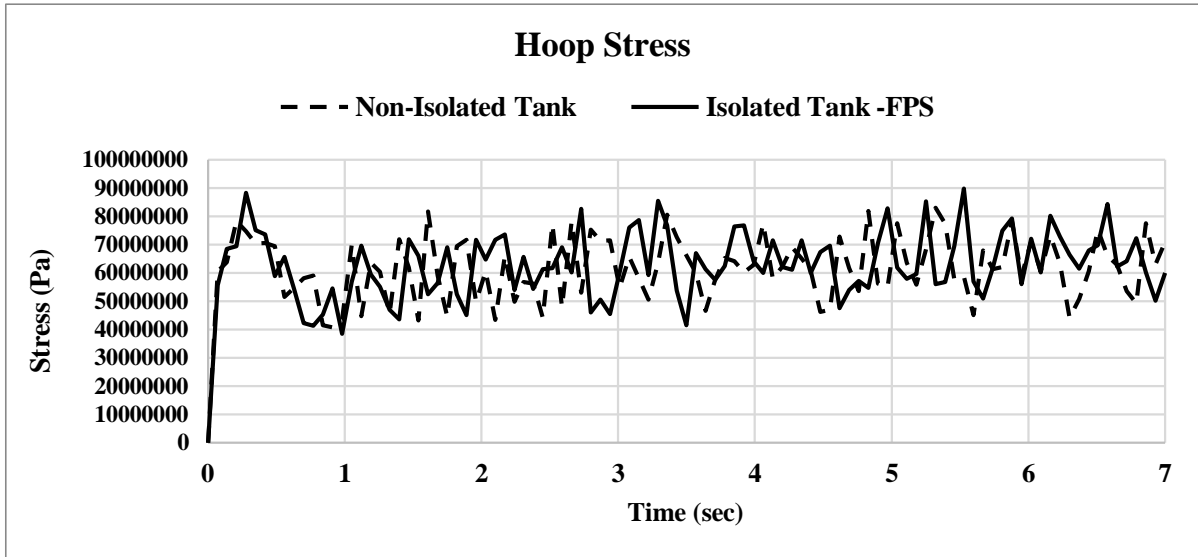


Figure 5.15: Shell stress over time

5.3.3 Water interaction

The water inside the tank is modelled as an acoustic domain. This approach is suitable for simulating the interaction between the water and the tank wall, as well as for effectively capturing pressure wave propagation. The earthquake load is applied in the horizontal direction using the ET signal, with a gravitational acceleration of 9.81 m/s^2 . Sloshing waves are defined at the top surface of the water using impedance properties within the interaction module of Abaqus. For the non-isolated tank, the acoustic analysis revealed significant pressure variations along the tank walls during seismic excitation. The impulsive and convective mass contributed to the stress and displacement of the tank, generating pressure waves that interacted with the tank walls. This additional stress increases the risk of wall buckling or tank failure Figure 5.15. However, in the isolated model, the results showed a difference in water behaviour compared to the non-isolated tank as a result of the base isolation system absorbing seismic forces. The movement of the isolator reduced water displacement, resulting in less dynamic pressure on the tank walls. The base isolation system effectively dampened the water movement, improving the overall performance of the tank and tower structure. The lower dynamic pressure minimised the risk of damage or structural failures Figure 5.17.

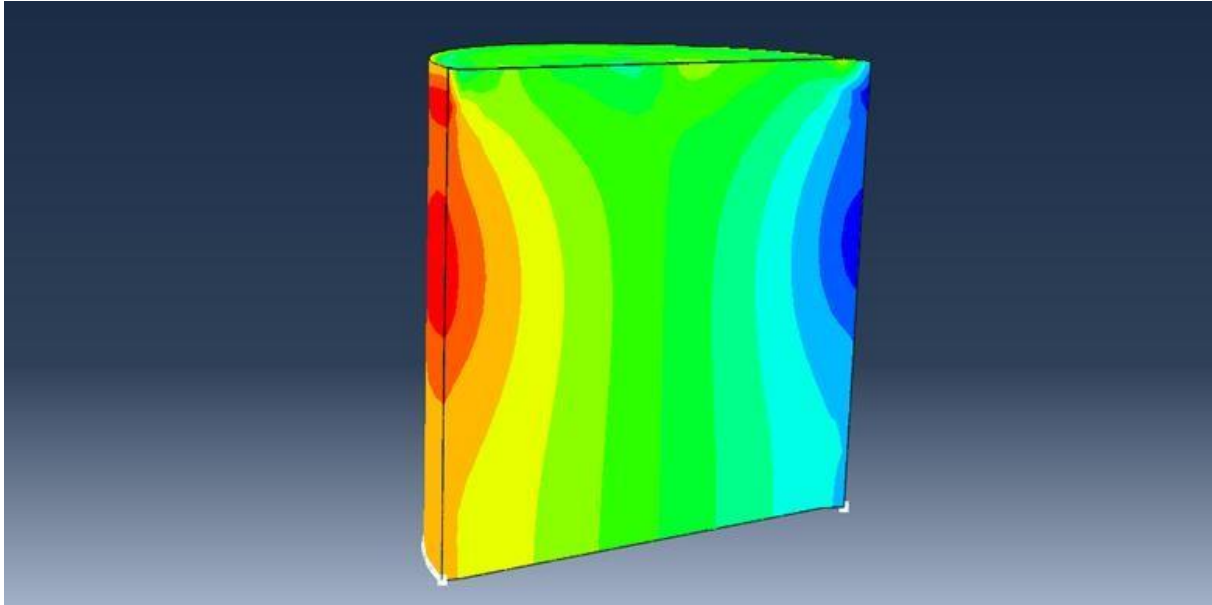


Figure 5.16: Hydrodynamic pressure of water for a non-isolated tank at t =6.9 sec

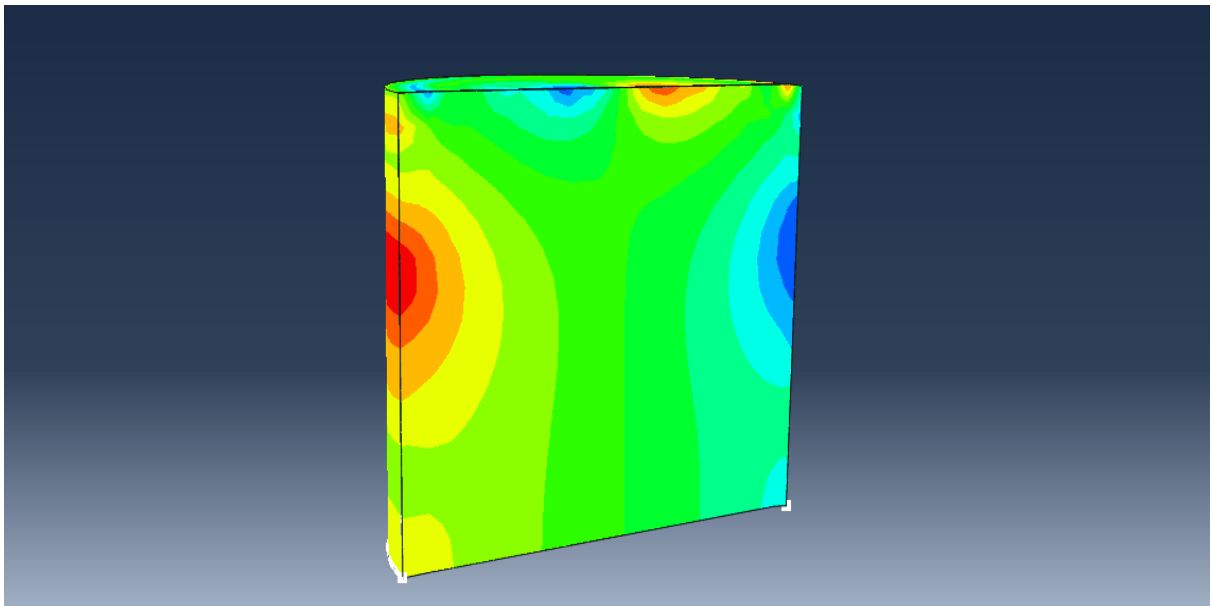


Figure 5.17: Hydrodynamic pressure of water for isolated tank at t = 6.9 sec

Figures 5.18 and 5.19 illustrate the variation of water pressure and water sloshing over time. In the water pressure analysis, both models remain close to zero with minor oscillation from 0 to 2 seconds. The non-isolated model between 4 – 7 seconds exhibits higher pressure, indicating unstable water movement and greater fluctuations. Since the isolated model demonstrated

A smoother variation, strong stability was observed as a result of absorption of the seismic force by the isolator, reducing structural movement and controlling pressure distribution.

In the water sloshing pattern, both models started smoothly, then the oscillation started to increase in amplitude. In the graph, water fluctuation started after 3 seconds, with higher sloshing for the non-isolated model than the isolated model. The non-isolated model yielded more chaotic water movement that could heighten risk and tank damage, or water overflow. In contrast, the isolated model yielded stability by reducing water sloshing. Thus, these findings establish the effectiveness of the isolation system in reducing the turbulence and maintaining more consistent pressure behaviour.

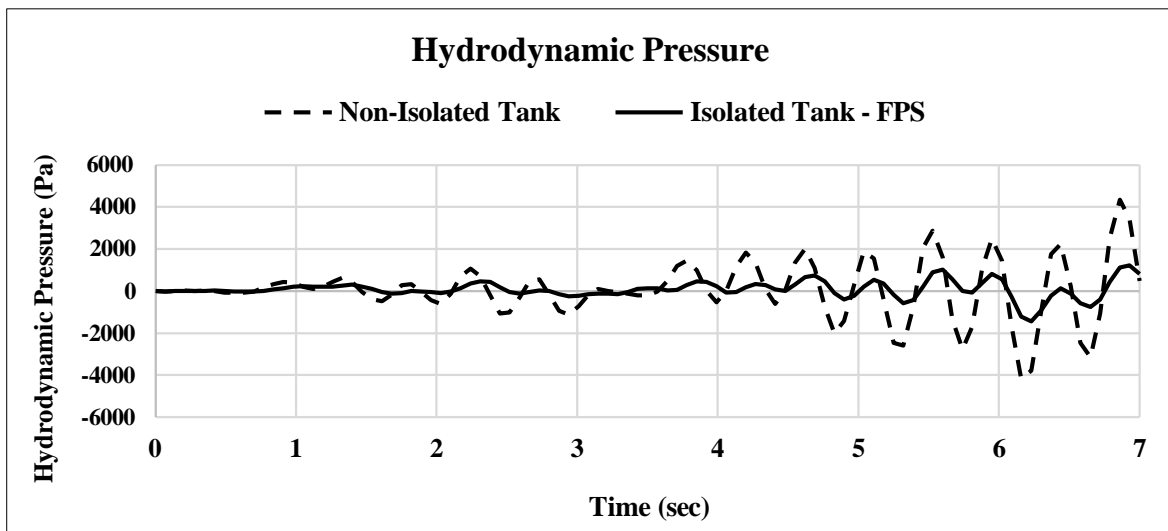


Figure 5.18: Comparison of the impact of hydrodynamic pressure

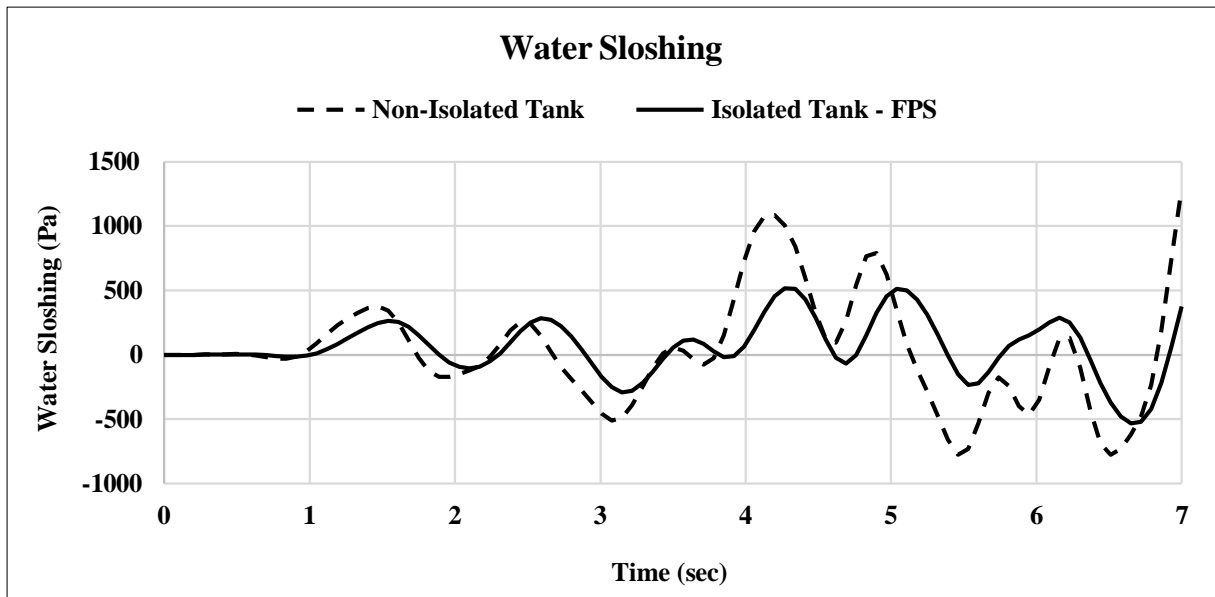


Figure 5.19: Water sloshing over time

5.3.4 Base shear analysis

In this research, the base shear analysis is used to evaluate the effectiveness of base isolation in reducing the earthquake force applied to the foundation of elevated water storage tanks as experienced in both non-isolated and isolated models. In the non-isolated model, Figure 5.20 indicates increased variations after 4 seconds, with a high peak and trough in base shear. For the isolated model, less variations and improved stability were observed. The isolation system is more effective in reducing shear force, indicating better performance for water storage tanks under earthquake force. Table 5.4 presents the outcomes of non-isolated and isolated tanks for the variables.

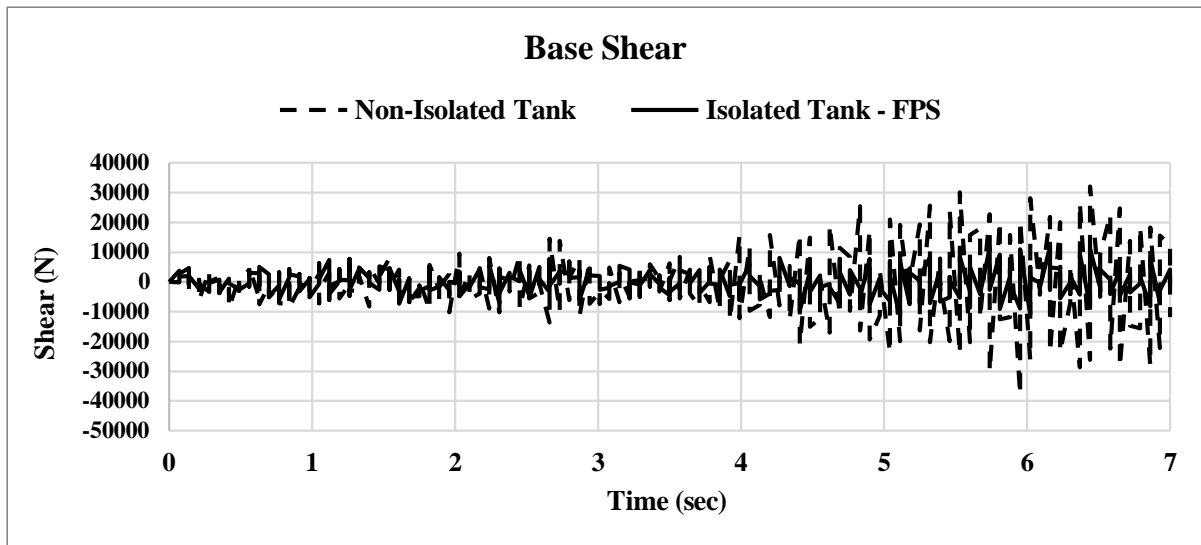


Figure 5.20: Base shear over time

Table 5.4: Outcomes of non-isolated and isolated tanks for variables

Variable	Non-Isolated	Isolated
Displacement of the tank (cm)	6.1	1.7
Hydrodynamic pressure (kPa)	4.351	1.212
Water Sloshing (cm)	13.2	5.3
Base Shear (kN)	32.11	11.85
Base Shear (kN) Experimental results	34.45	-

5.4 Chapter Summary

This chapter details the foundational development of the finite element method (FEM) for analysing the seismic behaviour of elevated water tanks, both with and without base isolation. The isolated model was simulated using Abaqus software, which captured the dynamic interaction between the water tank, supporting tower, and the friction pendulum system (FPS). The modelling procedure was systematically structured, beginning with the specification of material properties. Steel was selected for both the tank and tower, while an acoustic element was utilised to represent the water. Careful consideration was given to the geometry and mesh to ensure simulation accuracy. The FPS was incorporated by decoupling the base of the tower from the foundation and modelling it as a spring element.

Based on the results obtained, this study demonstrates the significant benefits of base isolation in enhancing the seismic performance of elevated steel water storage tanks. The isolation system decoupled the tank structure from ground motion, reducing the direct transmission of seismic force. The isolated tank shows a smoother distribution over time compared to the non-isolated tank. On displacement analysis in the isolated tank, a significant 72% reduction in horizontal maximum

Displacement was observed compared to the non-isolated tank with increased erratic displacement, which indicates potential collapse. In addition, the acoustic analysis of water in the isolated tank yielded less hydrodynamic pressure than in the non-isolated tank. The isolation system dampens the water movement and reduces the risk of wall buckling or tank failure, which represents a 72.14% decrease. This reduction demonstrates the efficiency of the isolation system in alleviating fluid-induced forces. The water sloshing pattern moved more smoothly in the isolated tank than in the non-isolated tank, indicating better control of water behaviour at 60% less during seismic events.

The effectiveness of the base shear in the isolation system reduces the earthquake force applied to the foundation. The base shear values of isolated tanks are lower and more stable, being 63% less than those of non-isolated tanks. This led to the isolation system significantly decreasing the lateral forces transmitted to the structure base. The outcomes highlight the importance of implementing base isolation systems in the seismic design of elevated steel water storage tanks and similar structures. The use of an isolation system significantly reduces the risk of structural failure or collapse caused by earthquake force, thereby ensuring the durability of water storage facilities.

This research utilised a 3D model simulation conducted with Abaqus FEA to acquire robust benefits of isolation systems. However, the study focuses on one type of isolation system. Experimental validation of the simulation outcomes is essential to strengthen the reliability of the results. Additionally, investigating the long-term performance of base isolation under repeated seismic loading would provide valuable insights. Comparative studies between the base isolation system (FPS) and another isolation technology, as well as analysis of the impact of soil conditions and wind loads, could further enhance understanding and application of seismic isolation systems.

CHAPTER SIX

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter presents a comprehensive summary of the research performed. It includes a restatement of the research objectives, a critical assessment of the literature, and a discussion of the significance of the findings. The literature review provided a solid understanding of the role of steel water storage tanks in various industries, including water supply systems, chemical storage, and nuclear power plant operations. This foundational knowledge enabled a focused analysis of the research problem and helped identify the gap addressed in this study. The findings offer valuable insights, leading to well-supported conclusions and recommendations that emphasise the importance of implementing base isolation systems to enhance the seismic resilience of steel water storage tanks.

6.2 Evaluation of the research aim, objectives, and outcomes

The research aim was to develop base isolation for elevated steel water storage tanks during an earthquake by separating vertical and horizontal loads, which results in a more stable structural system as well as minimising the forces and stresses the tank may bear to reduce the risk of structural damage, collapse, and liquid sloshing.

The base isolation simulation analysis was carefully applied to enable the actualisation of the research objectives through the use of Abaqus software to model the tank and its base isolation system. The simulation-based analysis was pioneered by adopting a qualitative approach to examine the efficiency of the base isolation technique in the seismic design of steel water storage tanks pertaining to the tank seismic response during earthquakes with or without base isolation.

The findings obtained from the application of the qualitative approach are summarised in this chapter into subsequent subsections.

6.2.1 Develop and validate a finite element model of elevated water tanks equipped with base isolation under earthquake motion

Concerning this objective, observation indicated that the dynamic behaviour of structures and the adoption of the base isolation technique enable a reliable and robust seismic design of a liquid tank. Further observation indicated that this technique increases the structure's period vibration, high vertical stiffness, and substantial damping, wherein FPS is considered more effective and does not depend on the mass of the structure during an earthquake or seismic activity. Based on this objective, findings demonstrated that isolation considerably decreases responses under far-field ground motions compared

to near-fault ground motions, which are obvious in tanks of different aspect ratios (Bagheri & Farajian, 2018). Further understanding indicated that this has a nominal influence on the sloshing displacement as impulsive displacement, structural base shear, and overturning moment tend to reduce with longer isolation periods or friction coefficients (Bagheri & Farajian, 2018). The study established that isolation periods of approximately 3 seconds decreased peak responses, which cultivates the need to augment the seismic design strategies required for the design of a robust liquid storage tank using FPS base isolation (Bagheri & Farajian, 2018). This essentiality is expected to improve their seismic resilience as well as contribute to the progress of engineering practices in this aspect.

On the other hand, a study on the use of VFPS in comparison with traditional FPS was conducted to ascertain the implementation efficiency of both techniques in designing robust liquid storage tanks by considering such parameters as dynamic behaviour of isolated tanks, changes in base shear, sloshing displacement, impulsive displacement, and isolator displacement (Panchal & Jangid, 2008). Additional findings showed that a substantial decrease in various response parameters of the base-isolated tank compared to an equivalent fixed-base tank occurs as a result of relating the liquid masses, such as convective mass, impulsive mass, and base mass, to the tank wall through the use of springs and dampers (Bagheri & Farajian, 2016). Ren (2023) also claimed that the use of FPS decreases the seismic forces caused by ground motions; that is, decreasing impulse displacement and base shear and increasing convective displacement.

To substantiate the research indications above, the findings derived from the analysis of the seismic displacement of elevated tanks, with and without base isolation and non-isolation, revealed that the impact of seismic forces was observed at the top of a non-isolated tank, while maximum reduction of displacement was exhibited by the isolated tank. These observations validate the claims that the isolation system is effective in improving the structural performance of a liquid tank. Therefore, FPS dampens oscillations and displacement by improving the resilience and performance of the isolated liquid tank. This demonstrated the ability of the isolator to absorb the seismic forces to decrease the risk of damage and tank behaviour.

6.2.2 Conduct an analysis of seismic response loads with and without FPS of the "SBS ST05" to evaluate the effectiveness of water motion under earthquake excitation

Based on this objective, this study established that isolation efficiencies of various isolation techniques could possibly be estimated with the support of analytical seismic response of isolated tanks. This technique adequately quantifies the effects of the significant parameterisation system of base isolation for the liquid storage tanks. Relevant literature was studied to substantiate the need to attain this particular objective, to quantify the efficiency of water motion from the parametric assessment of seismic response loads with and without FPS.

A study presented a parametric analysis conducted to ascertain the effect of critical system parameters on the efficiency of the seismic isolation, wherein a comparative assessment of both isolated and non-isolated tanks revealed a reduction in base shear caused by impulsive forces and rigid mass dynamics (Shrimali & Jangid, 2003). An additional study on parametric analysis established that the strength of isolation systems is proportional to the increased flexibility of the sliding systems to protect tanks (Shrimali & Jangid, 2002). Findings showed that the increase in flexibility of the sliding systems improves the strength of the isolation system of a liquid tank. The study provided some crucial system parameters (aspect ratio of the tank and period of the isolation systems) required to aid parametric analysis of the seismic response loads. In this case, observation indicated that FPS was substantially effective in limiting the seismic response loads that can affect the flow of water, but the use of the N-Z isolation system was more effective (Jadhav & Jangid, 2004).

Pertaining to this objective, the result of the acoustic analysis conducted showed that significant pressure variations along the tank walls during seismic excitation were detected. The pressure was caused by the impulsive and convective masses, which contributed to the stress and displacement of the tank. Findings revealed that unstable water movement was observed in the non-isolated model, which was due to significant pressure that caused more fluctuation. In the case of an isolated model, smoother variation and more stability were observed as a result of the isolator absorbing the seismic force. This controls pressure distribution and reduces structural movement by daunting the ineffective flow of water in the tank. Observations regarding water sloshing revealed that the non-isolated model exhibited more chaotic water movement, which can increase the risk of tank damage and/or water overflow. On the other hand, the isolated model indicated water sloshing reduction, which demonstrated stable water movement within the tank. Therefore, this substantiates the efficacy of the isolation system in decreasing the turbulence and sustaining consistent pressure behaviour.

6.2.3 Analyse the impact of sliding bearings on the seismic performance of steel water tanks.

The study provided clarity on the sliding bearings of the seismic isolation of steel water storage tanks as a decoupling mechanism that aids the reduction of the seismic forces transferred to the tanks (Rawat et al., 2015). From the study, sliding isolation techniques were observed as an efficient technique for seismic isolation, particularly during a severe earthquake situation. Sliding isolation techniques are known for their versatility to mitigate seismic effects, which makes them insensitive to the frequency of earthquakes and reduces superstructure acceleration as a result of the force acting on the tank during seismic events (Rawat et al., 2015). Sliding bearings have a significant impact on the impulsive dynamic pressure by fortifying the steel water storage tanks against seismic forces (Wang et al., 2001). This is achieved by separating the base and foundation of the structure, thereby reducing the influence of earthquake responses.

Findings obtained from the analysis of the sliding bearings (decoupling) of the seismic isolation of steel water storage demonstrated risk reduction of wall buckling or tank failure, better control of water behaviour, and stable base shear values. Based on this study, the impacts achieved by sliding bearings (decoupling) relating to seismic isolation of steel water storage are highlighted as follows:

- Smoother distribution over time—reducing the water sloshing effect,
- Isolation system's efficiency—alleviating fluid-induced forces, and
- Base share efficiency—reducing the earthquake force applied to the foundation.

These impacts demonstrate the significance of the isolation system in decreasing the lateral forces transmitted to the base of the structure, as well as promoting the importance of implementing this system in the seismic design of elevated steel water storage tanks and other related structures.

6.3 Conclusion

This study demonstrated, discussed, and validated the model developed through the simulation-based analysis of evaluating the impact of base isolation systems on the seismic behaviour an elevated water tank. The study questions and objectives were structured towards determining the appropriate design parameters for the development of the model. The study evaluated the efficient performance of the base isolation systems in validating the structural performance of the water storage tank during earthquakes. Abaqus software was applied to analyse data collected and simulate the tanks and their base isolation systems. The simulation analysis represented the seismic response of base isolation and liquid interaction by FPS during the earthquake by comparing the liquid interaction and base isolation response at different times and vibrations. The behaviour of the tanks was analysed and subject to several seismic excitations, including displacement, acceleration and stress.

The analysis yielded relevant findings that established the importance of applying FPS to mitigate the effect of seismic behaviour in an elevated water tank. A major decrease in displacement for isolated tanks was observed, with evidence of a 72% decrease in horizontal maximum displacement. Structural movement reduction, pressure distribution control, and water sloshing reduction were observed, with evidence of a 60% decrease in water behaviour. Also, a 72.14% decrease in wall buckling (tank failure) risk was observed along with a 63% decrease in bearing shear rates.

These findings established that the application of FPS in mitigating the effect of seismic behaviour in elevated water tanks is effective in enhancing both structural performance and integrity of the water tank. FPS also decreased tank behaviour, deterred tank damage pertaining to buckling and collapse of the tank walls and structural failure of the ground anchorage system. Other improvements accomplished by the use of FPS are as follows: smoother variation in water flow, stable water movement, and reduction in fluid-induced forces.

6.4 Contribution of this research

The main contribution of this research was the practical development of the model for the evaluation of the impact of the base isolation systems on the seismic behaviour in the elevated water tank. The study established simulation and modelling strategies that included various objectives of applying FPS and integrating several observations to understand and ascertain the theoretical interpretation of mitigating seismic forces affecting an elevated water tank. Applicable findings were determined from the combined studies to define the parameters for the model development.

Other main contributions were the application of Abaqus software, which involves the use of the ALE technique, to establish interaction between the model and the environment. The software created a simulation-based analysis to compute the seismic response of base isolation and liquid interaction by FPS during an earthquake. This was applied to establish a comparative study of liquid interaction in both isolated and non-isolated water tanks to validate the study objectives. The result derived from the application of Abaqus software revealed a similar pattern of behaviour compared to the results obtained from the experimental research.

This research has made a significant contribution to existing knowledge by presenting a simulation-based model that provides key parameters for evaluating the seismic response of base isolation and fluid–structure interaction using FPS during earthquake events. The model established positive essentials about the application of FPS as follows:

- Displacement and fluctuations were practically dampened in the simulation analysis; the resilience and performance of the isolated liquid tank were enhanced accordingly.
- The strength of isolation systems is relative to the increased flexibility of the sliding systems to protect tanks.
- Pressure-induced chaotic water movement in the liquid tank was dampened to avoid water overflow and tank damage.

6.5 Recommendations for future research

Studies on the application of base isolation systems in seismic design of steel water storage tanks are increasingly becoming a central point in Civil Engineering, especially in the South African water engineering industry. The findings of this study, which are outlined below, are the areas that could be explored to strengthen awareness of the application of FPS in mitigating the effect of seismic behaviour in elevated water tanks:

- Further research can be conducted through the experimental validation of the simulation results of the base isolation system in the seismic design of steel water storage to substantiate past studies.

- Future research can be initiated by investigating the long-term performance of base isolation under repeated seismic loading. This research initiative will offer constructive insights.
- Additional investigation can be carried out by considering comparative studies between FPS and another isolation technology, including the analysis of the impact of soil conditions and wind loads to enhance the understanding and application of seismic isolation systems.

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APPENDICES

Appendix A: Finite Element Model Report

Appendix A1: Introduction

In this report, two models of elevated steel water storage tanks with and without base isolation have been described. The modelling process began with data extracted from the original design drawings. Material properties and model specifications, including assembly details, loading conditions, and boundary constraints, were discussed in Chapter 5.

The following Figure 7.1 illustrates the drawing datasheet of the elevated steel water storage tanks.

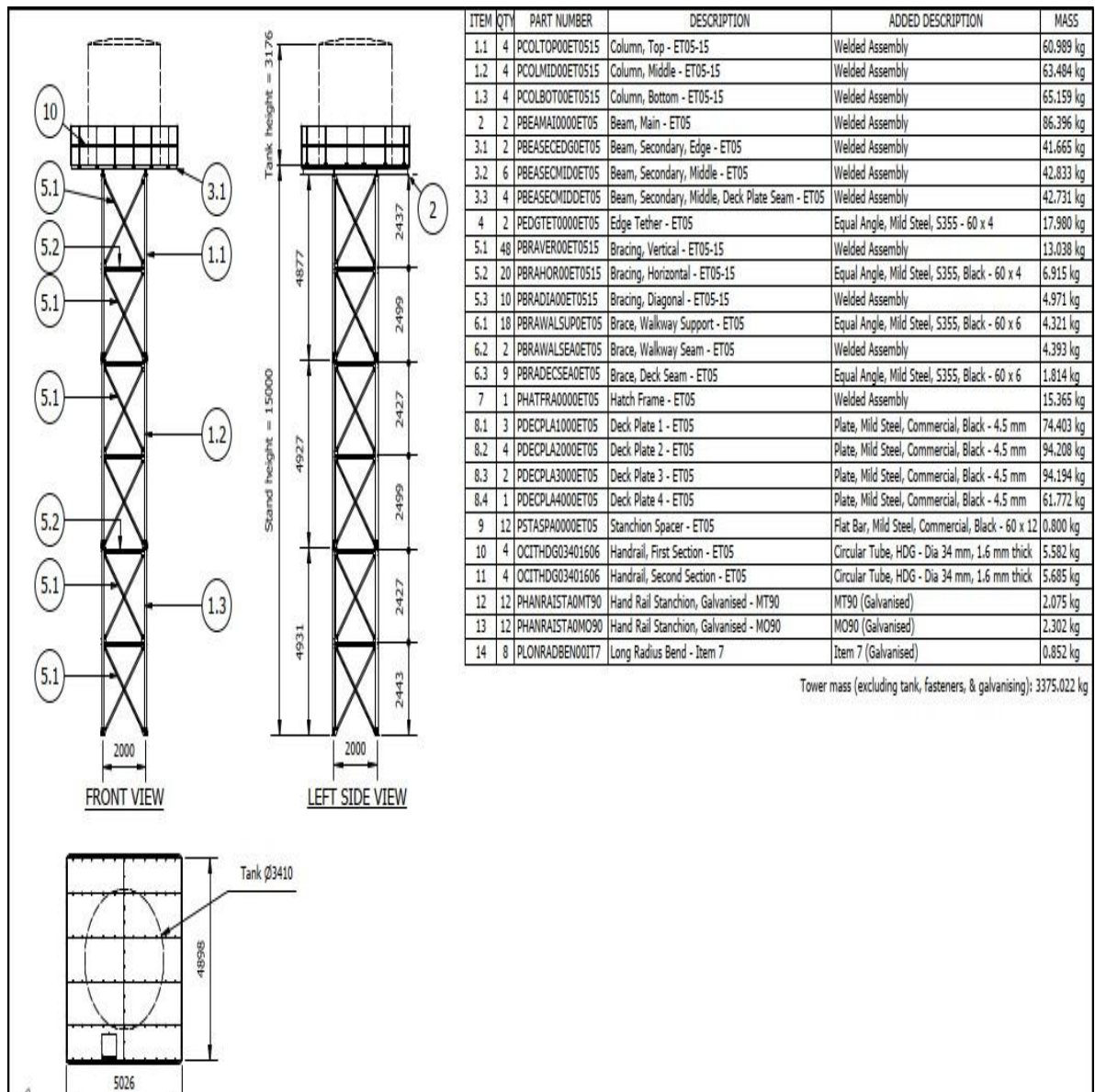


Figure 7.1: datasheet drawing of water tank provided via SBS Tanks

Appendix A2: Meshing Elements

In finite element analysis, meshing plays a crucial role in the modelling process. The mesh subdivides the geometry into smaller nodes, which directly influence the accuracy and computational efficiency of the simulation. The table below presents the number of nodes assigned to each element, as generated using Abaqus.

Table 7.1: Instance table

Instant name	# Nodes
Main beam	12
Ring beam	36
Secondary beam	11
Side beam	11
Steel plate	366
Tank	385
Tower	848
Water	5536
Wind girt	12
Foundation	4624
Bottom Plate	1922

Appendix A3: Summary

Water tanks are essential structures to store and maintain water, such as for water supply and industrial purposes. Several types of water tanks exist, such as elevated tanks, ground-level tanks, and underground tanks. This thesis describes the elevated steel water storage tank with and without base isolation using the FPS technique, developed by Abaqus software. The finite element model was analysed dynamically under a seismic load. The loads applied were pressure and gravity. Boundary conditions were applied to constrain the structure. The ET signal was applied for dynamic analysis to be compatible with ground acceleration from SANS 10160-4:2017. The results obtained from the analysis showed that the hydrodynamic pressure was decreased with the isolation system compared to the non-isolated. The displacement of the structure exhibited a significant 72% decrease.