

BASE SHEAR AND SLOSHING RESPONSE CONTROL IN BASE-ISOLATED LIQUID STORAGE TANKS

ARUNA RAWAT (NEE GUPTA)



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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by

ARUNA RAWAT (NEE GUPTA)

DEPARTMENT OF CIVIL ENGINEERING

submitted

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**Fondly dedicated to
my parents and family
for their endless love, support, and encouragement.**

CERTIFICATE

This is to certify that the thesis titled, “**BASE SHEAR AND SLOSHING RESPONSE CONTROL IN BASE-ISOLATED LIQUID STORAGE TANKS**” being submitted by **Ms. Aruna Rawat (nee Gupta)** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by her. She worked under our supervision for the submission of the thesis, which to our knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of this research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of our knowledge and belief.

Prof. Vasant A. Matsagar

(Professor)
Department of Civil Engineering,
Indian Institute of Technology (IIT) Delhi,
Hauz Khas, New Delhi - 110 016,
India.

Prof. A. K. Nagpal

(Retired Professor)
Department of Civil Engineering,
Indian Institute of Technology (IIT) Delhi,
Hauz Khas, New Delhi - 110 016,
India.

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Aruna Rawat

ABSTRACT

The liquid storage tanks are the lifeline structures used in any civil society as part of water supply facilities, fire-fighting systems in industries, and in nuclear reactors for storage of various types of liquids. In the earthquake-prone areas, it becomes necessary to prevent damages to the tank, to safeguard invaluable human lives and avoid economic losses. Therefore, in-depth study on the seismic behavior of liquid storage tanks is indispensable. Subsequently, finding improved solutions over the causes of failure of the tanks during earthquakes becomes important. For this, the base isolation technology has been extensively used to improve the seismic performance of the liquid storage tanks. From the past researches on the base-isolated tanks using the elastomeric and sliding systems, it has been observed that sloshing response is rather unaffected or increased due to the addition of the base isolation systems. Also, to the best of the knowledge of this author, so far no attempt has been made on studying the effectiveness of rolling base isolation system for seismic protection of the tanks. Hence, in the present study a new rolling base isolation system along with an added surface diaphragm (SD) floating on the free liquid surface is proposed to respectively control the base shear induced in the tank wall and sloshing response of the liquid contained in the ground-supported cylindrical tanks.

A new rolling base isolation system in oblate shape is devised and proposed herein, named the oblate spheroid base isolation (OSBI) system. The OSBI system has an elliptical shape in any of its vertical plane, thus having an additional advantage to restore back to its original position after an earthquake event. Hence, it does not require additional supplemental devices as needed by some of the conventional isolation systems. The detailed mathematical formulation, governing dynamical equations of motion, and energy formulation for the tank mounted on the OSBI system are derived and solved. The seismic response of the ground-supported cylindrical tank isolated using the OSBI system is investigated using mechanical lumped-mass model of the tank. The study is carried out for the relatively broad and slender tanks subjected to uni-directional harmonic excitations and bi-directional horizontal components of the earthquake ground motions.

Further, a three-dimensional (3-D) finite element (FE) analysis of the liquid storage tank mounted on the OSBI system along with the surface diaphragm (SD) is carried out. As analytical solution becomes intricate, especially analytical or closed-form solutions may become intractable, the finite element method (FEM) may be relied on for conducting seismic analysis of the tank mounted on the OSBI system along with the SD. For the FE-based

analyses of the liquid storage tanks initially, a mesh convergence study is performed using free vibration analysis of a thin circular cylindrical shell. In addition, the seismic analysis of the fixed-base ground-supported 3-D cylindrical tank is investigated using a coupled acoustic-structural (CAS) approach in the FEM. Here, rigid and flexible tanks of two different aspect ratios, broad and slender, are subjected to uni-directional, bi-directional, and tri-directional (tri-axial) components of earthquake ground motions are investigated. The dynamic responses obtained from the FE-based modeling and analyses are also compared with the conventional lumped-mass model of the tank available in the literature.

The efficacy of the SD was also studied by conducting a series of laboratory experiments on the 3-D non-isolated and base-isolated square liquid storage tanks. The tests were performed by varying the base excitation frequency, water level in the tank, and for different SD materials of varying thicknesses. Further, numerical study is also performed based on the CAS and the coupled Eulerian-Lagrangian (CEL) approaches in the FEM to model the coupled fluid-structure interaction (FSI) in the liquid storage tank. The experimental and numerical results are compared to study the performance of surface diaphragm in controlling the sloshing response of the liquid in then on-isolated and base-isolated tanks. Furthermore, the seismic responses of the 3-D rigid and flexible base-isolated tanks along with the SD are investigated using the CAS approach in the FEM. A parametric study of the 3-D base-isolated tank using the conventional isolation system is conducted to assess the efficacy of different base isolation system in dynamic response reduction. The parameters used in the parametric investigation include, rigid and flexible, broad and slender tanks, three different vibration period of isolation system, aspect ratio of the tank, and thicknesses of surface diaphragm.

Based on the abovementioned comprehensive experimental, numerical, and FE-based studies carried on the non-isolated and base-isolated liquid storage tanks using surface diaphragm (SD), finally, seismic analysis of the 3-D base-isolated tank mounted on the OSBI along with the SD is investigated using the CAS approach. By conducting the numerous studies, it is concluded that the invented and proposed new rolling base isolation system, OBSI is indeed effective in mitigating the seismic responses; whereas, the floating surface diaphragm is effective in controlling the sloshing response of the free liquid surface in the tank. Thereby, base shear and sloshing response control in base-isolated liquid storage tanks is achieved by respectively using the oblate spheroid base isolation (OSBI) system and the floating surface diaphragm.

सार

तरल (जल) भंडारण टैंक (टंकी) किसी भी नागरिक समाज में जल आपूर्ति सुविधाओं, उद्योगों में अग्निशमन प्रणाली, और विभिन्न प्रकार के तरल पदार्थों के भंडारण के लिए परमाणु रिएक्टरों के हिस्से के रूप में उपयोग की जाने वाली जीवनरेखा संरचनाएं हैं। भूकंप-प्रवण क्षेत्रों में, टैंक को नुकसान को रोकने, अमूल्य मानव जीवन की रक्षा और आर्थिक नुकसान से बचने के लिए आवश्यक हो जाता है। इसलिए, तरल भंडारण टैंक के भूकंपीय व्यवहार पर गहराई से अध्ययन अनिवार्य है। इसके बाद, भूकंप के दौरान टैंकों की विफलता (गिरावट) के कारणों में बेहतर समाधान ढूंढना महत्वपूर्ण हो जाता है। इसके लिए, तल (बेस) अलगाव (विलगता) प्रौद्योगिकी का व्यापक रूप से तरल भंडारण टैंक के भूकंपीय प्रदर्शन में सुधार के लिए उपयोग किया जाता है। इलास्टोमर और स्लाइडिंग (सरकन) प्रणाली (सिस्टम) का उपयोग कर आधार-पृथक टैंक पर पिछले शोध से, यह देखा गया है कि आधार अलगाव प्रणाली के अतिरिक्त के कारण प्रतिक्रिया बल्कि अप्रभावित या वृद्धि हुई है। इसके अलावा, इस लेखक के ज्ञान के सर्वोत्तम जानकारी से, टैंकों की भूकंपीय सुरक्षा के लिए रोलिंग (लुढ़कनी) आधार-पृथक प्रणाली की प्रभावशीलता का अध्ययन करने के लिए अब तक कोई प्रयास नहीं किया गया है। इसलिए, वर्तमान अध्ययन में एक नई रोलिंग आधार-पृथक प्रणाली मुक्त तरल सतह पर तैरते हुए एक अतिरिक्त सतह- (पटल) डायफ्राम (एसडी) के साथ क्रमशः टैंक दीवार में प्रेरित आधार कतरनी को नियंत्रित करने और जमीन में निहित तरल की स्लोशिंग (लहर) प्रतिक्रिया को नियंत्रित करने का प्रस्ताव है।

चपटा पटल/अंडाकार आकृति (ऑब्लेट) आकार में एक नया रोलिंग आधार-पृथक प्रणाली तैयार और प्रस्तावित किया गया है, जिसका नाम चपटा अंडाकार आकृति आधार-पृथक (ऑब्लेट स्फेराइड बेस आइसोलेशन) (ओएसबीआई) प्रणाली है। ओएसबीआई सिस्टम में इसके किसी लंबवत विमान में अंडाकार आकार होता है, इस प्रकार भूकंप की घटना के बाद अपनी मूल स्थिति में वापस बहाल करने के लिए एक अतिरिक्त लाभ होता है। इसलिए, इसे कुछ पारंपरिक अलगाव प्रणालियों द्वारा आवश्यक अतिरिक्त पूरक उपकरणों की आवश्यकता नहीं है। विस्तृत गणितीय सूत्रीकरण (फॉर्मूलेशन), गति के गतिशील समीकरणों को नियंत्रित करना, और ओएसबीआई सिस्टम पर लगाए गए टैंक के लिए ऊर्जा निर्माण तैयार किया गया है और हल किया गया है। ओएसबीआई सिस्टम का उपयोग करके पृथक जमीन-समर्थित बेलनाकार टैंक की भूकंपीय प्रतिक्रिया टैंक के यांत्रिक ढेला-भार (लम्पड-मास) प्रतिमान (मॉडल) का उपयोग करके जांच की जाती है। यह अध्ययन अपेक्षाकृत व्यापक और पतले टैंकों के लिए किया जाता है जो भूकंप के जमीन के गति (मोशन) के एक(यूनी)-दिशात्मक लयबद्ध (हार्मोनिक) उत्तेजनाओं और द्वि-दिशात्मक क्षैतिज घटकों के अधीन होते हैं।

इसके अलावा, तीन-आयामी (३-डी) के साथ ओएसबीआई प्रणाली (सिस्टम) पर लगाए गए तरल भंडारण टैंक तथा सतह-पटल डायफ्राम का त्रि-आयामी (३-डी) परिमित तत्व विश्लेषण (परिमित अव्यव विधि - एफई) किया है। चूंकि, विश्लेषणात्मक समाधान जटिल हो जाता है, विशेष रूप से विश्लेषणात्मक या बंद-प्रारूप (फॉर्म) समाधान अचूक हो सकते हैं, एसडी के साथ ओएसबीआई प्रणाली पर लगाए गए टैंक के भूकंपीय विश्लेषण के संचालन के लिए परिमित तत्व विधि (एफई)

पर भरोसा किया जा सकता है। शुरुआत में तरल भंडारण टैंक के एफई-आधारित विश्लेषणों के लिए, एक जाल अभिसरण अध्ययन एक पतली परिपत्र गोल (बेलनाकार/ सिलेंड्रिकल) खोल के मुक्त कंपन विश्लेषण का उपयोग करके किया है। इसके अलावा, स्थायी-तल (फिक्स्ड-बेस) जमीन (ग्राउंड)-समर्थित ३-डी बेलनाकार टैंक के भूकंपीय विश्लेषण की जांच एफई में एक युग्मित ध्वनिक-संरचनात्मक (सीएस) दृष्टिकोण का उपयोग किया है। यहां, दो अलग-अलग पहलू अनुपात, व्यापक और पतले के कठोर और लचीले टैंक, भूकंप ग्राउंड मोशन की यूनी-दिशात्मक, द्वि-दिशात्मक, और त्रि-दिशात्मक (त्रि-अक्षीय) घटकों के अधीन हैं। एफई-आधारित मॉडलिंग और विश्लेषण से प्राप्त गतिशील प्रतिक्रियाओं की तुलना साहित्य में उपलब्ध टैंक के पारंपरिक लम्प्ड-मास मॉडल से भी की है।

एसडी की प्रभावकारिता का अध्ययन ३-डी गैर-पृथक और आधार-पृथक वर्ग तरल भंडारण टैंक पर प्रयोगशाला प्रयोगों की एक श्रृंखला आयोजित करके किया गया। परीक्षण बेस उत्तेजना आवृत्ति, टैंक में पानी के स्तर, और विभिन्न मोटाई के विभिन्न एसडी सामग्री के लिए किया गया। इसके अलावा, तरल भंडारण टैंक में युग्मित द्रव-संरचना इंटरैक्शन (एफएसआई) का मॉडल करने के लिए सीएस और युग्मित यूलरियन-लैंग्रेगियन (सीईएल) दृष्टिकोण के आधार पर संख्यात्मक अध्ययन भी किया है। प्रयोगात्मक और संख्यात्मक परिणामों की तुलना सतह पर डायफ्राम के प्रदर्शन को अध्ययन करने के लिए तुलना की है, ताकि तरल की धीमी प्रतिक्रिया को अलग-अलग और आधार-पृथक टैंक में नियंत्रित किया जा सके। इसके अलावा, एसडी के साथ ३-डी कठोर और लचीला आधार-पृथक टैंकों के भूकंपीय प्रतिक्रियाओं को एफई में सीएस दृष्टिकोण का उपयोग करके जांच की है। गतिशील प्रतिक्रिया में कमी के विभिन्न बेस अलगाव प्रणाली की प्रभावकारिता का आकलन करने के लिए पारंपरिक अलगाव प्रणाली का उपयोग करके ३-डी आधार-पृथक टैंक का एक प्राचल (पैरामीट्रिक) अध्ययन आयोजित किया है। पैरामीट्रिक जांच में उपयोग किए गए पैरामीटर में कठोर और लचीला, व्यापक और पतला टैंक, अलगाव प्रणाली की तीन अलग कंपन अवधि, टैंक का पहलू अनुपात, और सतह डायफ्राम की मोटाई शामिल हैं।

सतही डायफ्राम (एसडी) का उपयोग करते हुए गैर-पृथक और आधार-पृथक तरल भंडारण टैंकों पर किए गए उपरोक्त व्यापक प्रयोगात्मक, संख्यात्मक, और एफई-आधारित स्टडीज के आधार पर, अंत में, ओएसबीआई पर लगाए गए ३-डी आधार-पृथक टैंक का भूकंपीय विश्लेषण एसडी के साथ सीएस दृष्टिकोण का उपयोग करके जांच की जाती है। कई अध्ययनों का संचालन करके, यह निष्कर्ष निकाला गया है कि आविष्कारित और प्रस्तावित नई रोलिंग आधार अलगाव प्रणाली, ओबीएसआई भूकंपीय टैंक प्रतिक्रियाओं को कम करने में वास्तव में प्रभावी है, जबकि, फ्लोटिंग सतह डायफ्राम मुक्त तरल सतह की चमकदार प्रतिक्रिया को नियंत्रित करने में प्रभावी है। इस प्रकार, आधार-पृथक तरल भंडारण टैंक में आधार कतरनी और लहर प्रतिक्रिया नियंत्रण क्रमशः ओब्लेट स्टेरॉयड बेस अलगाव (ओएसबीआई) प्रणाली और फ्लोटिंग सतह डायफ्राम का उपयोग करके हासिल किया है।

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE NO.
	Abstract	iv
	l kj	vi
	Table of Contents	viii
	List of Figures	xiii
	List of Tables	xxix
	Mathematical Notations	xxxiii
	Abbreviations	xliii
CHAPTER-1	Introduction	
1.1	General Introductory Remarks	1
1.2	Liquid Storage Tanks	1
1.2.1	<i>Failures in liquid storage tanks due to earthquakes</i>	2
1.3	Motivation of the Present Study	5
1.4	Scopes of the Present Study	6
1.5	Organization of the Thesis Report	8
CHAPTER-2	Literature Review	
2.1	General	15
2.2	Previous Research on Dynamic Behavior of Tanks	15
2.3	Modern Aseismic Techniques	20
	2.3.1 <i>Elastomeric system</i>	22
	2.3.2 <i>Sliding system</i>	23
	2.3.3 <i>Rolling system</i>	28
2.4	Base Isolation System for Liquid Storage Tanks	32
2.5	Sloshing in Liquid Storage Tanks	35
	2.5.1 <i>Sloshing control devices</i>	37
2.6	Need and Relevance of the Present Study	38
2.7	Closure	39
CHAPTER-3	Seismic Analysis of Cylindrical Liquid Storage Tank using Oblate Spheroid Base Isolation (OSBI) System	
3.1	General	51
3.2	New Rolling Base Isolation System	55
	3.2.1 <i>Working principle</i>	57
	3.2.2 <i>Force-deformation relationship of OSBI system</i>	57
3.3	Modeling of Liquid Storage Tank Mounted on OSBI System	63
3.4	Governing Dynamic Equations of Motion	64
	3.4.1 <i>Time integration scheme</i>	66
	3.4.2 <i>Conditions for rolling/ non-rolling phase</i>	67
	3.4.3 <i>Energy formulation of tank mounted on OSBI system</i>	67
3.5	Numerical Study	69

CHAPTER	TITLE	PAGE NO.
	3.5.1 <i>Seismic responses of tanks mounted on OSBI system subjected to harmonic ground motions</i>	70
	3.5.2 <i>Seismic responses of tanks mounted on OSBI system subjected to bi-directional earthquake ground motions</i>	72
	3.5.2.1 <i>Input energy and recoverable energy</i>	74
	3.5.2.2 <i>Influence of coefficient of friction</i>	75
	3.5.2.3 <i>Effect of aspect ratio of tank</i>	75
	3.5.2.4 <i>Effectiveness of base-isolation in liquid storage tanks</i>	75
3.6	First and Second Derivatives of the above Equations	76
3.7	Closure	77
CHAPTER-4	Free Vibration Analysis of Thin Circular Cylindrical Shell Using Finite Element Method	
4.1	General	101
4.2	Finite Element (FE) Modeling of Cylindrical Shell	101
4.3	Numerical Study and Discussions	109
	4.3.1 <i>Iteration method</i>	109
	4.3.2 <i>Mesh convergence study</i>	110
	4.3.3 <i>Geometric and boundary conditions study</i>	111
4.4	Effect of Different Closures on the Modal Frequency of Circular Cylindrical Shell	112
4.5	Closure	116
CHAPTER-5	Seismic Analysis of Fixed-Base Cylindrical Liquid Storage Tank using Finite Element Method	
5.1	General	138
5.2	Seismic Analysis of Fixed-Base Cylindrical Liquid Storage Tank	138
5.2.1	Governing Equations of Motion of Liquid Storage Tank	141
5.3	Modeling of Liquid Storage Tank	142
	5.3.1 <i>Mechanical lumped mass/analytical model of the tank</i>	142
	5.3.2 <i>Finite element modeling of the tank</i>	143
5.4	Validation of the Finite Element Model	145
5.5	Numerical Study	147
	5.5.1 <i>Response to harmonic ground motions</i>	147
	5.5.2 <i>Response to bi-directional components of earthquake ground motions</i>	148
	5.5.3 <i>Response to tri-directional components of earthquake ground motions</i>	150
5.6	Closure	151
CHAPTER-6	Earthquake-Induced Sloshing in Tanks using Hydrocodes	

CHAPTER	TITLE	PAGE NO.
6.1	General	180
6.2	Review of the Coupled Acoustic-Structure (CAS)and Coupled Euler-Lagrange (CEL) Approaches	180
6.3	Finite Element (FE) Modeling Approaches	183
	6.3.1 <i>Coupled acoustic-structure (CAS)approach</i>	183
	6.3.2 <i>Coupled Eulerian-Lagrangian(CEL)approach</i>	184
6.4	Analytical Approach	187
6.5	Verification of the Hydrocodes	188
6.6	Numerical Study	191
6.7	Closure	194
CHAPTER-7	Sloshing Response Control in Tank using Surface Diaphragm: Experimental and Numerical Studies	
7.1	General	210
7.2	Sloshing Response Control in Tank using Surface Diaphragm	210
7.3	Mathematical Formulation	213
7.4	Experimental Study in Laboratory	213
7.5	Finite Element (FE)-based Numerical Study	216
	7.5.1 <i>Coupled acoustic-structural (CAS) approach</i>	216
	7.5.2 <i>Coupled Eulerian-Lagrangian (CEL) approach</i>	218
	7.5.3 <i>FE modeling base isolator</i>	219
7.6	Sloshing Displacement by Wave Gauge and Image Processing Technique	220
7.7	Non-Isolated Tank With and Without Surface Diaphragm	220
	7.7.1 <i>Effect of liquid height</i>	221
	7.7.2 <i>Effect of excitation frequency</i>	221
	7.7.3 <i>Effect of thickness of surface diaphragm</i>	222
7.8	Base-Isolated Tank With and Without Surface Diaphragm	223
7.9	Closure	225
CHAPTER-8	Numerical Study of Base-Isolated Cylindrical Liquid Storage Tanks	
8.1	General	244
8.2	Base-Isolated Liquid Storage Tank	244
8.3	Mechanical Lumped-Mass Model of Base-Isolated Tank	246
	8.3.1 <i>Mechanical two lumped-mass model of rigid base-isolated tank</i>	246
	8.3.2 <i>Mechanical three lumped-mass model of flexible base-isolated tank</i>	247
	8.3.3 <i>Modeling of base isolation systems</i>	249
	8.3.4 <i>Equations of motion for base-isolated liquid storage tank</i>	252
	8.3.5 <i>Mechanical lumped-mass FE model of base- isolated tank</i>	253

CHAPTER	TITLE	PAGE NO.
8.4	Numerical Study of Mechanical Lumped-mass FE model	253
8.5	Finite Element Formulation of Base-Isolated Tank	254
	8.5.1 <i>Boundary conditions</i>	254
	8.5.2 <i>Coupled acoustic-structural (CAS) equations of motion</i>	255
8.6	Three-Dimensional Modeling of Base-Isolated Liquid Storage Tank	259
	8.6.1 <i>Finite element (FE) modeling of the tank</i>	260
	8.6.2 <i>Analysis procedure</i>	261
8.7	Numerical Study of 3-D Base-Isolated Tank	262
	8.7.1 <i>Sloshing displacement</i>	263
	8.7.2 <i>Base shear</i>	264
	8.7.3 <i>Hydrodynamic pressure</i>	265
8.8	Sloshing Response Control of Base-Isolated using Surface Diaphragm	266
8.9	Closure	267
CHAPTER-9	An Oblate Spheroid Base Isolator and Floating Surface Diaphragm for Seismic Protection of Liquid Storage Tank	
9.1	General	299
9.2	Rolling Mechanism-Based Base Isolation System	303
	9.2.1 <i>Working principle of OSBI system</i>	304
	9.2.2 <i>Force-deformation relationship of OSBI system</i>	305
9.3	Finite Element Formulation	308
	9.3.1 <i>Boundary conditions</i>	308
	9.3.2 <i>Coupled acoustic-structural (CAS) equations of motion</i>	309
	9.3.3 <i>Equations of motion for base-isolated tank</i>	313
9.4	Modeling of Liquid Storage Tank	314
	9.4.1 <i>FE modeling of base-isolated tank</i>	314
	9.4.2 <i>Mechanical mass model of the tank</i>	316
9.5	Numerical Study	318
	9.5.1 <i>Uni-directional harmonic excitation</i>	320
	9.5.2 <i>Uni-directional earthquake excitation</i>	322
	9.5.3 <i>Tri-directional earthquake excitation</i>	324
9.6	Closure	326
CHAPTER-10	Summary and Conclusions	
10.1	Summary	345
10.2	Conclusions	346
10.3	Future Scope of Work	350
	References	351
APPENDIX-A	Validations of Base Isolation System	
A1	Introduction	384

CHAPTER	TITLE	PAGE NO.
A2	Elastomeric Base Isolation System	384
	A2.1 <i>Mathematical formulation</i>	384
	A2.2 <i>Validation of elastomeric system</i>	387
A3	Sliding Base Isolation System	388
	A3.1 <i>Mathematical formulation</i>	388
	A3.2 <i>Validation of sliding system</i>	390
A4	Rolling Base Isolation System	391
	A4.1 <i>Circular rolling isolation system</i>	391
APPENDIX-B	Elliptical Rolling Rod (ERR) Base Isolation System	
B1	Introduction	409
B2	Modeling of Base-Isolated Dynamical System Mounted on ERR	411
B3	Kinematics of an ERR Base Isolation System	411
B4	Dynamical Equations of Motion for the ERR System	413
	B4.1 <i>Dynamical equations of motion</i>	415
	B4.2 <i>Integration of equations of motion</i>	418
	B4.3 <i>Conditions for rolling/ non-rolling phase</i>	418
B5	Validation of the Present Study	419
B6	Numerical Study	419
B7	Closure	425
APPENDIX-C	Liquid Storage Tank Response Validations	
C1	Introduction	435
C2	Validation 1: Base-Isolated Tank using Elastomeric Bearing	435
C3	Validation 2: Base-Isolated Tank using Sliding System	436
C4	Validation 3: Sloshing Response	436
C5	Validation 4: Impulsive Hydrodynamic Pressure	437
C6	Validation 5: Sloshing in Tank with Floating Roof	437
APPENDIX-D	Characters of Earthquakes Used	
D1	Time History of Earthquakes	445
	D1.1 <i>Response spectra of earthquakes</i>	445
D2	Time History of Near-Fault Earthquakes	445
	D2.1 <i>Response spectra of near-fault earthquakes</i>	445
	List of Publications	450
	Bio-Data	453

LIST OF FIGURES

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure 1.1:	Classification of liquid storage tank (Mirzabozorg et al. 2012)	10
Figure 1.2:	Fluid-structure interaction (FSI) in liquid storage tank	10
Figure 1.3:	Failure modes in tanks due to earthquakes	12
Figure 1.4:	Base-isolated tanks (earthquakeprotection.com)	13
Figure 1.5:	Objectives flowchart of the present work	14
Figure 2.1:	Various vibration control systems	41
Figure 2.2:	Laminated rubber bearing (LRB)	41
Figure 2.3:	New-Zealand (N-Z) base isolation system	42
Figure 2.4:	Pure-friction system	43
Figure 2.5:	Resilient-friction base isolation (R-FBI) system	44
Figure 2.6:	Electricite de France (EDF) base isolation system	45
Figure 2.7:	Sliding resilient-friction isolation system	45
Figure 2.8:	Friction pendulum system	46
Figure 2.9:	Double concave friction pendulum (DCFP) system Fenz and Constantinou (2006)	47
Figure 2.10:	Variable curvature friction pendulum system (VCFPS) Tsai et al. (2003)	48
Figure 2.11:	Double variable frequency pendulum isolator (DVFPI) system (Soni et al. 2011a)	48
Figure 2.12:	Circular rolling rods isolation system (Lin 1993, Jangid 1995)	48
Figure 2.13:	Rolling ball rubber isolator (Muhr 1997)	49
Figure 2.14:	Elliptical rolling rods isolation system (Londhe and Jangid 1998)	49
Figure 2.15:	Balls placed in concave sliding surface (Zhou et al. 1998)	49
Figure 2.16:	Sloped rolling-type bearing (RTB) (Lee and Liang 2003, Tsai et al. 2006)	50
Figure 2.17:	Rolling isolators by frictionless pins (Chung et al. 2009)	50

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure 2.18:	Ball-n-cone (BNC) bearing (Kesti et al. 2010)	50
Figure 3.1:	Geometry and degrees-of-freedom of OSBI system (in x -plane)	83
Figure 3.2(a):	Free-body diagram of forces acting on the OSBI system (x - z plane)	83
Figure 3.2(b):	Force-deformation diagram of OSBI system for different eccentricity values	84
Figure 3.2(c):	Schematics of exploded views of OSBI system	84
Figure 3.3:	Mechanical lumped mass model of flexible cylindrical tanks with OSBI system	85
Figure 3.4:	Flowchart showing working principle of OSBI system for tanks	86
Figure 3.5:	Relationship between rotation angle and base displacement in the OSBI ($r_x = 0.2$ m)	87
Figure 3.6:	Time history of the base shear, sloshing displacement, impulsive displacement, and base displacement of broad tank isolated with OSBI ($\mu = 0.01$) and P-F system ($\mu = 0.01$) subjected to sinusoidal excitation ($PGA = 0.45g$)	88
Figure 3.7:	Time history of the base shear, sloshing displacement, impulsive displacement, and base displacement of slender tank isolated with OSBI ($\mu = 0.01$) and P-F system ($\mu = 0.01$) subjected to sinusoidal excitation ($PGA = 0.45g$)	89
Figure 3.8:	Variation of base shear, sloshing displacement, impulsive displacement, and base displacement of broad tank isolated with OSBI ($\mu = 0.01$) and P-F system ($\mu = 0.01$) for various values of PGA	90
Figure 3.9:	Variation of base shear, sloshing displacement, impulsive displacement, and base displacement of slender tank isolated with OSBI ($\mu = 0.01$) and P-F system ($\mu = 0.01$) for various values of PGA	91
Figure 3.10:	Time history of the base shear, sloshing displacement,	92

FIGURE	FIGURE CAPTIONS	PAGE NO.
	impulsive displacement, and base displacement of broad tank isolated with OSBI ($e = 0.5$, $\mu = 0.01$) subjected to Imperial Valley 1940 earthquake along x -axis	
Figure 3.11:	Time history of the base shear, sloshing displacement, impulsive displacement, and base displacement of broad tank isolated with OSBI ($e = 0.5$, $\mu = 0.01$) subjected to Imperial Valley 1940 earthquake along y -axis	93
Figure 3.12:	Time history of the base shear, sloshing displacement, impulsive displacement, and base displacement of slender tank isolated with OSBI ($e = 0.5$, $\mu = 0.01$) subjected to Imperial Valley 1940 earthquake along x -axis	94
Figure 3.13:	Time history of the base shear, sloshing displacement, impulsive displacement, and base displacement of slender tank isolated with OSBI ($e = 0.5$, $\mu = 0.01$) subjected to Imperial Valley 1940 earthquake along y -axis	95
Figure 3.14:	Variation of the normalized base shear (V_b/W) and convective (sloshing) displacement (x_c) with respect to coefficient of rolling friction (μ_r) and eccentricity (e) of the OSBI	96
Figure 3.15:	Time history of E_{input} and E_{rec} for broad and slender tanks subjected to Imperial Valley, 1940 earthquake	97
Figure 3.16:	Variation of the V_b/W , R_c , R_i , R_b , E_{input} , and E_{rec} with coefficient of rolling friction of the broad tank subjected to bi-directional components of different earthquakes ($e = 0.5$)	98
Figure 3.17:	Variation of the V_b/W , R_c , R_i , R_b , E_{input} , and E_{rec} with coefficient of rolling friction of the slender tank subjected to bi-directional components of different earthquakes ($e = 0.5$)	99
Figure 3.18:	Variation of the V_b/W , R_c , R_i , R_b , E_{input} , and E_{rec} with aspect ratio of tank subjected to bi-directional	100

FIGURE	FIGURE CAPTIONS	PAGE NO.
	components of different earthquakes ($e = 0.5$, $\mu = 0.01$)	
Figure 4.1:	(a) Co-ordinate system, (b) circumferential and (c) axial and radial modes of circular cylindrical shell	129
Figure 4.2:	Accuracy of the present FE model	129
Figure 4.3:	Comparison between block Lanczos and subspace iteration methods for shell with C-C boundary condition	130
Figure 4.4:	Mesh convergence study of shell for $H/R = 2, 10, 15$, and 20	130
Figure 4.5:	Modal frequencies for C-C shell ($m = 1$) (a) for different h/R ratios, $H/R = 2$, (b) for different h/R ratios, $H/R = 10$, (c) for different h/R ratios, $H/R = 20$, (d) for different H/R ratios for $h/R = 1/10$, and (e) for different h/R ratios for $H/R = 2$ and 10 (1, 3), (1, 7)	131
Figure 4.6:	Modal frequencies for C-F shell ($m = 1$) (a) for different h/R ratios, $H/R = 2$, (b) for different h/R ratios, $H/R = 10$, (c) for different h/R ratios, $H/R = 20$, (d) for different H/R ratios for $h/R = 1/10$, and (e) for different h/R ratios for $H/R = 2$ and 10 (1, 3), (1, 7)	132
Figure 4.7:	Comparison of modal frequencies for C-C and C-F shell for $H/R = 2$ and for $h/R = 1/50, 1/100$, and $1/200$	133
Figure 4.8:	Modal frequencies for S-S shell ($m = 1$) (a) for different h/R ratios, $H/R = 2$, (b) for different h/R ratios, $H/R = 10$, (c) for different h/R ratios, $H/R = 20$, (d) for different H/R ratios for $h/R = 1/10$, and (e) for different h/R ratios for $H/R = 2$ and 10 (1,3), (1,7)	134
Figure 4.9:	Cylindrical steel tanks with different types of roof (Virella et al. 2003). $H = 19.337$ m, 12.191 m, 7.257 m, $h_1 = 2.425$ m, $h_2 = 2.416$ m, $h_3 = 2.858$ m, $t_1 = 0.0127$ m, $t_2 = 0.0095$ m, $t_3 = 0.0079$ m, $t_4 = 0.0127$ m	135
Figure 4.10:	Circular cylindrical shell with different type of closures	135
Figure 4.11:	Modal frequencies in cylindrical shell with closures for	136

FIGURE	FIGURE CAPTIONS	PAGE NO.
	$H/R = 0.6$ (a) $h_r/h = 1$ for open, flat, cone, and dome closures, (b) flat closure, (c) cone closure, and (d) dome closure ($h_r/h = 0.5, 1.0, 1.5$, and 2.0)	
Figure 4.12:	Modal frequencies in cylindrical shell with closures for $H/R = 1.85$ (a) $h_r/h = 1$ for open, flat, cone, and dome closures, (b) flat closure, (c) cone closure, and (d) dome closure ($h_r/h = 0.5, 1.0, 1.5$, and 2.0)	137
Figure 4.13:	Fundamental frequency in cylindrical shell with closures for $H/R = 0.6$ and 1.85	137
Figure 5.1:	Lumped mass model for (a) rigid and (b) flexible cylindrical fixed-base tanks	164
Figure 5.2:	Coupled acoustic-structure FE model of 3-D cylindrical liquid storage tank	165
Figure 5.3:	Hydrodynamic impulsive pressure distribution and time history at $r = R, z = 0$ in broad and slender rigid tanks subjected to Kobe, 1995 earthquake	166
Figure 5.4:	Sloshing displacement response in cylindrical tank	167
Figure 5.5:	Sloshing response in broad and slender flexible cylindrical tank subjected to harmonic ground motions	168
Figure 5.6:	Effect of amplitude and excitation frequency of harmonic motion on rigid and flexible tanks (dotted line for FE model and solid line for lumped mass model)	169
Figure 5.7:	Sloshing displacement response in x-axis ($\theta = 0^\circ$) and y-axis ($\theta = 90^\circ$) in broad and slender flexible tanks under bi-directional components of earthquakes	170
Figure 5.8:	Impulsive and convective base shear time history responses in x- axis ($\theta = 0^\circ$) and y- axis ($\theta = 90^\circ$) in broad tank subjected to bi-directional components of earthquakes	171
Figure 5.9:	Impulsive and convective base shear time history responses in x- axis ($\theta = 0^\circ$) and y- axis ($\theta = 90^\circ$) in	172

FIGURE	FIGURE CAPTIONS	PAGE NO.
	slender tank subjected to bi-directional components of earthquakes	
Figure 5.10:	Hydrodynamic impulsive pressures in broad and slender tanks subjected to bi-directional components of earthquakes using FE model	173
Figure 5.11:	Sloshing displacement time history response in x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) of broad tank under bi-directional horizontal and tri-directional components of earthquakes	174
Figure 5.12:	Sloshing displacement time history response in x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) of slender tank under bi-directional horizontal and tri-directional components of earthquakes	175
Figure 5.13:	Time history response of impulsive and convective components of base shear in x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) of broad tank under tri-directional components of earthquakes	176
Figure 5.14:	Time history response of impulsive and convective components of base shear in x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) of slender tank under tri-directional components of earthquakes	177
Figure 5.15:	Peak response of impulsive and convective base shear components in broad and slender cylindrical tanks	178
Figure 5.16:	Absolute peak hydrodynamic impulsive pressure in broad and slender tanks	179
Figure 6.1:	Cylindrical and rectangular liquid storage tanks	200
Figure 6.2:	FE analysis procedure for coupled acoustic-structure (CAS) approach	201
Figure 6.3:	Coupled acoustic-structure (CAS) approach of modeling cylindrical and rectangular liquid storage tanks (H_L/R and $H_L/L = 0.6$)	201

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure 6.4:	FE analysis procedure for Coupled Eulerian-Lagrangian (CEL) approach	202
Figure 6.5:	The fraction of fluid (f) in each Eulerian element	202
Figure 6.6:	Coupled Eulerian-Lagrangian (CEL) approach of modeling cylindrical and rectangular liquid storage tanks (H_L/R and $H_L/L = 0.6$)	202
Figure 6.7:	Sloshing displacement time-history responses of the cylindrical tank subjected to harmonic motions (a) non-resonant frequency, $\omega_f = 5.16$ rad/sec and (b) resonant frequency, $\omega_f = 5.74$ rad/sec	203
Figure 6.8:	Sloshing displacement time-history responses of the rectangular tank subjected to harmonic motions (a) non-resonant frequency, $\omega_f = 3.41$ rad/sec and (b) resonant frequency, $\omega_f = 3.79$ rad/sec	204
Figure 6.9:	Response spectra of earthquake ground motions used in this study	205
Figure 6.10:	Sloshing displacement time-history responses of the cylindrical tank subjected to earthquake ground motions	205
Figure 6.11:	Sloshing displacement time-history responses of the rectangular tank subjected to earthquake ground motions	206
Figure 6.12:	Normalized impulsive and convective components of hydrodynamic pressure in cylindrical tank	207
Figure 6.13:	Normalized impulsive and convective components of hydrodynamic pressure in rectangular tank	207
Figure 6.14:	Normalized total hydrodynamic pressure in cylindrical tank	208
Figure 6.15:	Normalized total hydrodynamic pressure in rectangular tank	208
Figure 6.16:	Sloshing and total hydrodynamic pressure in cylindrical tank	209
Figure 7.1:	Base-isolated square tank	230

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure 7.2:	Experimental setup for liquid storage under base excitation	231
Figure 7.3:	Schematic diagram of the experimental setup	231
Figure 7.4:	Steps involved in image processing technique	232
Figure 7.5:	Schematic diagrams of the LRB	232
Figure 7.6:	Finite element (FE) models	233
Figure 7.7:	Comparison of sloshing displacement without surface diaphragm using image processing and wave gauge for non-isolated tank	234
Figure 7.8:	Sloshing displacement without surface diaphragm by experimental and numerical approaches at excitation frequency 0.7 Hz for non-isolated tank	235
Figure 7.9:	Sloshing displacement without surface diaphragm by experimental and numerical approaches for liquid height 300 mm for non-isolated tank	236
Figure 7.10:	Sloshing displacement without surface diaphragm by experimental and numerical approaches for liquid height 400 mm for non-isolated tank	237
Figure 7.11:	Experimental results of sloshing displacement with PU surface diaphragm for liquid height 300 mm under the excitation frequency 0.7 Hz for non-isolated tank	237
Figure 7.12:	Effect of thickness of EPS surface diaphragm on the sloshing displacement along the length for non-isolated tank	238
Figure 7.13:	Sloshing displacement without surface diaphragm by experimental and numerical approaches at excitation frequency 0.7 Hz for LRB36 base-isolated tank	239
Figure 7.14:	Sloshing displacement without surface diaphragm by experimental and numerical approaches at excitation frequency 0.7 Hz for LRB78 base-isolated tank	240
Figure 7.15:	Experimental results of sloshing displacement with PU	241

FIGURE	FIGURE CAPTIONS	PAGE NO.
	surface diaphragm for liquid height 300 mm for LRB36base-isolated tank	
Figure 7.16:	Experimental results of sloshing displacement with EPS surface diaphragm for liquid height 400 mm for LRB36 base-isolated tank	241
Figure 7.17:	Peak sloshing displacement by experimental and numerical approaches for LRB36 base-isolated tank	242
Figure 7.18:	Experimental results of sloshing displacement with PU surface diaphragm for liquid height 400 mm for LRB78 base-isolated tank	242
Figure 7.19:	Peak sloshing displacement by experimental and numerical approaches for LRB78 base-isolated tank	243
Figure 8.1:	Mechanical lumped-mass idealization of base-isolated tanks	276
Figure 8.2:	Mechanical lumped-mass FE models of non-isolated and base-isolated tanks	276
Figure 8.3:	Time history responses of base-isolated flexible broad tank by FPS using mechanical three lumped-mass and FE lumped-mass models	277
Figure 8.4:	Time history response of base-isolated flexible slender tank by FPS using three lumped-mass and Abaqus spring-mass models	278
Figure 8.5:	Schematic diagram of coupled acoustic-structural (CAS) approach	278
Figure 8.6:	Coupled acoustic-structure (CAS) finite element (FE) model of cylindrical liquid storage tank	279
Figure 8.7:	Time history responses of sloshing displacement in base-isolated rigid broad tank by LRB using 3-D FE model subjected to bi-directional components of earthquakes	280
Figure 8.8:	Time history responses of sloshing displacement in base-isolated rigid slender tank by LRB using 3-D FE model	281

FIGURE	FIGURE CAPTIONS	PAGE NO.
	subjected to bi-directional components of earthquake	
Figure 8.9:	Time history responses of sloshing displacement in base-isolated flexible broad tank by FPS using 3-D FE model	282
	subjected to bi-directional components of earthquake	
Figure 8.10:	Time history responses of sloshing displacement in base-isolated flexible slender tank by FPS using 3-D FE model	283
	subjected to bi-directional components of earthquake	
Figure 8.11:	Sloshing displacement for rigid and flexible, broad tanks using 3-D FE model	284
Figure 8.12:	Sloshing displacement for rigid and flexible, slender tanks using 3-D FE model	284
Figure 8.13:	Time history responses of impulsive and convective base shear for Type B base-isolated rigid and flexible broad tanks by LRB using 3-D FE model	285
Figure 8.14:	Time history responses of impulsive and convective base shear for Type B base-isolated rigid and flexible slender tanks by LRB using 3-D FE model	286
Figure 8.15:	Time history responses of impulsive and convective base shear for Type B base-isolated rigid and flexible broad tanks by FPS using 3-D FE model	287
Figure 8.16:	Time history responses of impulsive and convective base shear for Type B base-isolated slender rigid and flexible tanks by FPS using 3-D FE model	288
Figure 8.17:	Convective base shear for rigid and flexible broad tanks using 3-D FE model	289
Figure 8.18:	Convective base shear for rigid and flexible slender tanks using 3-D FE model	289
Figure 8.19:	Impulsive base shear for rigid and flexible broad tanks using 3-D FE model	290
Figure 8.20:	Impulsive base shear for rigid and flexible slender tanks using 3-D FE model	290

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure 8.21:	Hydrodynamic impulsive pressure for base-isolated rigid and flexible broad tanks by LRB using 3-D FE model	291
Figure 8.22:	Hydrodynamic impulsive pressure for base-isolated rigid and flexible broad tanks by FPS using 3-D FE model	292
Figure 8.23:	Hydrodynamic impulsive pressure for base-isolated rigid and flexible slender tanks by LRB using 3-D FE model	293
Figure 8.24:	Hydrodynamic impulsive pressure for base-isolated rigid and flexible slender tanks by FPS using 3-D FE model	294
Figure 8.25:	Base-isolated liquid storage tank along with the surface diaphragm	295
Figure 8.26:	FE model of surface diaphragm for 3-D cylindrical liquid storage tank	295
Figure 8.27:	Time variation of the sloshing in base-isolated broad tank by LRB along with surface diaphragm subjected to bi-directional components of earthquakes	296
Figure 8.28:	Time variation of the sloshing in base-isolated slender tank by LRB along with surface diaphragm subjected to bi-directional components of earthquakes	297
Figure 8.29:	Peak sloshing displacement in non-isolated and base-isolated tank subjected to bi-directional components of earthquakes (IMV: Imperial Valley, 1940, NR: Northridge, 1994, and KBE: Kobe, 1995)	298
Figure 9.1:	Geometry and degrees-of-freedom of OSBI system (in x - z plane)	332
Figure 9.2(a):	Free-body diagram of forces acting on the OSBI system (x - z plane)	333
Figure 9.2(b):	Force-deformation diagram of OSBI system for different eccentricity values	333
Figure 9.3:	Schematic diagram of coupled acoustic-structural (CAS) approach	334
Figure 9.4:	Finite element model of base-isolated broad and slender	334

FIGURE	FIGURE CAPTIONS	PAGE NO.
	tank	
Figure 9.5:	Mechanical lumped-mass model of tanks on OSBI system	335
Figure 9.6:	Relationship between theta and tank base displacement ($r_x = 200$ mm)	335
Figure 9.7:	Number of isolators used for broad and slender tanks	336
Figure 9.8:	Comparison of base shear and sloshing displacement using mechanical mass and FE models for non-isolated and base-isolated broad tank ($e = 0.5$ and $\mu_r = 0.01$) broad tank subjected to PGA of $0.075g$	337
Figure 9.9:	Comparison of base shear and sloshing displacement for non-isolated and base-isolated broad and slender tanks with and without surface diaphragm using FE model subjected to PGA of $0.075g$ ($e = 0.5$ and $\mu_r = 0.01$)	338
Figure 9.10:	Comparison of base shear and sloshing displacement for non-isolated and base-isolated broad and slender tanks with and without surface diaphragm using FE model subjected to PGA $0.15g$ ($e = 0.5$ and $\mu_r = 0.01$)	339
Figure 9.11:	Comparison of base shear and sloshing displacement for non-isolated and base-isolated broad tank with and without surface diaphragm using FE model subjected to Northridge, 1994 earthquake ($e = 0.5$ and $\mu_r = 0.01$)	340
Figure 9.12:	Peak sloshing displacement in non-isolated and base- isolated tank subjected to earthquakes (Abbreviation of earthquake: IMV: Imperial Valley, 1940, NR: Northridge, 1994, and KBE: Kobe, 1995)	341
Figure 9.13:	Hydrodynamic impulsive pressure using 3-D FE model. ($\mu_r = 0.01$)	342
Figure 9.14:	Base shear and sloshing response control in base-isolated liquid storage tank respectively using OSBI system and surface diaphragm	343
Figure 9.15:	Peak hydrodynamic impulsive pressure in base-isolated.	344

FIGURE	FIGURE CAPTIONS	PAGE NO.
	broad and slender tanks ($e = 0.5$ and $\mu_r = 0.01$)	
Figure A1:	Schematic diagram of laminated rubber bearing (LRB).	396
Figure A2:	Schematic diagram New-Zealand (N-Z) bearing	396
Figure A3:	Time variation of fifth mass absolute acceleration and base displacement of five degrees-of-freedom dynamical system using N-Z base isolation system subjected to Imperial Valley, 1979 (Array # 5) earthquake ground motion ($T_b = 2.5$ sec)	397
Figure A4:	Sliding system used in dynamical system	398
Figure A5:	Time variation of base mass displacement in five degrees-of-freedom dynamical system by P-F, FPS and R-FBI systems subjected to Imperial Valley, 1940 earthquake ($T_s = 0.5$ sec)	399
Figure A6:	Time variation of fifth mass acceleration in five degrees-of-freedom dynamical system by P-F, R-FBI and FPS systems subjected to Imperial Valley, 1940 earthquake ground motion ($T_s = 0.5$ sec)	400
Figure A7:	Variation of frictional force in five degree-of-freedom dynamical system by P-F, R-FBI and FPS systems subjected to Imperial Valley, 1940 earthquake ground motion ($T_s = 0.5$ sec)	401
Figure A8:	Peak base mass displacement against the fundamental time period of dynamical system for different earthquakes	402
Figure A9:	Single degree-of freedom dynamical system isolated using circular rolling rods	402
Figure A10:	Free-body diagram of base mass and circular rolling system	403
Figure A11:	Time variation of mass absolute acceleration subjected to Imperial Valley, 1940 (N00E component) earthquake ($T_s = 0.5$ sec, $\zeta_s = 0.05$)	404
Figure A12:	Time variation of base mass displacement subjected to	405

FIGURE	FIGURE CAPTIONS	PAGE NO.
	Imperial Valley, 1940 (N00E component) earthquake ($T_s = 0.5$ sec, $\zeta_s = 0.05$)	
Figure A13:	Time variation of mass absolute acceleration for SDOF system subjected to Taft, 1952 (S69E component) earthquake ($T_s = 0.5$ sec, $\zeta_s = 0.05$)	406
Figure A14:	Time variation of base mass displacement for SDOF system subjected to Taft, 1952 (S69E component) earthquake ($T_s = 0.5$ sec, $\zeta_s = 0.05$)	407
Figure A15:	Variation of base mass displacement with respect to m_b/m , m_r/m and T_s for Taft, 1952 (S69E component) earthquake	408
Figure B1:	Schematic diagram of dynamical system mounted on elliptical rolling rods (ERR)	427
Figure B2:	Relationship between displacements of the base mass and ERR in x - z plane.	428
Figure B3:	Free-body diagram of the base mass and rolling rods along the x -direction.	428
Figure B4:	Time variation of top floor absolute acceleration and base displacement to S69E component of Taft, 1952 earthquake ground motion ($T_s = 0.5$ sec, $e = 0.5$ and $\mu = 0.01$)	429
Figure B5:	Time variation of $\ddot{y}_b$, θ , F_b/W , and F_s/W to S69E component of Taft, 1952 earthquake ground motion ($T_s = 0.5$ sec, $e = 0.5$, and $\mu_r = 0.01$)	430
Figure B6:	Time history response of the fifth mass absolute acceleration and base displacement subjected to Northridge, 1994 earthquake ($T_s = 0.5$ sec, $\mu_r = 0.01$)	431
Figure B7:	Time history response of θ , $\ddot{u}_{bx}/g$, F_b/W , F_s/W subjected to Northridge, 1994 earthquake ($T_s = 0.5$ sec, $e = 0.5$ and $\mu = 0.01$)	432

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure B8:	Time history response of sum of $\ddot{u}_{bx} / g$ along x - and y -directions subjected to Northridge, 1994 earthquake ($T_s = 0.5$ sec, $e = 0.5$, and $\mu = 0.01$)	433
Figure B9:	Effect of fundamental time period of dynamical system on peak average fifth mass absolute acceleration and bearing displacement of a base-isolated dynamical system ($\mu_r = 0.01$)	434
Figure B10:	Effect of coefficient of friction on peak average fifth mass absolute acceleration and base mass displacement of a base-isolated dynamical system ($T_s = 0.5$ sec)	434
Figure C1:	Comparison of time histories of impulsive overturning base moment and total (impulsive plus convective) overturning base moment for non-isolated and base-isolated broad and slender tanks between the present study and published results	438
Figure C2:	Comparison of time histories of vertical displacement due to free-surface sloshing in non-isolated and base-isolated tanks between the present study and published results	440
Figure C3:	Comparison of time histories response of slender tank in the x -direction isolated by the FPS system subjected to Imperial Valley, 1940 earthquake between the present study and published results	440
Figure C4:	Comparison of time histories response of slender tank in the y -direction isolated by the FPS system subjected to Imperial Valley, 1940 earthquake between present study and published results	441
Figure C5:	Comparison of time variation of sloshing response between present study by CAS approach and Tippmann et al. (2009)	442
Figure C6:	Comparison of impulsive hydrodynamic pressure in shallow tank	443

FIGURE	FIGURE CAPTIONS	PAGE NO.
Figure C7:	Comparison of sloshing displacement for tank with and without roof between the present study and published results by Matsui (2007)	444
Figure D1:	Time history of earthquake ground motions used in the present study	446
Figure D2:	Response spectra of earthquake ground motions	447
Figure D3:	Time history of near-fault earthquake ground motions	448
Figure D4:	Response spectra of near-fault earthquake ground motions	449

LIST OF TABLES

TABLE	TABLE CAPTIONS	PAGE NO.
Table 2.1:	List of liquid storage tanks damaged due to sloshing of liquid (Koketsu and Miyake 2008)	40
Table 3.1:	Peak seismic responses in cylindrical tank subjected to harmonic ground motions	78
Table 3.2:	Characteristics of the earthquake ground motions.	79
Table 3.3:	Resultant peak seismic responses in cylindrical tank subjected to bi-directional earthquake ground motions ($e = 0.5$ and $\mu = 0.01$)	80
Table 3.4:	Comparison between the different isolation systems and OSBI system subjected to Imperial Valley, 1940 earthquake	81
Table 4.1:	Comparison of modal frequencies for a clamped-clamped (C-C) cylindrical shell between present method and results obtained by Zhang et al. (2001) ($H = 20$ m, $R = 1$ m, $h = 0.01$ m)	117
Table 4.2:	Comparison of modal frequencies in Hz between present FEM and results obtained by Lee and Kwak (2015) ($H = 600$ mm, $R = 150$ mm, $h = 1$ mm)	118
Table 4.3:	Modal frequencies in Hz in cylindrical shell ($m = 1$) for $H/R = 2$	119
Table 4.4:	Geometrical and material properties (Haroun1980)	120
Table 4.5:	Modal frequencies in Hz for non-closure shell	120
Table 4.6:	Modal frequencies in Hz for non-closure shell	121
Table 4.7:	Circumferential mode shape $\cos(n\theta)$ type for non-closure cylindrical shells	122
Table 4.8:	Modal frequencies in Hz for non-closure cylindrical shells	123
Table 4.9:	Time period in seconds for $H/D = 0.63$ of tank	124
Table 4.10:	Time period in seconds for $H/D = 0.40$ of tank	125
Table 4.11:	Time period in seconds for $H/D = 0.24$ of tank	126

TABLE	TABLE CAPTIONS	PAGE NO.
Table 4.12:	Modal frequencies in Hz for cylindrical shell with closure for $H/R = 0.6$	127
Table 4.13:	Modal frequencies in Hz for cylindrical shell with closure for $H/R = 1.85$	138
Table 5.1:	Geometrical dimensions of cylindrical tank	153
Table 5.2:	Parameters of cylindrical tank and water	153
Table 5.3:	FE mesh convergence study for rigid broad and slender tanks	153
Table 5.4:	Peak sloshing displacement and base shear in cylindrical tank subjected to harmonic ground motion	154
Table 5.5:	Characteristics of the five earthquake ground motions	156
Table 5.6:	Comparison of peak responses in rigid and flexible broad cylindrical tanks subjected to bi-directional components of earthquake	157
Table 5.7:	Comparison of peak responses in rigid and flexible slender cylindrical tanks subjected to bi-directional components of earthquake	159
Table 5.8:	Peak impulsive hydrodynamic pressure in rigid and flexible tanks subjected to bi-directional components of earthquakes	161
Table 5.9:	Comparison of peak response quantities in cylindrical tank along x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$)	162
Table 5.10:	Comparison of absolute peak hydrodynamic impulsive pressure in tank along x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$)	163
Table 6.1:	Geometrical dimensions of the cylindrical tank	195
Table 6.2:	Geometrical dimensions of the rectangular tank	195
Table 6.3:	Number of elements used in the CAS approach	196
Table 6.4:	Parameters of water used in the CAS approach	196
Table 6.5:	Number of elements used in the CEL approach	197
Table 6.6:	The EoS parameters used to model water in the CEL approach	197

TABLE	TABLE CAPTIONS	PAGE NO.
Table 6.7:	Characteristics of the earthquake ground motions	198
Table 6.8:	Maximum sloshing displacement in the cylindrical tank	198
Table 6.9:	Maximum sloshing displacement in the rectangular tank	199
Table 7.1:	Material properties of surface diaphragm material (Seo et al. 2004)	226
Table 7.2:	Peak sloshing displacement (mm) in non-isolated tank	227
Table 7.3:	Peak sloshing displacement (mm) in base-isolated tank (LRB36)	228
Table 7.4:	Peak sloshing displacement (mm) in base-isolated tank (LRB78)	229
Table 8.1:	Parameters for modeling isolation systems (for lumped-mass model)	268
Table 8.2:	Comparison of peak responses for flexible base-isolated tank using mechanical lumped-mass and mechanical lumped-mass FE models for Imperial Valley, 1940 earthquake	269
Table 8.3:	Geometrical dimensions of cylindrical tank	270
Table 8.4:	Parameters of cylindrical tank and contained liquid.	270
Table 8.5:	Characteristics of the earthquake ground motions	270
Table 8.6:	Parameters for modeling isolation systems.	270
Table 8.7	Peak responses in rigid and flexible, broad ($S = 0.6$) base-isolated tanks for Type A, B, and C isolation systems along x -axis	271
Table 8.8:	Peak responses in rigid and flexible, broad ($S = 0.6$) base-isolated tanks for Type A, B, and C isolation systems along y -axis	272
Table 8.9:	Peak responses in rigid and flexible, slender ($S = 1.85$) base-isolated tanks for Type A, B, and C isolation systems along x -axis	273
Table 8.10:	Peak responses in rigid and flexible, slender ($S = 1.85$) base-isolated tanks for Type A, B, and C isolation	274

TABLE	TABLE CAPTIONS	PAGE NO.
	systems along y -axis	
Table 8.11:	Peak impulsive hydrodynamic pressure (kPa) in rigid and flexible tanks	275
Table 9.1:	Peak seismic responses for non-isolated broad and slender tanks with and without surface diaphragm subjected to uni-directional excitations	327
Table 9.2:	Peak seismic responses for base-isolated broad and slender tanks with and without surface diaphragm ($e = 0.5$ and $\mu_r = 0.01$) subjected to uni-directional excitations	328
Table 9.3:	Peak impulsive hydrodynamic pressure (kPa) subjected to uni-directional excitations	329
Table 9.4:	Comparison of peak response quantities in base-isolated tank along x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) for $e = 0.5$ and $\mu_r = 0.01$	330
Table 9.5:	Peak impulsive hydrodynamic pressure in base-isolated tank along x -axis ($\theta = 0^\circ$) and y -axis ($\theta = 90^\circ$) for $e = 0.5$ and $\mu_r = 0.01$	331
Table A1:	Peak response quantities for LRB and N-Z isolation systems	395
Table A2:	Parameters for sliding systems	395
Table B1:	Near-fault earthquake ground motions	426

MATHEMATICAL NOTATIONS

$\ddot{u}_{bx}$ and $\ddot{u}_{by}$	Horizontal acceleration of the base mass relative to the ground in x - and y -directions, respectively
u_{bx} and u_{by}	Horizontal displacement of the base mass relative to the ground in x - and y -directions, respectively
$\dot{u}_{bx}$ and $\dot{u}_{by}$	Horizontal velocity of the base mass relative to the ground in x - and y -directions, respectively
$\ddot{u}_{rxx}$ and $\ddot{u}_{rxy}$	Vertical acceleration of the base mass due to the motion of rollers along the x -direction and y -direction, respectively
A_c	Convective pseudo-acceleration
u_c	Displacement of the convective mass
θ_x	Eccentric angle (angle with respect to the major radius, r_x) in x - z plane
θ_y	Eccentric angle (angle with respect to the major radius, r_y) in y - z plane
$E_{\mu,x}$	Energy dissipated by rolling friction in x -axis
$E_{\mu,y}$	Energy dissipated by rolling friction in y -axis
ω_c	Frequency of the convective mass
a_x	Half the horizontal distance between the upper and lower points in x - z plane
a_y	Half the horizontal distance between the upper and lower points in y - z plane
u_{bx}	Horizontal displacement of the base mass relative to the ground along x -axis
u_{by}	Horizontal displacement of the base mass relative to the ground along y -axis
a_n	Acceleration component along the direction vector for an outward pointing normal
$\dot{u}_{out}$	Acoustic particle velocity in outward normal direction of the acoustic medium
ζ_s	Critical damping ratio of the superstructure
$[C_{ss}]$	Damping matrix of order $2N \times 2N$ for the fixed-base building
∇_s	Differential operator
u_c	Displacement of the convective mass
θ_x	Eccentric angle (angle with respect to the major radius, r_x) in x - z plane

θ_y	Eccentric angle (angle with respect to the major radius, r_y) in y - z plane
$\underline{\Phi}^N$	Eigenvector (the mode of vibration)
$E_{\mu_r x}$	Energy dissipated by rolling friction in x -axis
$E_{\mu_r y}$	Energy dissipated by rolling friction in y -axis
$\{\ddot{u}_g\}$	External excitation
$\bar{I}_1$	First invariant of the deviatoric strain tensor of the left Cauchy-Green deformation tensor
$\bar{I}_1$	First invariant of the deviatoric strain tensor of the left Cauchy-Green deformation tensor
$\ddot{x}_g(t)$	Ground acceleration
u_{ox}	Horizontal displacement of the center of mass of the OSBI relative to ground along x -axis
u_{oy}	Horizontal displacement of the center of mass of the OSBI relative to ground along y -axis
u_{rx}	Horizontal displacement of the center of mass of the roller relative to ground in x -direction
$[I_{bb}]$	Influence coefficient matrix for the base mass of order 2×2
$[I_{ss}]$	Influence coefficient matrix for the superstructure of order $2N \times 2$
E_m	Internal energy per unit mass
E_m	Internal energy per unit mass
∇^2	Laplacian operator
$[M]$	Mass matrix of order $(2N + 2) \times (2N + 2)$ for the base-isolated building
$[M_{ss}]$	Mass matrix of order $2N \times 2N$ for the fixed-base building
∇	Matrix operator (gradient and divergence) of variable
$\ddot{u}$	Nodal acceleration
$1/k_1$	Proportionality coefficient between the pressure and the displacement in the normal direction to the surface
$1/c_1$	Proportionality coefficient between the pressure and the velocity in the normal direction to the surface

$\{u_b\}$	Relative base mass displacement vector with respect to the ground of order 2×1
$\{u_s\}$	Relative floor displacement vector with respect to the base mass of order $N \times 1$
u_R	Resultant displacement
θ_{oy}	Rotation of the OSBI system about the x-axis
θ_{ox}	Rotation of the OSBI system about the y-axis
θ_{rx}	Rotation of the rolling rod about the y-axis
$[K_{ss}]$	Stiffness matrix of order $2N \times 2N$ for the fixed-base building
$[K]$	Stiffness matrix of order $(2N + 2) \times (2N + 2)$ for the base-isolated building
ϵ_s	Strain
σ_s	Stress
$\bar{t}_s$	Surface traction
$\dot{p}$	Time rate of change of the acoustic pressure
U_p	Velocity of liquid particles
U_s	Velocity of shock particle
C_0	Velocity of sound through the liquid
ϕ	Velocity potential function
u_{ozx}	Vertical displacement relative to the ground along z-axis (in x-z plane)
u_{ozy}	Vertical displacement relative to the ground along z-axis (in y-z plane)
u_{rzz}	Vertical displacement relative to the ground in z-direction
η	Volumetric compressive strain as a function of initial density, ρ_0
γ	Characteristic impedance of material at the boundary
μ_r	Coefficient of rolling friction between the base mass and the OSBI system
μ_s	Coefficient of sliding friction
$\ddot{u}_{ox}, \ddot{u}_{oy}$	Acceleration of the OSBI system along the x- and y-axes, respectively
$\ddot{\theta}_{ox}, \ddot{\theta}_{oy}$	Angular acceleration of the OSBI system along the x- and y-axes, respectively
$\ddot{u}_{gx}, \ddot{u}_{gy}$	Ground acceleration along the x- and y-axes, respectively
$\dot{u}_{bx}, \dot{u}_{by}$	Relative velocity of the base mass in the x- and y-axes, respectively

$\ddot{u}_{\text{ozx}}, \ddot{u}_{\text{ozy}}$	Vertical acceleration of the OSBI system along the x - and y -axes, respectively
$\ddot{u}_{\text{bzx}}, \ddot{u}_{\text{bzy}}$	Vertical acceleration in base mass along the x - and y -axes, respectively
$I_1(\cdot); I_1'(\cdot)$	Modified Bessel function of first order and its derivative, respectively
$\Gamma_0; s$	Material constants
$[C]$	Damping matrix of the system
$[C_A]$	Acoustic fluid element damping
$[C_S]$	Structural element damping
$[K]$	Stiffness matrix of the system
$[K_A]$	Acoustic fluid element stiffness
$[K_S]$	Structural element stiffness
$[M]$	Mass matrix of the system
$[M_A]$	Acoustic fluid element mass
$[M_S]$	Structural element mass
$[Q_{SA}]$	Spatial coupling matrix
$\{F_A\}, \{F_B\}$	Structural element forces
$\{F_S\}, \{F_q\}$	Acoustic fluid element forces
$\{r\}$	Influence coefficient matrix
$\{U_S\}$	Nodal displacement values and over-dots indicate derivative with respect to time
$\partial\Omega_p$	Fluid boundaries are given by prescribed pressure
$\partial\Omega_t$	Structure boundaries are given by prescribed force vector
$\partial\Omega_u$	Structure boundaries are given by prescribed displacement
∇p	Prescribed normal pressure gradient
μ	Dynamic viscosity of water in $\text{N}\cdot\text{sec}/\text{m}^2$
A	Amplitude of motion (maximum displacement from the reference line).
a	Major radius of ERR
$A; B; C$	Undetermined constants
a_0	Amplitude of external acceleration
a_n	Acceleration component along the direction vector for an outward pointing normal n to the fluid region
$\ddot{u}_{\text{gx}}$ and $\ddot{u}_{\text{gy}}$	Ground acceleration along x - and y -directions, respectively

F_{bx} and F_{by}	Inertial force of the bottom and top rollers acting tangentially along x -and y -directions, respectively at the two points of contact of the rods
F_{sx2} and F_{sy2}	Isolator rolling frictional force for the bottom and top rollers along the x -and y -directions, respectively
F_{sx1} and F_{sy1}	Restoring force of the bottom and top rollers, by virtue of its elliptical shape, acting tangentially along x -and y -directions, respectively
a_x	Half the horizontal distance between the upper and lower points in x - z plane
a_y	Half the horizontal distance between the upper and lower points in y - z plane
b	Minor radius of ERR
B	Width of the tank
b_s	Body force
b_x	Half the vertical distance between the lower and upper points (O_1 and O_2) of the system in the x - z plane
b_y	Half the vertical distance between the lower and upper points (O_1 and O_2) of the system in the y - z plane
c_0 or c	Speed of sound in liquid
C_{10} and D_1	Temperature-dependent material parameters in Neo-Hookean model
C_A	Acoustic fluid domain damping matrices
c_b	Damping of the base isolation system
c_c	Damping constant of the sloshing/convective mass
c_i	Damping constant of the impulsive mass
C_{ij}	Coefficients which are the functions of λ_m , n
C_S	Structural damping matrices of the structural domain
c_x	Half the horizontal distance between the upper and lower pole points (A and B)
D	Diameter of the shell
D_S	constitutive matrix for an isotropic material relating stresses and strains
e	Eccentricity of the oblate spheroid
E	Modulus of elasticity of shell material
$E_{input,x}$	Input energy in x -axis
$E_{input,y}$	Input energy in y -axis
E_{kx}	Absolute kinetic energy in x -axis
E_{ky}	Absolute kinetic energy in y -axis

E_{px}	Potential energy in x -axis
E_{py}	Potential energy in y -axis
$E_{rec,x}$	Recoverable energy in x -axis
$E_{rec,y}$	Recoverable energy in y -axis
E_{sx}	Elastic strain energy in x -axis
E_{sy}	Elastic strain energy in y -axis
E_t	Modulus of elasticity of tank wall material
$E_{\zeta x}$	Energy dissipated by damping in x -axis
$E_{\zeta y}$	Energy dissipated by damping in y -axis
F	Generalized force
f	Natural frequency in Hz.
$f(t)$	scalar model coordinate corresponding to the mode shapes $U(x, \theta)$, $V(x, \theta)$, and $W(x, \theta)$
F_b	Restoring force induced in the isolator
F_e	External nodal forces
F_F	Rolling frictional force of isolator due to its geometry
F_f	Amplitude of displacement
F_I	Inertial (relativistic) force of isolator
F_{pr}	Nodal forces exerted on the tank wall due to the pressure imparted by the oscillation of the liquid contained in the tank
F_R	Total restoring force of the isolation system
F_S	Restoring force of isolator due to its geometry
f_v	Eulerian volume fraction (EVF).
F_x and F_y	Base shears in x - and y -directions, respectively
g	Acceleration due to gravity
G_0	Initial shear modulus
h	Constant thickness of the cylindrical shell
H	Height (or length) of the cylindrical shell
h	Sloshing displacement in the tank.
H_c	Height of convective mass from bottom of the tank
H_i	Height of impulsive mass from bottom of the tank
H_L	Liquid height in the tank
h_m	Sloshing displacement in the image
H_r	Height of rigid mass from bottom of the tank

h_r	thickness of the closure
I	internal forces resisted by the tank liquid materials
J^{el}	Elastic volume ratio (EVR)
J_o	Mass moment of inertia of the OSBI system
J_r	sum of mass moment of inertia of the bottom rollers
K	bulk modulus of the liquid in MPa
k	Transformation coefficient.
K_0	Initial bulk modulus
K_A	Acoustic fluid domain stiffness matrices
k_b	Stiffness of isolator.
k_c	Convective spring stiffness
k_i	Impulsive spring stiffness
$\underline{K}^{\text{MN}}$	Stiffness matrix
K_S	Structural stiffness matrices of the structural domain
L	Length of the tank
L_{ij}	Differential operator
L_m	Length of tank in the image
M	Nodal mass
m	Superstructure floor mass
$M; N$	Degrees-of-freedom
M_A	Acoustic fluid domain mass matrices
m_b	Mass of isolator
m_c	Convective mass of liquid in the tank
m_{cx}, m_{cy}	Convective mass in x- and y-axes, respectively
m_i	Impulsive mass of liquid in the tank
m_{ix}, m_{iy}	Impulsive mass in x- and y-axes, respectively
$\underline{M}^{\text{MN}}$	Mass matrix
m_o	Mass of the OSBI system
m_r	Rigid mass
m_r	Sum of mass of the bottom rolling rods
m_{rx}, m_{ry}	Rigid mass in x- and y-axes, respectively
M_S	Structural mass matrices of the structural domain
M_T	Total effective mass of the tank
n	Fluid region

n	Circumferential mode
N	Normal vector
n_A	Boundary normal vector point outward from the fluid domain
N_A	FE shape functions for the acoustic fluid domain
n_s	Boundary normal matrix pointing outward from the structural domain
N_s	FE shape functions for structural domain
P	Dimensionless parameter
p	Acoustic pressure at the top surface of the liquid.
p	Hydrodynamic pressure at any point
$p(t)$	Acoustic fluid, dynamic pressure
P_A	Nodal pressure
p_x	Half the vertical distance between the lower and upper pole points (A and B)
$q_A(t)$	Added fluid mass per unit volume
r	Transformation vector that couples each degree-of-freedom to the ground motion
R	Radius of the cylindrical shell/ tank
r_x	Major radius of the oblate spheroid along the two horizontal axes (x - and y -axis)
r_z	Minor radius of the oblate spheroid along the vertical axis (z -axis)
S	Aspect ratio of the tank
s	Fluid acoustic-structural surface area
$\text{sgn}(\cdot)$	Sign function, i.e. $\text{sgn}(\dot{u}_b) = \dot{u}_b / \dot{u}_b $
t	Time
T	Transpose
T_b	Isolation time period
T_c	Time period of convective mass
T_i	Time period of impulsive mass
T_n	Natural period of the system
T_s	Fundamental time period of the superstructure
t_s	Thickness of tank wall
U	Strain energy per unit reference volume
$u; v; w$	Displacements of the shell in the x , θ and z directions, respectively
u_A	Displacement of fluid particles

u_b	Isolator relative displacement with respect to the ground
u_{bx}	Horizontal displacement of the base mass relative to the ground along x -axis
u_{by}	Horizontal displacement of the base mass relative to the ground along y -axis
u_c	Displacement of the convective mass
u_{cx}, u_{cy}	Absolute displacement of convective masses in x - and y -axes, respectively
u_{ix}, u_{iy}	Absolute displacement of impulsive masses in x - and y -axes, respectively
u_{rx}, u_{ry}	Absolute displacement of rigid masses in x - and y -axes, respectively
u_s	Structural domain displacement
V	Elemental volume
v	Velocity distribution of liquid.
V_x, V_y	Base shear generated in the x - and y -axes of the tank, respectively
W	Weight of tank
$w(t)$	Vertical displacement of the surface diaphragm and the over-dot represents its derivative with respect to time, t
x_b, y_b	Displacements of the base mass relative to the ground in x - and y -axes, respectively
$x_{b,max}$	Maximum limit for the isolator displacement
x_c, y_c	Displacements of the convective mass relative to the base of the tank in x - and y -axes, respectively
x_i, y_i	Displacements of the impulsive mass relative to the base of the tank in x - and y -axes, respectively
ζ_b	Damping ratio of isolator.
ζ_c	Damping ratio of convective mass
ζ_i	Damping ratio of impulsive mass
ζ_s	Damping ratio of tank material
$\theta; z$	Co-ordinates in the circumferential and radial directions of the shell, respectively
$\lambda_m; n$	Axial wave number and the circumferential wave parameter, respectively
ν	Poisson's ratio of material
ρ	Density of shell material
ρ_L	Density of the liquid in kg/m^3 .
ρ_s	Density of material in kg/m^3 .
ρ_t	Mass density of the steel tank
ρ_w	Density of water in kg/m^3

Φ	Velocity potential
Ω	Frequency parameter
ω	Angular/ circular frequency of natural vibration or excitation frequency or circular frequency in rad/sec
Ω_A	Acoustic fluid domain
ω_f	Forcing frequency
Ω_p	Acoustic fluid boundaries are prescribed by pressure
Ω_S	Structure domain
Ω_{SA}	Boundary between acoustic fluid domain and structural domain
Ω_z	Acoustic fluid boundaries with prescribed impedance

ABBREVIATIONS

2-D	Two-dimensional
3-D	Three-dimensional
AC3D8R	Acoustic continuum 3-D eight-node element with reduced integration
ACI	American Concrete Institute
ALE	Arbitrary Lagrangian-Eulerian
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
BE-FE	Boundary element-fluid element
BEM	Boundary element method
BI	Base-isolated
BNC	Ball-n-cone
C	Convective
C3D8R	Continuum 3-D eight-node element with reduced integration
C3D8RH	Continuum 3-D eight-node element with reduced integration and hybrid formulation
CAS	Coupled acoustic-structural
C-C	Clamped-clamped
CEL	Coupled Eulerian-Lagrangian
C-F	Clamped-free
CFPI	Conical friction pendulum isolator
CPM	Consistent particle method
DCFP	Double concave friction pendulum
DM	Donnell-Mushtari
DOFs	Degrees-of-freedom
DVFPI	Double variable frequency pendulum isolator
EC3D8R	Eulerian continuum 3-D eight-node element with reduced integration
EDF	Electricite de France
EERL	Earthquake Engineering Research Laboratory
EoS	Equation-of-state
EPS	Expanded polystyrene

ERR	Elliptical rolling rods
EVF	Eulerian volume fraction
FDM	Finite difference method
FEM	Finite element method
FLH	Flügge
FPS	Friction pendulum system
FSI	Fluid-structure interaction
GPa	Giga Pascal
HDRB	High-damping rubber bearing
I	Impulsive
IMV	Imperial Valley, 1940
JMA	Japan Meteorological Agency
KBE	Kobe, 1995
kN	kilo Newton
kPa	kilo Pascal
LGP	Los Gatos Presentation
LNG	Liquefied natural gas
LP	Loma Prieta, 1989
LRB	Laminated rubber bearing
LRB36	Laminated rubber bearing 36 mm thick
LRB78	Laminated rubber bearing 78 mm thick
LST	Liquid storage tank
MFPS	Multiple friction pendulum system
MN	Mega Newton
MPa	Mega Pascal
NHF	Newhall Fire station
NI	Non-isolated
NR	Northridge (Sylmar Converter Center), 1994
NR(NH)	Northridge (Newhall), 1994
N-Z	New-Zealand
NZS	New Zealand Standard
OPRCB	Orthogonal pairs of rollers on concave beds
OSBI	Oblate spheroid base isolation
P-F	Pure-friction

PFPI	Polynomial friction pendulum isolator
PGA	Peak ground acceleration
PU	Polyurethane
R3D3	Rigid 3-Dthree-node triangular discrete rigid elements
R3D4	Rigid 3-D four-node bi-linear quadrilateral discrete rigid elements
R-FBI	Resilient-friction base isolator
RISs	Rolling isolation systems
RNC	Roll-n-cage
RTB	Rolling-type bearing
S3R	Shell three-node triangular three-dimensional element with reduced integration and hourglass control
S4R	Shell four-node quadrilateralthree-dimensional element with reduced integration and hourglass control
S-C	Simply-supported - clamped
SD	Surface diaphragm
SD-SD	Shear diaphragm - shear diaphragm
SPH	Smoothed particle hydrodynamics
SR-F	Sliding resilient-friction
S-S	Simply-supported - simply-supported
SSM	Simplified sloshing model
TARRC	Tun Abdul Razak Research Centre
UK	United Kingdom
USA	United State of America
VCFPS	Variable curvature friction pendulum system
VFFPI	Variable frequency and variable friction pendulum isolator system
VFI	Variable friction isolator
VFPI	Variable friction pendulum isolator
VFPS	Variable friction pendulum isolator system
VFRB	Variable-frequency rocking bearing
VOF	Volume of fluid