

UNCERTAINTY QUANTIFICATION AND SEISMIC FRAGILITY OF BASE-ISOLATED LIQUID STORAGE TANKS

SANDIP KUMAR SAHA



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
NEW DELHI - 110 016, INDIA
AUGUST 2014**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2014

UNCERTAINTY QUANTIFICATION AND SEISMIC FRAGILITY OF BASE-ISOLATED LIQUID STORAGE TANKS

by

**SANDIP KUMAR SAHA
DEPARTMENT OF CIVIL ENGINEERING**

*submitted
in fulfilment of the requirements of the degree of*

DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

NEW DELHI - 110 016, INDIA

AUGUST 2014

Dedicated to my parents and wife

For their endless love, support and encouragement

CERTIFICATE

This is to certify that the thesis titled, “**UNCERTAINTY QUANTIFICATION AND SEISMIC FRAGILITY OF BASE-ISOLATED LIQUID STORAGE TANKS**” being submitted by **Mr. Sandip Kumar Saha** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. He worked under our supervision for the submission of thesis, which to our knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of his 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.

Dr. Vasant A. Matsagar

Associate Professor

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

Prof. Arvind K. Jain

Professor

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

ACKNOWLEDGEMENTS

I have come across several people whose guidance, love and encouragement helped me to come at this point of accomplishment. I wish to convey my gratitude to all those wonderful people who directly or indirectly helped me during my doctoral study at the Indian Institute of Technology (IIT) Delhi.

My words are not enough to express my sincere gratitude and appreciation to my supervisors, Dr. Vasant A. Matsagar and Prof. Arvind K. Jain for their constant guidance, support and inspiration. I gratefully acknowledge their crucial contributions towards the completion of this research work. I would also like to express my sincere thanks to them for their generosity in providing financial supports to attend several conferences and workshops nationally and internationally.

I am particularly grateful to Dr. Matsagar for his critical observations and exceptionally thoughtful approach that actually shaped my doctoral research. He has always showed confidence on my ability, and encouraged me to deliver the best. I have never come across such an individual like him, who can critically review his own work as an independent referee. Whenever I found myself stuck in the research, his immense patient to understand the bottleneck and inspiring technical discussion have always paved the way for progress. He has ensured that I have had all possible experiences and opportunities that will provide a solid foundation for my career.

I would like to convey my sincere gratitude to Prof. Steffen Marburg, for giving me opportunity to work with his research group at the Universität der Bundeswehr (UniBW) München, Neubiberg, Germany. It was a great experience to work under the guidance of a brilliant expert in dynamics like him. I specially thank Dr. Kheirollah Sepahvand for sharing his excellent expertise on the stochastic modeling of dynamical systems, and guiding me during my research stay at the UniBW. I would also like to express my heartiest gratitude to Prof. Subrata Chakraborty from Indian Institute of Engineering Science and Technology (ISET), Shibpur, West Bengal, India for teaching me the basics of response surface methodology, and its application in uncertainty modeling.

Apart from this, I gratefully acknowledge the financial support provided by the Deutscher Akademischer Austausch Dienst (DAAD) in the form of “DAAD - Stipendien-und Betreuungsprogramm (STIBET)-III” scholarship during my research stay in Germany. I am thankful to Department of Science and Technology (DST), Government of India for conferring me the “International Travel Support” award to attend the International

Conference on Structural Safety and Reliability (ICOSSAR 2013), held at the Columbia University, New York, USA. I also sincerely acknowledge the financial support provided by the Industrial Research and Development (IRD) Unit, IIT Delhi for attending the ICOSSAR 2013.

I extend my deepest gratitude to my research committee members, Prof. K. G. Sharma, Prof. Alok Madan and Dr. A. K. Darpe for their valuable advices that have helped to make my research objectives more focused. I would also like to thank Prof. T. K. Datta, Dr. G. S. Benipal, Dr. D. R. Sahoo and Dr. T. Chakraborty, who always have taken keen interest in my research, and provided me with their invaluable suggestions.

I would like to express sincere appreciation to the Department of Civil Engineering, IIT Delhi for providing excellent academic environment and computational facilities. I specially thank all Civil Engineering faculty and staff members for their instant support whenever I needed. I am also grateful to the staff members of the departmental and central library for providing books, journals and other research materials, which actually have made this research work possible.

This is the right occasion to thank all the persons attached to the Multi-Hazard Protective Structures (MHPS) Laboratory, for maintaining such a nice research environment. I would like to specially thank Mr. Pravin Jagtap, Mr. Elias Rahimi, Mrs. Aruna Rawat, Mr. Naseef Ummer, Mr. Ankit Bhardwaj, Mr. M. Sathishkumar, Ms. Arundhuti Banerjee, Mr. Anil Kumar, Mr. Pratik Bhatt and Mr. Rohit Tiwari for their contributions in making my stay at IIT Delhi more productive. Their charming friendship has ensured this prolonged stay enjoyable, and their unconditional support has always helped me to meet many deadlines. I also thank Dr. Ganesh Rathod, Dr. Manmohan Dass Goel and Dr. Shantanu Patra for their support and encouragement on various occasions.

I am forever indebted to my parents, in-laws, grandmother, sister, brother-in-law, uncle and other family members whose blessings and affection have always encouraged me to reach for the stars. Whatever I have achieved in my life till now was not possible without constant support from my parents. Lastly and most specially, I would convey my warmest gratitude and love for my wife Priyanka, for listening to my problems, providing her perspective, and sometime helping me with her technical expertise. Most importantly, she is always there whenever I need.

Date:

(Sandip Kumar Saha)

Place: New Delhi

ABSTRACT

Liquid storage tanks play an important role in civil society and in many industries such as aviation, oil refinery, nuclear, power generation and others. Failure of such lifeline structures during earthquake may impart extreme difficulties on rescue operation due to unavailability of the basic needs, such as water, milk, fuel and power. Besides these direct impacts, failure of tanks may cause further catastrophic accidents by initiating fire or spreading radioactive substances. In nutshell, the risk of human life loss and huge economic loss, due to such failures, necessitate increased protection of the liquid storage tanks from devastating earthquakes. One of the effective measures, to protect structures against earthquake force, is to use seismic base isolation technique. Moreover, seismic analysis of structures in the probabilistic domain and reliability based design has gained popularity over the years among the structural engineering community. In addition, it is important to consider the uncertainties involved in the earthquake excitation as well as in the isolation parameters during seismic response analysis of base-isolated structures. The assessment of the seismic protection can be performed using fragility analysis, in a more convincing way, by considering the uncertainty in the seismic demand and capacity.

Herein, the effects of the modeling approaches for the liquid storage tank and base isolation system on the seismic response of the base-isolated liquid storage tanks under uni- and bi-directional earthquakes are investigated. The response of the base-isolated liquid storage tanks under near-fault earthquakes is studied to examine the suitability of the equivalent pulse type acceleration input in place of recorded near-fault earthquake acceleration. Seismic fragility of the base-isolated liquid storage tanks is evaluated under stochastic earthquake ground motions using Monte Carlo (MC) simulation. Different earthquake intensity measure (IM) parameters are compared for the fragility analysis. Influence of the uncertain isolation parameters and level of uncertainties, on the peak response distribution of the base-isolated liquid storage tanks, is investigated using response surface model (RSM). Thereafter, seismic fragility of base-isolated liquid storage tanks, considering the uncertainty involved in the isolator parameters and earthquake ground motions, are carried out using the RSM based simulation technique. Further, generalized polynomial chaos (gPC) expansion technique is used to investigate the effect of uncertainties in the isolation parameters on the peak response quantities and fragility of base-isolated liquid storage tanks under random base excitation. Different approaches, presented herein, to evaluate the seismic fragility of base-isolated liquid storage tanks are also compared. An assessment of various isolation systems, to enhance

the protection level of liquid storage tanks under devastating earthquake, is carried out through development of fragility curves.

It is observed that the modeling approaches, for the liquid storage tanks and isolation systems, significantly affect the peak seismic response of base-isolated liquid storage tanks. Generalized polynomial chaos (gPC) expansion technique is found to be capable of modeling the parametric uncertainties in dynamic analysis of base-isolated liquid storage tank. Uncertainties in the excitation and isolation parameters significantly influence the peak seismic response, and thereby play a crucial role in the evaluation of seismic fragility of the base-isolated liquid storage tanks. However, it is further observed that the uncertainty in the isolation damping has lesser effect on the seismic fragility of base-isolated liquid storage tanks. Furthermore, equivalent linear modeling of the isolator non-linear hysteretic behavior does not affect the seismic fragility for the base-isolated liquid storage tanks significantly. It is observed that the base isolation helps to reduce the probability of failure of liquid storage tanks and it diminishes the effect of uncertainties in the base excitation, i.e. earthquake. The RSM based and gPC expansion based simulations are observed to be accurate and time efficient alternative to direct MC simulation that requires high computational efforts. Further, it is observed that the enhancement in the seismic performance of the liquid storage tanks varies significantly for the different isolation systems commonly used in practice.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE NO.
	Abstract	v
	Table of Contents	vii
	List of Figures	xiii
	List of Tables	xix
	Mathematical Notations	xxi
	Abbreviations	xxv
CHAPTER-1	Introduction	1-18
1.1	General	1
1.2	Behavior of Liquid Storage Tanks during Earthquake	1
1.2.1	<i>Codal provisions for seismic design for liquid storage tanks</i>	2
1.2.2	<i>Buckling analysis of liquid storage tanks</i>	4
1.3	Base Isolation Technique	6
1.3.1	<i>Laminated rubber bearing (LRB)</i>	7
1.3.2	<i>Lead-rubber bearing (NZ system)</i>	7
1.3.3	<i>Pure friction (PF) system</i>	8
1.3.4	<i>Friction pendulum system (FPS)</i>	8
1.3.5	<i>Resilient friction base isolator (RFBI)</i>	9
1.3.6	<i>Electric de France (EDF) system</i>	9
1.4	Seismic Base Isolation for Liquid Storage Tanks	10
1.5	Need and Relevance of the Present Study	11
1.6	Objectives of the Present Study	12
1.7	Organization of the Report	13
CHAPTER-2	Comparison of Base-Isolated Liquid Storage Tank Models under Bi-Directional Earthquakes	19-40
2.1	General	19
2.2	Modeling of Base-Isolated Liquid Storage Tanks	20
2.2.1	<i>Two mass model (Model 1)</i>	20
2.2.2	<i>Three mass model (Model 2)</i>	22
2.3	Modeling of Isolation Systems	24
2.4	Equations of Motion for Base-Isolated Liquid Storage Tanks	24
2.5	Numerical Study	27
2.5.1	<i>Comparison of seismic response obtained from two models</i>	28
2.5.2	<i>Effect of interaction on the peak seismic response</i>	29
2.6	Closure	30
CHAPTER-3	Behavior of Base-Isolated Cylindrical Liquid Storage Tanks under Near-Fault Earthquakes	41-74
3.1	General	41
3.2	Base-Isolated Structures under Near-Fault Earthquakes: A Review	42

CHAPTER	TITLE	PAGE NO.
	3.2.1 <i>Base-isolated buildings under near-fault earthquake</i>	42
	3.2.2 <i>Base-isolated bridges under near-fault earthquake</i>	43
	3.2.3 <i>Base-isolated liquid storage tanks under near-fault earthquake</i>	43
3.3	Equivalent Pulses for Near-Fault Ground Motion	44
3.4	Modeling of Base-Isolated Liquid Storage Tanks	46
3.5	Numerical Study	46
	3.5.1 <i>Response under equivalent pulse and residual pulse</i>	48
	3.5.2 <i>Effect of isolator time period</i>	49
	3.5.3 <i>Effect of isolator damping</i>	51
3.6	Closure	52
CHAPTER-4	Influence of Different Isolator Models on Earthquake Response of Base-Isolated Liquid Storage Tanks	75-100
4.1	General	75
4.2	Mathematical Modeling of Liquid Storage Tanks	76
4.3	Different Isolator Models	76
	4.3.1 <i>Equivalent linear elastic - viscous damping model of isolators</i>	77
	4.3.2 <i>Bi-linear hysteretic model of isolators</i>	77
4.4	Solution of Equations of Motion	78
4.5	Numerical Study	79
	4.5.1 <i>Comparison of equivalent linear and bi-linear modeling of isolator</i>	80
	4.5.2 <i>Effect of non-linear hysteretic modeling of isolator on peak response</i>	81
	4.5.3 <i>Effect of isolation time period on peak response</i>	83
	4.5.4 <i>Effect of tank slenderness ratio on peak response</i>	84
4.6	Closure	84
CHAPTER-5	Seismic Fragility of Base-Isolated Liquid Storage Tanks	101-128
5.1	General	101
5.2	Modeling of Base-Isolated Liquid Storage Tank for Seismic Fragility Analysis	103
5.3	Stochastic Ground Motion Model	104
5.4	Solution of Equations of Motion	106
5.5	Seismic Fragility Analysis	107
	5.5.1 <i>Selection of intensity measure (IM) parameter</i>	107
	5.5.2 <i>Definition of limit states of failure</i>	108
	5.5.3 <i>Procedure for seismic fragility analysis</i>	110
	5.5.4 <i>Convergence of probability of failure</i>	110

CHAPTER	TITLE	PAGE NO.
5.6	Numerical Study	111
5.6.1	<i>Fragility of fixed-base and base-isolated liquid storage tanks</i>	111
5.6.2	<i>Influence of isolation time period on seismic fragility</i>	112
5.6.3	<i>Influence of isolation damping on seismic fragility</i>	113
5.6.4	<i>Influence of yield strength and yield displacement of isolator on seismic fragility</i>	113
5.6.5	<i>Effect of the isolator modeling on seismic fragility</i>	114
5.7	Closure	115
CHAPTER-6	Uncertainty Quantification and Seismic Fragility Analysis using Response Surface Models	129-164
6.1	General	129
6.2	Response Surface Model (RSM) Representation	130
6.2.1	<i>Sampling design methods</i>	131
6.2.2	<i>Response surface models (RSM) for seismic response of liquid storage tanks</i>	132
6.2.3	<i>Numerical example</i>	133
6.2.4	<i>Influence of individual parameter uncertainties on the peak response distribution</i>	135
6.3	Seismic Fragility Analysis	136
6.3.1	<i>Procedure for seismic fragility analysis using RSM</i>	136
6.3.2	<i>Convergence of probability of failure</i>	139
6.3.3	<i>Fragility of fixed-base and base-isolated liquid storage tanks</i>	139
6.3.4	<i>Influence of isolation time period on seismic fragility</i>	140
6.4	Response Surface Model (RSM) Including PGA	141
6.5	Closure	142
CHAPTER-7	Modeling Uncertainty for Dynamic Analysis of Base-Isolated Liquid Storage Tanks using Generalized Polynomial Chaos Expansion	165-186
7.1	General	165
7.2	Stochastic Modeling of Base-Isolated Liquid Storage Tank	167
7.3	Procedure for Numerical Simulation	170
7.4	Numerical Study	173
7.4.1	<i>Probability distribution of peak response quantities</i>	175
7.4.2	<i>Effect of individual parameter uncertainties on the peak response</i>	175

CHAPTER	TITLE	PAGE NO.
	7.4.3 <i>Variation of peak response distribution with different uncertainty levels</i>	176
	7.4.4 <i>Effect of uncertainties on peak response of fixed-base and base-isolated liquid storage tanks</i>	177
7.5	Closure	178
CHAPTER-8	Generalized Polynomial Chaos Expansion Based Simulation for Fragility Analysis of Base-Isolated Liquid Storage Tanks	187-206
8.1	General	187
8.2	Stochastic Modeling for Fragility Analysis	187
8.3	Development of Fragility Curve	189
	8.3.1 <i>Definition of limit states of failure</i>	189
	8.3.2 <i>Computation of probability of failure</i>	189
8.4	Numerical Study	190
	8.4.1 <i>Effects of input parameter distribution on fragility curves</i>	192
	8.4.2 <i>Efficiency of gPC expansion based simulation over direct Monte Carlo simulation</i>	192
	8.4.3 <i>Comparing fragility of fixed-base and base-isolated liquid storage tanks</i>	193
	8.4.4 <i>Influence of uncertain isolator parameters on fragility curves</i>	194
	8.4.5 <i>Comparison of gPC based simulation with response surface model (RSM) based simulation for fragility analysis</i>	195
8.5	Closure	196
CHAPTER-9	Performance Evaluation of Seismic Base Isolation Systems for Liquid Storage Tanks using Fragility Analysis	207-224
9.1	General	207
9.2	Governing Equations of Motion for Base-Isolated Liquid Storage Tank	208
	9.2.1 <i>Laminated rubber bearing (LRB)</i>	208
	9.2.2 <i>Lead-rubber bearing (NZ system)</i>	209
	9.2.3 <i>Pure friction (PF) system</i>	209
	9.2.4 <i>Friction pendulum system (FPS)</i>	210
	9.2.5 <i>Resilient friction base isolator (RFBI)</i>	210
	9.2.6 <i>Electric de France (EDF) system</i>	210
9.3	Seismic Fragility Analysis	211
9.4	Numerical Study	213
	9.4.1 <i>Comparison of fragility curves for different isolation systems</i>	213
	9.4.2 <i>Effect of isolator parameters on fragility curves</i>	214
9.5	Closure	216

CHAPTER	TITLE	PAGE NO.
CHAPTER-10	Summary and Conclusions	225-230
10.1	Summary	225
10.2	Conclusions	226
10.3	Future Scope of Work	230
	References	231
Appendix - 1	Incremental Solution for Equations of Motion	249-254
A1.1	General	249
A1.2	Incremental Solution of Equations of Motion for Base-Isolated Liquid Storage Tanks under Uni-Directional Earthquake Ground Motion	249
A1.3	Incremental Solution of Equations of Motion for Base-Isolated Liquid Storage Tanks under Bi-Directional Earthquake Ground Motion	251
Appendix - 2	Validation of Numerical Model of Tank	255-256
A2.1	Validation	255
Appendix - 3	Recorded Earthquake Ground Motion Database	257-262
Appendix - 4	Reliability Analysis of Base-Isolated Liquid Storage Tanks	263-278
A4.1	General	263
A4.2	Reliability Analysis of Structures	263
	A4.2.1 <i>First order second moment (FOSM) theory</i>	264
	A4.2.2 <i>Monte Carlo (MC) simulation</i>	265
A4.3	Reliability Analysis of Base-Isolated Structures	267
A4.4	Representation of Response Quantities using Generalized Polynomial Chaos	268
A4.5	Numerical Study	269
	A4.5.1 <i>Computation of reliability index (β)</i>	269
	A4.5.2 <i>Computation of probability of failure (p_f) using MC simulation</i>	270
	A4.5.3 <i>Effect of individual parameter uncertainty on probability of failure (p_f)</i>	272
	A4.5.4 <i>Effect of level of uncertainty on probability of failure (p_f)</i>	273
A4.6	Summary and Conclusions	274
	List of Publications	279
	Brief Bio-Data	281