SEISMIC PERFORMANCE ASSESSMENT OF BASE ISOLATED NUCLEAR POWER PLANTS

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To my Wife and Parents to whom I owe everything I have
achieved in my life

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ABSTRACT

Retrofit of structures is an inevitable task especially when buildings are not designed for seismic actions or their design was based on older design codes. Many retrofit strategies have been proposed and practiced. Use of dampers, base isolators, and active and semi-active energy dissipation devices are among the most common retrofitting methods. For base isolating, passive base isolator has been widely employed by engineers for conventional structures and bridges. However, very few applications of these base isolators for Nuclear Power Plants (NPPs) can be found in the literature. A new base isolation methodology based on intensity, which considered different earthquake parameters such distance of earthquake center to site was proposed by FEMA 58 in 2012 and this methodology has not been addressed in previous studies. Thus, this research investigated the effects of FEMA 58 base isolation method on the results of an analysis. This new analysis method investigated the distance effect of earthquake center to site. In this research, application of three types of base isolators for seismic retrofit of first generation NPP was investigated. Three levels of return periods comprising 10^5 years, $2.5*10^4$ years and 10^4 years were introduced to investigate the highest level of performance for NPP based on FEMA 58. The study applied both experimental and numerical analysis. For the experimental part, two scaled NPPs were constructed in laboratory with a scale factor of 1:36 and a total weight of approximately 1 ton. The NPPs were tested with the pushover method for two conditions: fixed and isolated base. Numerical studies were performed to investigate the effects of 11 earthquakes on the obtained results from the finite element models. Results indicated that regardless of the employed base isolators, the isolated NPP had a higher natural period and displacement compared to the fixed-base NPP. However, the isolated NPP showed significantly lower acceleration, stress, base shear, and overturning moment when compared with the fixed-base NPP. It was also observed that when frictional pendulum base isolator was used to retrofit, the highest energy dissipation and lowest base shear as well as overturning moment; and stress were achieved. Monitoring the strain distribution between base-isolated and fixed-base NPP revealed that the base isolators had reduced the strain in the containment of the NPPs. With regard to the results based near the fault and far field earthquake characteristics, it is concluded that the base isolators are more effective under or near the fault earthquake.

ABSTRAK

Pengubahsuaian semula struktur merupakan tugas yang tidak dapat dielakkan terutamanya apabila bangunan tidak direka untuk tindakan seismik atau reka bentuk mereka berdasarkan kod reka bentuk yang lebih lama. Banyak strategi pengubahsuaian telah dicadangkan dan diamalkan. Penggunaan peredam, pengasing asas, peranti pelesapan tenaga aktif dan separuh aktif adalah antara kaedah pengubahsuaian yang paling biasa. Untuk mengasingkan asas, isolator asas pasif telah digunakan secara meluas oleh jurutera untuk struktur konvensional dan jambatan. Walau bagaimanapun, hanya beberapa aplikasi isolator asas untuk loji kuasa nuklear (NPP) boleh didapati dalam kajian terdahulu. Metodologi pengasing asas baru berdasarkan intensiti yang menilai parameter gempa bumi yang berbeza, iaitu jarak pusat gempa ke tapak telah dicadangkan oleh FEMA 58 pada tahun 2012, dan kaedah ini belum ditangani dalam penyelidikan terdahulu. Oleh itu, kajian ini mengkaji kesan pengasingan asas kaedah FEMA 58 pada hasil analisis. Kaedah analisis baru ini mengkaji kesan jarak pusat gempa ke tapak. Dalam kajian ini, penggunaan tiga jenis isolator asas untuk pengubahsuaian seismik NPP generasi pertama dikaji. Tiga tahap tempoh pulangan yang terdiri daripada 10^5 tahun, $2.5*10^4$ tahun dan 10^4 tahun telah dicadangkan untuk mengkaji tahap prestasi tertinggi untuk NPP, berdasarkan FEMA 58. Kajian ini menggunakan kedua-dua eksperimen dan analisis berangka. Untuk kajian eksperimen, dua NPP berskala telah dibina di makmal dengan faktor skala 1:36 dan jumlah berat kira-kira 1 tan. NPP telah diuji dengan kaedah *pushover* untuk dua syarat asas, tetap dan terpencil. Kajian berangka telah dilaksanakan untuk mengkaji kesan sebelas gempa bumi pada hasil yang diperoleh daripada model unsur terhingga. Keputusan menunjukkan bahawa tanpa mengasingkan pengasing asas yang digunakan, NPP terpencil mempunyai tempoh semula jadi dan anjakan yang lebih tinggi berbanding dengan NPP asas tetap. Walau bagaimanapun, NPP terpencil menunjukkan pecutan, ketegangan, geseran asas dan momen pembalikan dengan ketara berbanding dengan NPP asas tetap. Ia juga diperhatikan bahawa, apabila penebat asas pendulum geseran digunakan untuk retrofit, pelesapan tenaga tertinggi dan ricih pangkalan terendah, momen membalik dan ketegangan dicapai. Pemantauan pengagihan ketegangan antara NPP asas terpencil dan asas tetap telah mengurangkan ketegangan dalam pembendungan NPP. Berkenaan dengan keputusan yang berasaskan ciri-ciri gempa bumi berhampiran dan jauh, dapat disimpulkan bahawa penebat asas memiliki lebih banyak keberkesanan di bawah gempa bumi berhampiran.

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LIST OF ABBREVIATIONS

ADRS	-	Acceleration-Displacement Response Spectrum
ABWRs	-	Advanced Boiling Water Reactors
ACI	-	American Concrete Institute
AISC	-	American Institute For Steel Construction
ASTM	-	American Society for Testing and Materials
ASCE	-	American Society of Civil Engineering
ASME	-	American Society of Mechanical Engineer
ATC	-	Applied technology council
BINPP	-	Base Isolated Nuclear Power Plants
BWR	-	Boiling Water Reactor
CoM	-	Center-of-Mass
CoR	-	Center-of-Rigidity
CP	-	Collapse Prevention
DBE	-	Design Based on Earthquake
DAP	-	Displacement-Based Adaptive Pushover
EPS	-	Earthquake Protective Systems
FB	-	Fixed Base
FE	-	Finite Element
FEMA	-	Federal Emergency Management Agency
FF	-	Far Field
FGBINPP	-	First Generation Base Isolated Nuclear Power Plants
FGNPP	-	First Generation Nuclear Power Plants
FBNPP	-	Fixed Base Nuclear Power Plants
FAP	-	Force-Based Adaptive Pushover
FBD	-	Force-Based Design
FPBI	-	Friction Pendulum Base Isolated
FP	-	Friction Pendulum
HDR	-	High Damping Rubber Bearing
HDRBI	-	High-Damping Rubber Base Isolators
HWR	-	Heavy Water Reactor

IO	-	Immediate Occupancy
IAEA	-	International Atomic Energy Agency
IPEEE	-	Individual Plant Examination of External Events
LRBI	-	Lead Rubber Base Isolated
LR	-	Lead-Rubber
LS	-	Life Safety
LWR	-	Light Water Reactor
LVDT	-	Linear Variable Displacement Transducer
LNG	-	Liquefied Natural Gas
LSF	-	Low Shape Factor
LDRBI	-	Low-Damping Rubber Base Isolators
MAFE	-	Mean Annual Frequency of Exceedance
MDF	-	Multiple-Degree-of-Freedom
NF	-	Near Fault
NAM	-	Non-Adaptive Modal
NANM	-	Non-Adaptive Non-Modal
NLTHAs	-	Nonlinear Time History Analysis
NPP	-	Nuclear Power Plant
NRC	-	Nuclear Regulatory Commission
PBD	-	Performance-Based Design Principles
PSHA	-	Probabilistic Seismic Hazard Assessment
PWR	-	Pressurized Water Reactor
RC	-	Reinforced-Concrete
SSE	-	Safe Shutdown Earthquake
SAFR	-	Sodium Advanced Fast Reactor
SBI	-	Seismic Base Isolation
SDB	-	Seismic Design Basis
SDC	-	Seismic Design Category
SDOF	-	Single Degree of Freedom System
SPRA	-	Seismic Probabilistic Risk Assessment
SRP	-	Standard Review Plan
SSCs	-	Structures, Systems, and Components
TEPCO	-	Tokyo Electric Power Company
TLP	-	Triangular Load Pattern

UBC	-	Uniform Building Code
USNRC	-	US Nuclear Regulatory Commission Regulatory

LIST OF SYMBOLS

ϕ	-	modal shapes
g	-	Gravity = 9.81 m/s2
ι	-	Force influence vector
μ	-	friction coefficient
$\dot{u}$	-	velocity
m	-	Mass
u	-	displacement
ω	-	Frequencies
L	-	length
D_D	-	maximum displacement at the experimental test
E_D	-	energy dissipation
G	-	shear modulus
Te	-	effective period
Ti	-	initial period
Sa	-	response spectrum acceleration
α	-	ratio of the post-yield stiffness to effective elastic stiffness
Vy	-	structure's yield strength
ζeq	-	equivalent damping ratio
fcr	-	cracking stress
fb	-	bending stress
D	-	distance
M	-	magnitude
A	-	Acceleration
DL	-	Dead load
LL	-	Live load
σE	-	Engineering stress
εE	-	Engineering strain
A_0	-	Original cross-sectional area

P	-	External axial tensile load
L_0	-	Original length
L_f	-	Final length
E	-	Young's modulus
v	-	Poisson’s ratio

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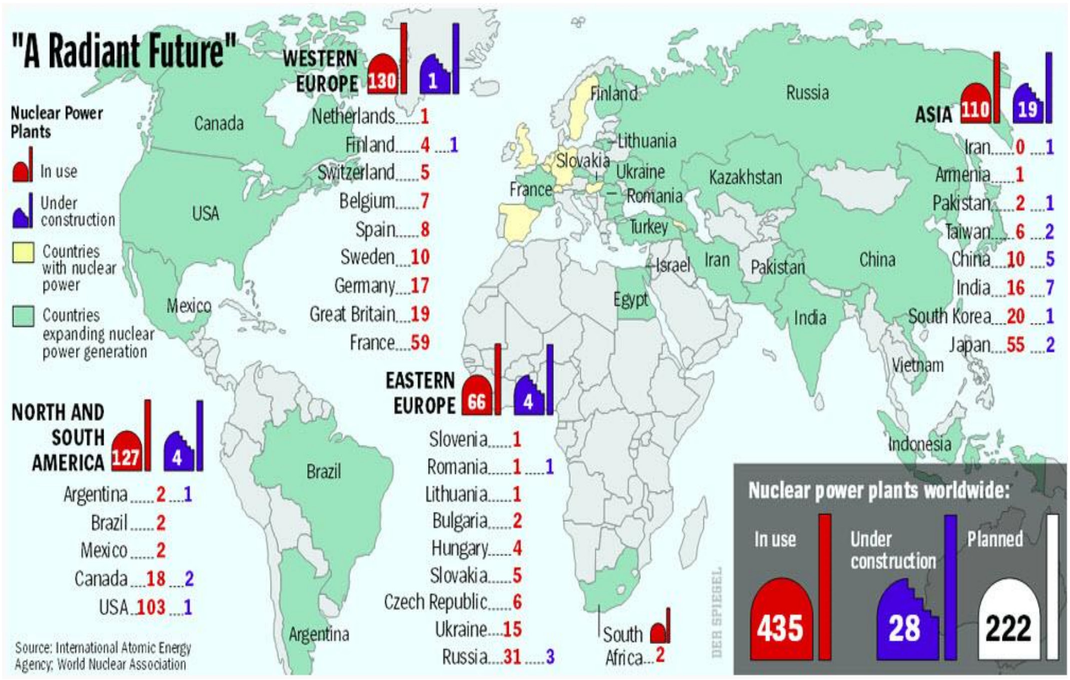
CHAPTER 1

INTRODUCTION

1.1 Introduction

In the recent decade, the use of Nuclear Power Plants (NPPs) in different fields of science and industry such as generation of electricity, medicine, agriculture, and military has increased dramatically. Figure 1.1 illustrates the world wide distribution of constructed and under-construction NPPs as well as those planned to be constructed.

Figure 1.1 Worldwide Distribution of Nuclear Power Plants (Association, 2010)



There are different types of NPPs based on their application and their structure, as can be seen in Figure 1.2.

In general, based on the way NPPs are applied, they are classified into two different categories, Light Water Reactor (LWR) and Heavy Water Reactor (HWR).

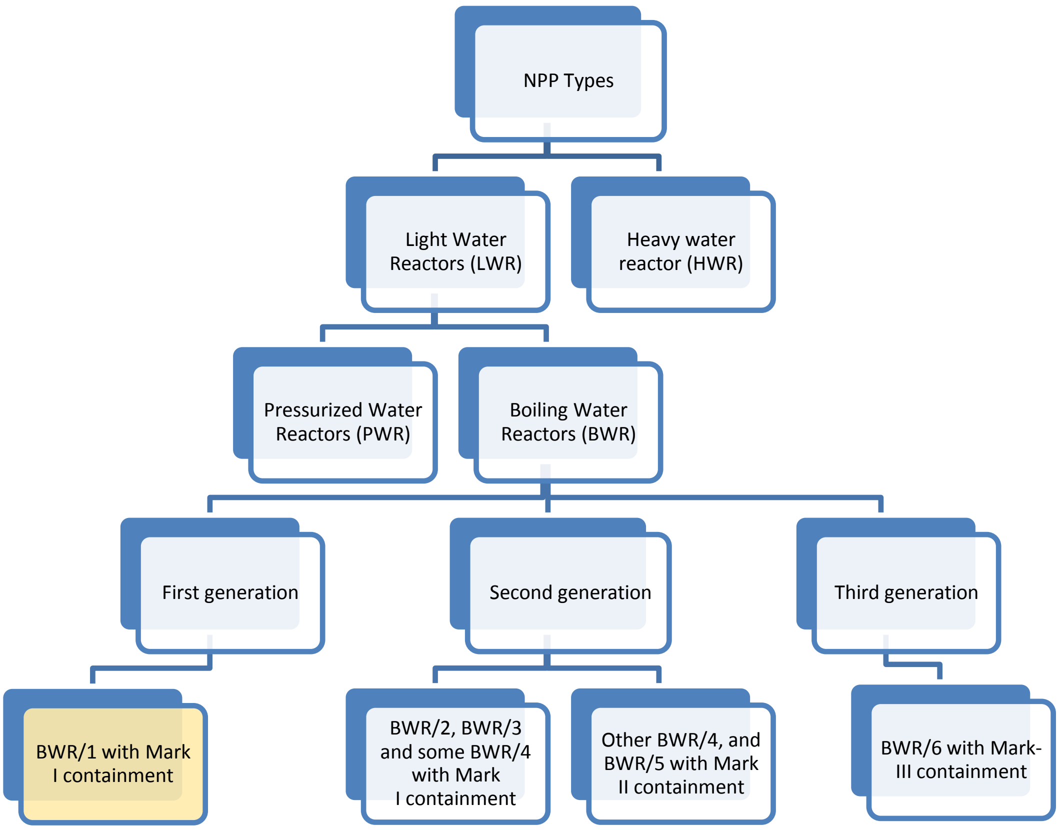


Figure 1.2 Different types of Nuclear Power Plants based on application and their structures (Ludwig & Renier, 1989)

Based on the structural system, there are three classes, which named containment mark (I) to containment mark (III). As can be seen in Figures 1.3-1.5, the NPP which marked by containment mark-I is constructed of two structural parts, the upper part is made up of steel and the lower part is constructed from concrete; the shape of secondary containment is rectangular. Although NPPs' containment mark-II has the cylindrical shape, it is also made up of two structural part, similar to mark-I. moreover, the NPPs' containment mark-III is made up of only concrete, which causes higher safety in this type of structure. Because of the structural weakness of the first generation NPPs (containment mark-I), this study is focused on this type of NPPs.

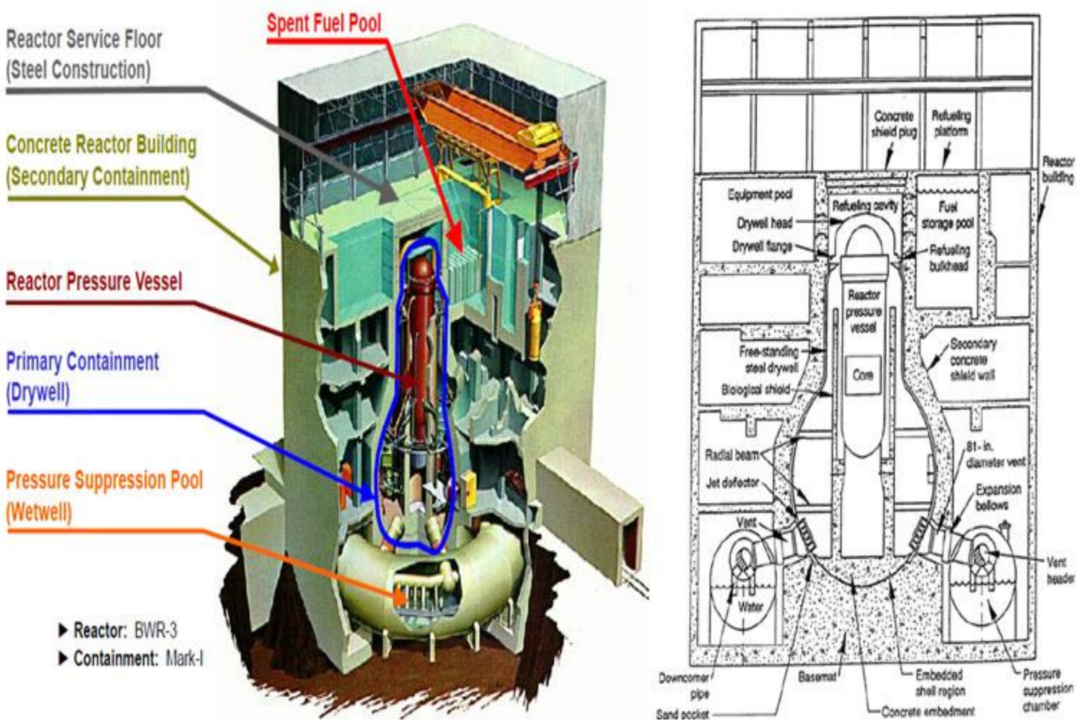


Figure 1.3 NPPs' Containment mark-I (Joskow & Parsons, 2012)

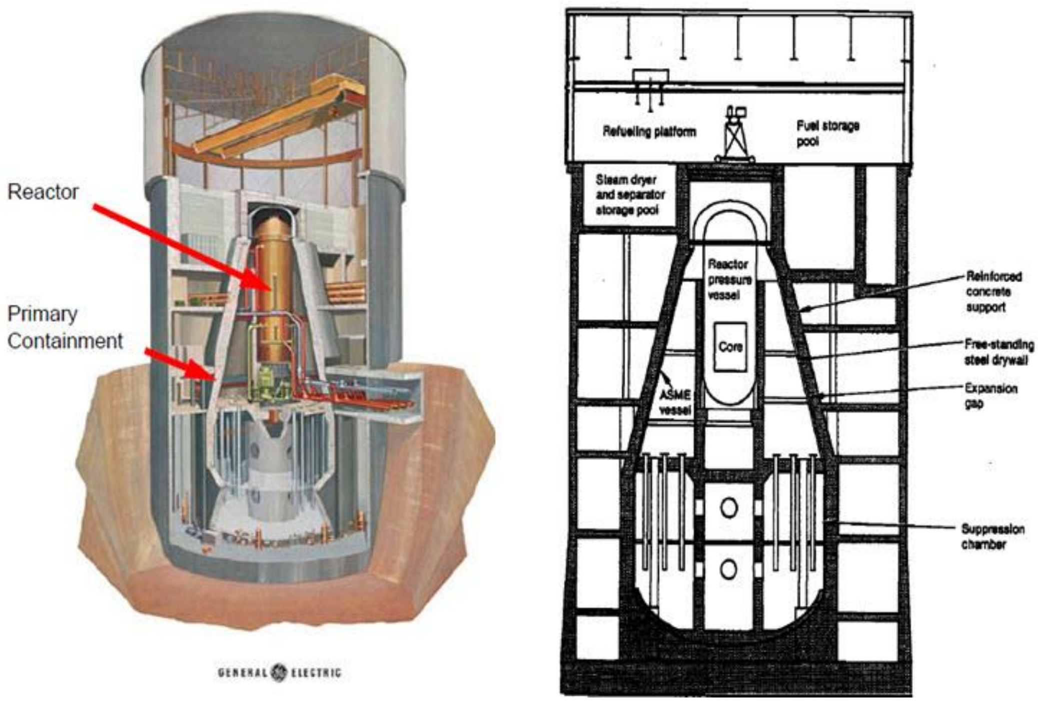


Figure 1.4 NPPs' Containment mark-II (Joskow & Parsons, 2012)

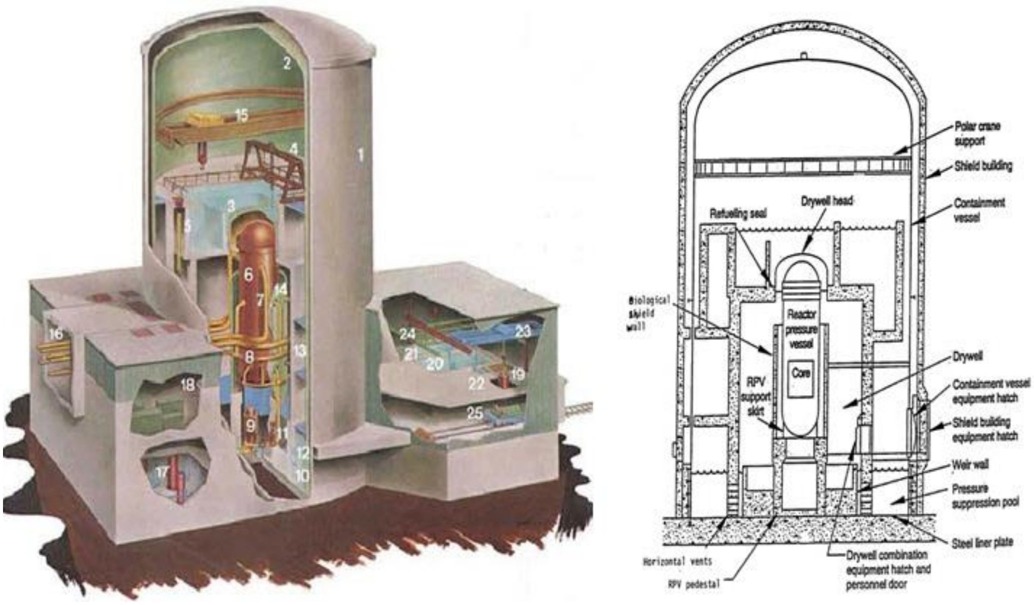


Figure 1.5 NPPs’ Containment mark-III (Joskow & Parsons, 2012)

It is well known that many structures designed based on older codes may be susceptible to severe damage during strong earthquakes. Older buildings have been structurally designed for much lower seismic actions compared to buildings that are designed today. This is because the relevant seismic codes have been continually revised as knowledge about seismic behavior has increased.

Many structures that are built prior to the 1970's were designed for either gravity loads alone, or combination of gravity loads and wind loads. Seismic loads often were not considered in the design of these structures. As a result, poor performance of these structures is anticipated and observed under moderate to severe seismic loading.

In some of the most important structures, such as NPPs, it is necessary to continue their service after different events such as an earthquake. Based on FEMA (2000) and ATC (2005) codes, this level of performance was called “immediate occupancy level”.

Therefore, the first generation of NPPs, which have not been designed based on new guidelines and codes, must be redesign and retrofit based on the latest cods (e.g. ASCE 43-05 (2005), FEMA 58 (2012)). One of the most effective methods to reduce damage during an earthquake is the use of energy dissipation devices in NPPs. These devices consume the earthquake energy and lead to a safer situation. Different types of energy dissipation devices have been used in infrastructures, as illustrated in Figure 1.6.

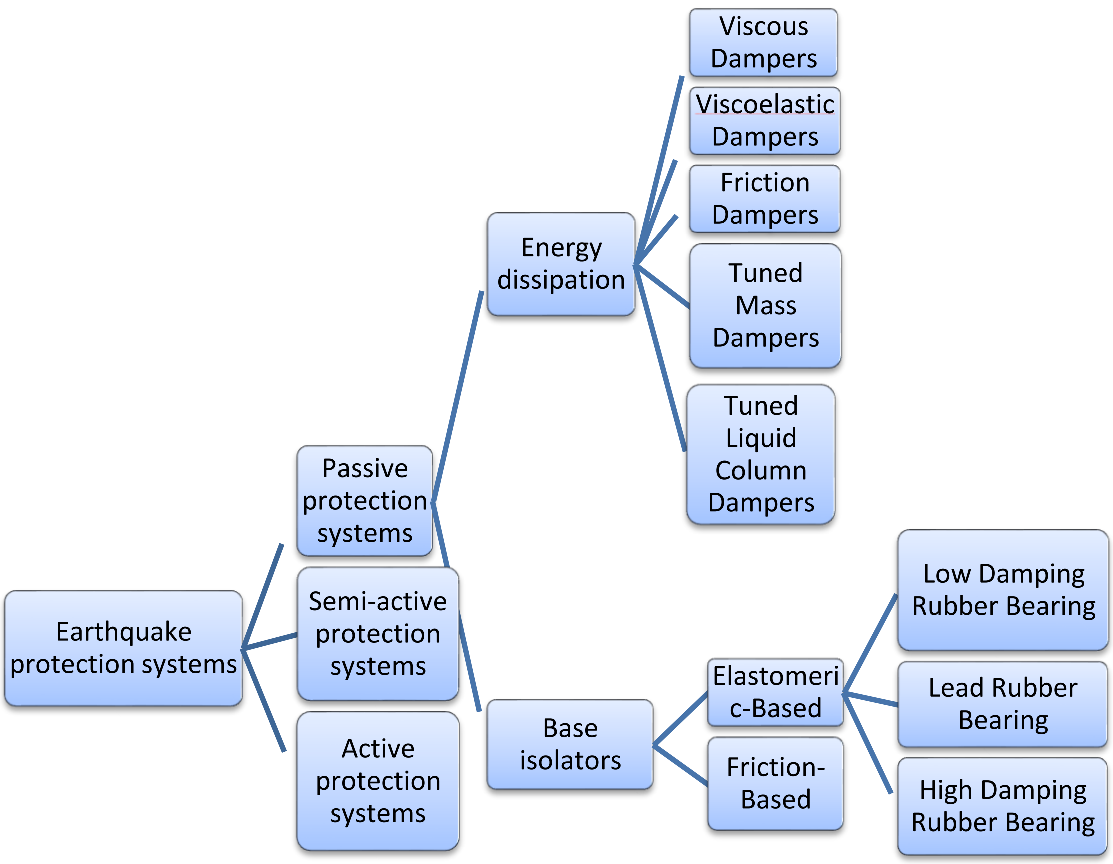


Figure 1.6 Unconventional earthquake protection systems (Castaldo, 2014)

This research investigates the behaviour of retrofitted NPPs by base isolators. Energy dissipation capacity, yield and ultimate load bearing capacity and failure mechanism of two scaled NPPs with isolated base and fixed base isolator were evaluated experimentally. Numerical studies were performed in order to investigate the effect of different base isolators on the seismic behavior of the retrofitted NPPs.

1.2 Problem Statement

In recent decade, earthquakes are the most important problems in NPPs, causing severe problems. To cope with that, codes and guidelines have been changed during recent decades. The design methods in many of the building codes are based on a strength criterion while according to surveys structure behaviors in recent earthquakes, strength alone cannot be considered as a single criterion in designing structures against earthquakes, and increasing the strength does not necessarily lead to increased safety. Therefore, in new codes, performance criterion is used instead of strength criterion in order to design the structures.

The use of base isolation systems in buildings and also some of particular structures such as bridges have been evaluated and their performance has been confirmed. However, the application of them to some other important structures such as NPPs, specially first generation NPP (due to their special loads and designing), has not been investigated comprehensively and there is a need for considering them specially in areas susceptible to natural disasters and phenomena.

In addition, there was a few research on the effects of seismic load on isolated NPPs, especially first generation NPPs. The performance response of the isolated and non-isolated NPPs will be useful for rehabilitation and retrofitting of existing and new generation of NPPs. Generally, the main problems of this study are:

i. Unknown isolated and non-isolated performance of the first generation NPPs under earthquake loads with respect to new criteria and conditions of guidelines and codes.
ii. Unknown isolated and non-isolated performance of the first generation NPPs under lateral loads with respect to new criteria and conditions of guidelines and codes.
iii. How accurate is the current Analysis method based on performance in the actual NPP under earthquake loads?

1.3 Objectives of the Study

This research develops assessments of NPP's seismic performance for two conditions of the base, namely fixed base and isolated base. A new procedure based on FEMA58 (2012) is considered based on intensity and time. Finally, the numerical seismic analysis responses of NPPs are compared with the result of laboratory tests. The objectives of the present research are as follow:

a) To evaluate the effectiveness of high damping rubber, frictional pendulum and lead rubber base-isolated NPPs through numerical studies.
b) To study the seismic response of high damping rubber base-isolated NPPs through comparing pushover laboratory test results and finite element model.
c) To evaluate the effectiveness of far field and near fault ground motion on isolated and fixed base NPPs through numerical studies.

1.4 Scope and Limitations

The The research is conducted to retrofitting the first generation NPP using base isolators. Experimental works are conducted on two scaled NPPs with scaling factor 1:38 of the actual model and scaled dimensions are 100 cm high,100 cm wide, and 4 cm thickness of wall with a total weight of approximately 1 ton. The compressive strength of concrete used in this study is 40 MPa for foundation and 35 MPa for NPPs' containment. The yield and ultimate stress of employed reinforcement bars are 355 N/mm2 and 532 N/mm2, respectively. The earthquake return period factors for scaling records are 10^4 years, $2.5*10^4$ years and 10^5 years return period. For retrofitting NPPs; High Damping Rubber (HDR), Frictional Pendulum (FP), and Lead Rubber Bearing (LR) base isolations were used in the base isolated NPPs. The resulting energy dissipation, base shear and stress are used to determine the levels of structural and non-structural damage inflicted on each base isolated NPPs. The tests conducted to performance assessment of base isolated NPP under FF and NF earthquake.

1.5 Significant of the Research

This study attempts to retrofit NPPs through the use of different Isolators. The outcome of this research can be used to increase the safety and performance level of NPPs and prevent the possibility of occurring any damage to NPPs under seismic loads.

1.6 Structure of the Thesis

The following paragraphs briefly describe the six chapters organized in the present thesis.

Chapter 1: Introduction. It presents a general overview of the research program. An introduction to other chapters is given and also the scope and objectives of the current research are highlighted.

Chapter 2: Literature review. This chapter reviews the key topics that are related to Nonlinear time history and pushover analysis of buildings. Moreover, the building codes required to design the base isolation and NPPs are described.

Chapter 3: Methodology. Design procedures of base isolated NPPs subjected to extreme loading were investigated. Design procedures for Frictional Pendulum (FP), Lead Rubber (LR), and High Damping Rubber bearing (HDR) were also considered in this chapter to address nonlinear time history and pushover requirements.

Chapter 4: Experimental work. In this chapter, the obtained results of the proposed retrofit technique for NPPs on the experimental tests are presented. In addition, the fabrication procedure and modeling setup are explained in detail. Changes to the stiffness and ductility of NPPs before and after retrofitting are explained as well.

Chapter 5: Numerical simulation. This chapter develops the case studies for assessment of the pushover and nonlinear time history. In addition, acceptance criteria and loading protocol for both of them are discussed in detail. For each loading protocol, the numerical simulation is explained.

Chapter 6: Results and discussion. It reports and discusses the results obtained from the experiments carried out on the base isolated NPPs exposed to pushover and nonlinear time history analysis tests in case of base-isolated NPPs in comparison with the fixed-base NPPs. This chapter also examines the stiffness degradation and the energy dissipation capacity of all three base isolations.

Chapter 7: Conclusion and recommendations. The research finding, contribution of the thesis and the recommendations for future work are also described in this chapter.

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