COMPARATIVE STUDY ON SEISMIC ANALYSIS OF BUILDINGS FOR DIFFERENT CODE OF PRACTICES COMMONLY USED IN SRI LANKA

K.P.N. Prasanna

(118624N)

University of Moratuwa, Sri Lanka.
Electronic Theses & Dissertations
www.lib.mrt.ac.lk
Degree of Master of Engineering in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa
Sri Lanka

March 2016
COMPARATIVE STUDY ON SEISMIC ANALYSIS OF BUILDINGS FOR DIFFERENT CODE OF PRACTICES COMMONLY USED IN SRI LANKA

K.P.N. Prasanna

(118624N)

University of Moratuwa, Sri Lanka.
Electronic Theses & Dissertations
www.lib.mrt.ac.lk

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa

Sri Lanka

March 2016
DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other university or institute of higher learning and to the best of my knowledge and believe it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also I hereby grant the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part, electronic or other medium. I retain the right to use this content in whole or part in future works.

Signature: ……………………….
Date: …...../…...…/…....…

The above candidate has carried out this research for the Degree of Masters in Engineering in Structural Engineering Designs under my supervision.

Signature: ………………………. Date: …....../……/……
ACKNOWLEDGEMENT

There are many people, who have contributed in making this research and the accompanying thesis a reality, to whom I am very grateful.

Firstly, I would like to express my deepest gratitude to Dr. C.S.Lewangamage, senior lecturer of the Department of Civil Engineering of University of Moratuwa and also the supervisor of this research, for his constant support to complete this research successfully. It is indeed his guidance, enthusiasm, constructive suggestions, encouragements and invaluable assistance provided throughout the project duration made this thesis possible.

My special thanks go to Prof. M.T.R. Jayasinghe, the former head of the Department of Civil Engineering of University of Moratuwa for making me interested in the field of seismology.

I would also like to express my gratitude to all other members of the academic and non-academic staff of the Department of Civil Engineering of University of Moratuwa, for their support extended towards me in various means to finalize this project successfully.

Finally, I wish to express my appreciation to my family members and friends for their assistance and encouragement given to me in completing this project.
ABSTRACT

Earthquake threat has been identified by many countries and analysis and design against seismic effects have therefore become almost a basic part of their structural design process. Sri Lanka has also identified the importance of designing buildings against seismic actions, specially due to recent incidents, which took place in and around the Island. However, Sri Lanka does not have its own code of practice for designing against seismic actions. Also there are not many established guidelines available in the country for this purpose. As a result, when it is required to analyze and design buildings against seismic actions, the engineers and scientists in the country face difficulties, basically with which codes and guidelines to follow. It is obvious that all of those codes are not equally suitable for conditions in Sri Lanka and also will not give out similar results.

The aim of this research is to check the performance level that a building can achieve when analyzed according to different codes of practice, which are commonly used in Sri Lanka in seismic analysis. In this context, three codes of practice were considered, taking into account their applicability over the others in Sri Lankan context, namely the Australian code (AS1170.4-2007), the Indian code (IS 1893 (Part 1):2002) and the Euro code (BS EN-1998-1:2004). The recommendations provided in the research, conducted by the University of Moratuwa, Sri Lanka, aimed at providing guidance on suitable analysis procedures for buildings in Sri Lanka, based on the euro code were also inco-operated in the analysis.

First, the seismic analysis procedures outlined in these codes with respect to both static and dynamic analysis were discussed in detail. Then, the analysis procedures introduced in the respective codes of practice were compared and contrasted, considering how they handle the major effects, characteristics of the structures and geotechnical considerations etc.

In order to demonstrate the analysis procedures and to make a comparison on results, three high-rise buildings, having floors between 10 to 20 were selected and analyzed according to the guidelines provided in the three selected codes of practice respectively. In this case, all the structures were analyzed for three different soil conditions, which could be found in Sri Lanka. The computer software “ETABS” has been used for finite element modeling of all the structures. Response Spectrum Analysis (RSA) was used in all the dynamic analysis purposes. Equivalent static analysis was also carried out as per requirements, established in particular codes of practice.

According to the results obtained in the analysis, it has been found that, irrespective of the code of practice, which has been used in the analysis, the structures have achieved Immediate Occupancy Level (IOL) in all twenty seven cases, according to FEMA356 standards. It was also found that the Indian code has given the highest drift values in many occasions while the Euro code also has given very close or sometimes similar drift values. In contrast, the Australian code has generally resulted lowest drift values. Further, it has also been identified that the Euro code has given the highest design base shear forces in all eighteen occasions. On the other hand, the Indian code has given lowest design base shear force in many occasions. The Australian code has also shown the lowest design base shear forces in few occasions.
# TABLE OF CONTENTS

1.0 INTRODUCTION ......................................................................................................................... 1

1.1 Background ................................................................................................................................. 1

1.2 Scope of the study ......................................................................................................................... 2

1.3 Objectives ..................................................................................................................................... 2

1.4 Methodology ................................................................................................................................. 3

1.5 Arrangement of the report .......................................................................................................... 3

2.0 LITERATURE REVIEW .............................................................................................................. 6

2.1 Analysis procedure as described in Euro code (EN 1998-1:2004) .............................................. 6

\[
\begin{align*}
2.1.1 & \text{Design seismic action} \quad \text{.........................................................} \quad 6 \\
2.1.2 & \text{Horizontal elastic response spectra} \quad \text{.......................................................} \quad 8 \\
2.1.3 & \text{Horizontal design response spectra} \quad \text{.........................................................} \quad 9 \\
2.1.4 & \text{Vertical component of the seismic action} \quad \text{.........................................................} \quad 11 \\
2.1.5 & \text{Seismic analysis of buildings} \quad \text{.................................................................} \quad 12 \\
2.1.5.1 & \text{Seismic mass of the building} \quad \text{..............................................................} \quad 12 \\
2.1.5.2 & \text{Seismic load combination} \quad \text{.................................................................} \quad 12 \\
2.1.5.3 & \text{Structural Regularity} \quad \text{.................................................................} \quad 14 \\
2.1.5.3.1 & \text{Criteria for regularity in plan} \quad \text{..........................................................} \quad 14 \\
2.1.5.3.2 & \text{Criteria for regularity in elevation} \quad \text{.........................................................} \quad 14 \\
2.1.5.4 & \text{Structural Analysis} \quad \text{.................................................................} \quad 15 \\
2.1.5.4.1 & \text{Static lateral force method of analysis} \quad \text{..................................................} \quad 16 \\
2.1.5.4.2 & \text{Modal response spectrum analysis} \quad \text{.....................................................} \quad 16 \\
2.1.5.5 & \text{Accidental torsional effects} \quad \text{.................................................................} \quad 17 \\
2.1.5.6 & \text{Displacements and drift} \quad \text{.................................................................} \quad 18 \\
2.1.5.6.1 & \text{Displacement} \quad \text{.................................................................} \quad 18 \\
2.1.5.6.2 & \text{Inter-storey drift} \quad \text{.................................................................} \quad 18 \\
2.1.5.7 & \text{P-Δ effects} \quad \text{.................................................................} \quad 18 \\
2.2 & \text{Analysis procedure as described in Australian code (AS 1170.4-2007)} \quad \text{..............} \quad 19 \\
2.2.1 & \text{Design seismic action} \quad \text{.................................................................} \quad 19
\end{align*}
\]
2.2.2 Horizontal elastic response spectra .................................................. 22
2.2.3 Vertical component of the seismic action ........................................ 23
2.2.4 Seismic analysis of buildings ............................................................ 23
  2.2.4.1 Seismic weight of the building .................................................. 23
  2.2.4.2 Seismic Load Combination ....................................................... 24
  2.2.4.3 Structural Analysis ................................................................. 24
    2.2.4.3.1 Equivalent Static Analysis ................................................. 24
    2.2.4.3.2 Modal response spectrum analysis ....................................... 29
  2.2.4.4 Earthquake design categories ................................................... 31
    2.2.4.4.1 Earthquake design category I (EDC I) ................................. 31
    2.2.4.4.2 Earthquake design category II (EDC II) ............................... 31
    2.2.4.4.3 Earthquake design category III (EDC III) .............................. 33
2.3 Analysis procedure as described in Indian code [IS 1893 (Part 1) : 2002] .... 34
  2.3.1 Horizontal elastic response spectra ............................................... 34
  2.3.2 Vertical component of the seismic action ...................................... 35
  2.3.3 Design horizontal seismic coefficient ............................................. 35
  2.3.4 Seismic analysis of buildings ......................................................... 38
    2.3.4.1 Seismic weight of the building ............................................... 38
    2.3.4.2 Structural Irregularity ............................................................. 38
      2.3.4.2.1 Plan irregularity ............................................................... 38
      2.3.4.2.2 Vertical irregularity ......................................................... 39
    2.3.4.3 Structural Analysis ............................................................... 40
      2.3.4.3.1 Static lateral force method of analysis ............................... 41
      2.3.4.3.2 Dynamic analysis - Response spectrum method ................ 42
    2.3.4.4 Torsional effects ................................................................. 43
    2.3.4.5 Storey drift limitation ............................................................ 44
2.4 Comparison of analysis procedures as described in the Euro code, the Australian code and the Indian code ......................................................... 44
  2.4.1 Sub-soil conditions ...................................................................... 44
2.4.2 Structural regularity ........................................................................................................... 45
2.4.3 Seismic hazard factor .......................................................................................................... 45
2.4.4 Design base shear force .................................................................................................... 45
2.4.5 Accidental Torsional effect .............................................................................................. 45
2.4.6 P-delta effects ................................................................................................................. 46
2.5 Review over previous research studies ............................................................................... 46
3.0 METHODOLOGY .................................................................................................................... 49
4.0 ANALYSIS ACCORDING TO EURO CODE { EN 1998-1:2004} .................................. 51
4.1 BUILDING "A" ..................................................................................................................... 51
4.1.1 Design seismic action ........................................................................................................ 51
4.1.2 Methods of analysis ......................................................................................................... 52
4.1.2.1 Structural Model ........................................................................................................ 53
4.1.2.2 Lateral force method of analysis ............................................................................... 55
4.1.2.2.1 Estimation of seismic mass of the building ......................................................... 55
4.1.2.2.2 Calculation of seismic base shear ......................................................................... 55
4.1.2.2.3 Distribution of lateral forces ................................................................................ 56
4.1.2.3 Modal response spectrum analysis .............................................................................. 57
4.1.2.3.1 General rules ........................................................................................................ 57
4.1.2.3.2 Periods and effective masses ............................................................................... 58
4.1.2.3.3 Torsional effects .................................................................................................. 58
4.1.2.3.4 Storey shear and displacement .......................................................................... 59
4.1.2.3.5 Inter-storey drift ................................................................................................. 61
4.1.2.3.6 P-Δ effects .......................................................................................................... 63
4.2 BUILDING "B" ..................................................................................................................... 65
4.2.1 Design seismic action ........................................................................................................ 65
4.2.2 Method of analysis ............................................................................................................ 66
4.2.2.1 Structural Model ........................................................................................................ 67
4.2.2.2 Lateral force method of analysis ............................................................................... 68
4.2.2.2.1 Estimation of seismic mass of the building ......................................................... 68
4.2.2.2 Calculating seismic base shear......................................................... 68
4.2.2.2.3 Distribution of lateral forces.......................................................... 69
4.2.2.3 Modal response spectrum analysis.................................................. 70
4.2.2.3.1 General rules ................................................................................ 70
4.2.2.3.2 Periods and effective masses ......................................................... 70
4.2.2.3.3 Torsional effects .......................................................................... 71
4.2.2.3.4. Storey shear and displacement ..................................................... 72
4.2.2.3.5 Inter-storey drift ........................................................................... 73
4.2.2.3.6 P-Δ effects ..................................................................................... 75

4.3 BUILDING "C" ..................................................................................... 77
4.3.1 Design seismic action ....................................................................... 77
4.3.2 Methods of analysis .......................................................................... 79
4.3.2.1 Structural Model .............................................................................. 79
4.3.2.2 Lateral force method of analysis ...................................................... 80
4.3.2.2.1 Estimation of seismic mass of the building .................................... 81
4.3.2.2.2 Calculating seismic base shear ....................................................... 81
4.3.2.2.3 Distribution of lateral forces ........................................................... 82
4.3.2.3 Modal response spectrum analysis .................................................. 83
4.3.2.3.1 General rules ................................................................................ 83
4.3.2.3.2 Periods and effective masses ......................................................... 83
4.3.2.3.3 Torsional effects .......................................................................... 83
4.3.2.3.4. Storey shear and displacement ..................................................... 84
4.3.2.3.5. Inter-storey drift ........................................................................... 85
4.3.2.3.6 P-Δ effects ..................................................................................... 87

5.0 ANALYSIS ACCORDING TO AUSTRALIAN CODE { AS 1170.4-2007} ....... 89
5.1 BUILDING "A" ..................................................................................... 89
5.1.1 Design seismic action ....................................................................... 89
5.1.2 Method of analysis .......................................................................... 90
5.1.2.1 Structural Model .............................................................................. 91
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1.2.2.2</td>
<td>Equivalent static analysis</td>
<td>92</td>
</tr>
<tr>
<td>5.1.2.2.2.1</td>
<td>Estimation of seismic weight of the building</td>
<td>93</td>
</tr>
<tr>
<td>5.1.2.2.2.2</td>
<td>Calculation of seismic base shear</td>
<td>93</td>
</tr>
<tr>
<td>5.1.2.2.2.3</td>
<td>Distribution of lateral forces</td>
<td>95</td>
</tr>
<tr>
<td>5.1.2.2.3</td>
<td>Modal response spectrum analysis</td>
<td>96</td>
</tr>
<tr>
<td>5.1.2.2.3.1</td>
<td>General rules</td>
<td>96</td>
</tr>
<tr>
<td>5.1.2.2.3.2</td>
<td>Periods and effective masses</td>
<td>96</td>
</tr>
<tr>
<td>5.1.2.2.3.3</td>
<td>Torsional effects</td>
<td>97</td>
</tr>
<tr>
<td>5.1.2.2.3.4</td>
<td>Storey shear and displacements</td>
<td>98</td>
</tr>
<tr>
<td>5.1.2.2.3.5</td>
<td>Storey drifts</td>
<td>99</td>
</tr>
<tr>
<td>5.1.2.2.3.6</td>
<td>P-Δ effects</td>
<td>100</td>
</tr>
<tr>
<td>5.2</td>
<td>BUILDING &quot;B&quot;</td>
<td>102</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Design seismic action</td>
<td>102</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Method of analysis</td>
<td>104</td>
</tr>
<tr>
<td>5.2.2.1</td>
<td>Structural Model</td>
<td>104</td>
</tr>
<tr>
<td>5.2.2.2</td>
<td>Equivalent static analysis</td>
<td>105</td>
</tr>
<tr>
<td>5.2.2.2.1</td>
<td>Estimation of seismic weight of the building</td>
<td>106</td>
</tr>
<tr>
<td>5.2.2.2.2</td>
<td>Calculation of seismic base shear</td>
<td>106</td>
</tr>
<tr>
<td>5.2.2.2.3</td>
<td>Distribution of lateral forces</td>
<td>108</td>
</tr>
<tr>
<td>5.2.2.3</td>
<td>Modal response spectrum analysis</td>
<td>108</td>
</tr>
<tr>
<td>5.2.2.3.1</td>
<td>General rules</td>
<td>108</td>
</tr>
<tr>
<td>5.2.2.3.2</td>
<td>Periods and effective masses</td>
<td>109</td>
</tr>
<tr>
<td>5.2.2.3.3</td>
<td>Torsional effects</td>
<td>109</td>
</tr>
<tr>
<td>5.2.2.3.4</td>
<td>Storey shear and displacements</td>
<td>110</td>
</tr>
<tr>
<td>5.2.2.3.5</td>
<td>Storey drifts</td>
<td>111</td>
</tr>
<tr>
<td>5.2.2.3.6</td>
<td>P-Δ effects</td>
<td>112</td>
</tr>
<tr>
<td>5.3</td>
<td>BUILDING &quot;C&quot;</td>
<td>114</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Design seismic action</td>
<td>114</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Method of analysis</td>
<td>116</td>
</tr>
</tbody>
</table>
5.3.2.1 Structural Model .......................................................................................... 116
5.3.2.2 Equivalent static analysis ............................................................................ 117
   5.3.2.2.1 Estimation of seismic weight of the building................................. 118
   5.3.2.2.2 Calculating seismic base shear ....................................................... 118
   5.3.2.2.3 Distribution of lateral forces ............................................................ 119
5.3.2.3 Modal response spectrum analysis ............................................................. 120
   5.3.2.3.1 General rules ..................................................................................... 120
   5.3.2.3.2 Periods and effective masses ......................................................... 121
   5.3.2.3.3 Torsional effects ............................................................................. 121
   5.3.2.3.4 Storey shear and displacements ..................................................... 122
   5.3.2.3.5 Storey drifts .................................................................................... 123
   5.3.2.3.6 P-Δ effects ...................................................................................... 124
6.0 ANALYSIS ACCORDING TO IS 1893(Part 1) : 2002 ........................................... 126
6.1 BUILDING "A" .................................................................................................. 126
   6.1.1 Design seismic action .............................................................................. 126
   6.1.2 Method of analysis ................................................................................... 127
      6.1.2.1 Structural Model .............................................................................. 127
      6.1.2.2 Lateral force method (Static analysis) ............................................... 129
         6.1.2.2.1 Seismic weight of the building .................................................... 130
         6.1.2.2.2 Design seismic base shear ......................................................... 130
         6.1.2.2.3 Distribution of lateral forces ....................................................... 131
      6.1.2.3 Modal response spectrum analysis ..................................................... 132
         6.1.2.3.1 General rules .............................................................................. 132
         6.1.2.3.2 Periods and effective masses ..................................................... 133
         6.1.2.3.3 Torsional effects ....................................................................... 133
         6.1.2.3.4 Storey shear forces by modal response spectrum analysis method . 134
         6.1.2.3.5 Storey displacement and drift .................................................... 136
6.2 BUILDING "B" .................................................................................................. 139
   6.2.1 Design seismic action ............................................................................... 139
6.2.2 Method of analysis

6.2.2.1 Structural Model

6.2.2.2 Equivalent static analysis

6.2.2.2.1 Seismic weight of the building

6.2.2.2.2 Design seismic base shear

6.2.2.2.3 Distribution of lateral forces

6.2.2.3 Modal response spectrum analysis

6.2.2.3.1 General rules

6.2.2.3.2 Periods and effective masses

6.2.2.3.3 Torsional effects

6.2.2.3.4 Storey shear forces by modal response spectrum analysis method

6.2.2.3.5 Storey displacement and drift

6.3 BUILDING "C"

6.3.1 Design seismic action

6.3.2 Method of analysis

6.3.2.1 Structural Model

6.3.2.2 Equivalent static analysis

6.3.2.2.1 Seismic weight of the building

6.3.2.2.2 Design seismic base shear

6.3.2.2.3 Distribution of lateral forces

6.3.2.3 Modal response spectrum analysis

6.3.2.3.1 General rules

6.3.2.3.2 Periods and effective masses

6.3.2.3.3 Torsional effects

6.3.2.3.4 Storey shear forces by modal response spectrum analysis method

6.3.2.3.5 Storey displacement and drift

7.0 COMPARISON OF PERFORMANCE LEVEL OF BUILDINGS WITH DIFFERENT CODES OF PRACTICE

7.1 Comparison based on target performance level
7.2 Comparison based on higheststorey drift ratios ................................................................. 163
7.3 Comparison based on design base shear force ................................................................. 164
8.0 CONCLUSION AND RECOMMENDATIONS ................................................................. 167
REFERENCES ........................................................................................................................ 168
APPENDIX A : BASIC DETAILS OF BUILDING - A ................................................................. 170
A1. Eighteen storied residential apartment building ............................................................. 170
A2. Basic calculations according to EN 1998-1:2004 ........................................................... 179
A2.1 Structural regularity ....................................................................................................... 179
A2.1.1 Criteria for regularity in plan ..................................................................................... 179
A2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration ......... 181
A2.1.2 Criteria for regularity in elevation .......................................................................... 184
APPENDIX B : BASIC DETAILS OF BUILDING - B ................................................................. 185
B1. Fourteen storied residential apartment building ............................................................. 185
B2. Basic calculations according to EN 1998-1:2004 ........................................................... 197
B2.1 Structural regularity ...................................................................................................... 197
B2.1.1 Criteria for regularity in plan ..................................................................................... 197
B2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration ......... 199
B2.1.2 Criteria for regularity in elevation .......................................................................... 200
APPENDIX C : BASIC DETAILS OF BUILDING - C ................................................................. 201
C1. Ten storied residential apartment building .................................................................... 201
C2. Basic calculations according to EN 1998-1:2004 ........................................................... 205
C2.1 Structural regularity ...................................................................................................... 205
C2.1.1 Criteria for regularity in plan ..................................................................................... 205
C2.1.1.1 Determining the structural eccentricities, torsional radii and radii of gyration ......... 207
C2.1.2 Criteria for regularity in elevation .......................................................................... 208
LIST OF TABLES

Table EN-1 : Classifications of buildings into important classes 7
Table EN-2 : Design peak ground acceleration values ($a_g$) 8
Table EN-3 : Soil classification and parameters defining horizontal elastic response spectra 9
Table EN-4 : Basic value of the behavior factor ($q_0$) for systems regular in elevation (EN 1998-1:2004/5.2.2.2 (Table 5.1)) 10
Table EN-5 : Factor $k_w$ reflecting the prevailing failure mode (EN 1998-1:2004/5.2.2.2 (11)P) 11
Table EN-6 : Approximate values for multiplication factor $\alpha_{it}/\alpha_1$ for buildings regular in plan (EN 1998-1:2004/5.2.2.2 (5)) 11
Table EN-7 : Recommended values of $\psi$ factors in EN 1990/Table A1.1 13
Table EN-8 : Definitions of different categories A-E 13
Table EN-9 : Values of $\varphi$ factors 14
Table EN-10 : Consequences of structural regularity on structural model and the analysis method 15
Table AS-1 : Reference probability of exceedance 19
Table AS-2 : Classification of buildings in to important classes 20
Table AS-3 : Selection of earthquake design categories 21
Table AS-4 : Probability factor $k_p$ 22
Table AS-5 : Equations for spectra 23
Table AS-6 : Structural ductility factor ($\mu$) and structural performance factor ($S_p$) - Basic structures 27
Table AS-7 : Value of $K_s$ for structures not exceeding 15m 32
Table IS-1 : Soil classification and parameters defining horizontal elastic response spectra 35
Table IS-2 : Zone factor, $Z$ (Table 2 of IS 1893 (Part 1) : 2002) 36
Table IS-3 : Importance Factor, $I$ (Table 6 of IS 1893 (Part 1) : 2002) 36
Table IS-4 : Response reduction factor $R$ (Table 7 of IS 1893 (Part 1) : 2002) 37
Table IS-5 : Percentage of imposed load to be considered in seismic weight calculation in (Table 8 of IS 1893 (Part 1) : 2002) 38
Table IS-6 : Consequences of structural regularity on structural model and the analysis method 40
Table EA-1 : Total seismic mass of building A 55
Table EA-2 : Correction factor, $\lambda$ for building A 56
Table EA-3 : Seismic base shear of building A 56
Table EA-4 : Distribution of seismic base shear at each storey level - Building A 57
Table EA-5 : Periods and effective modal mass participation of building A (Modal response spectrum analysis) 58
Table EA-6 : Torsional moments at each horizontal direction 59
Table EA-7 : Storey shear forces of building A (Modal response spectrum analysis method) 60
Table EA-8 : Design displacement ($d_s$) of the test building at each storey level (Modal response spectrum analysis method) 60
Table EA-9 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Soft soil conditions 61
Table EA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Medium soil conditions

Table EA-11 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Hard soil conditions

Table EA-12 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Soft soil conditions.

Table EA-13 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Medium soil conditions

Table EA-14 : Calculation of inter-storey drift sensitivity coefficient at each level of building A from modal response spectrum analysis – Hard soil conditions

Table EB-1 : Total seismic mass of building B

Table EB-2 : Correction factor, $\lambda$ for building B

Table EB-3 : Seismic base shear of building B

Table EB-4 : Distribution of seismic base shear at each storey level - Building B

Table EB-5 : Periods and effective modal mass participation of building B (Modal response spectrum analysis)

Table EB-6 : Torsional moments at each horizontal direction

Table EB-7 : Storey shear forces of building B (Modal response spectrum analysis method)

Table EB-8 : Design displacement ($d_s$) of the test building at each storey level (Modal response spectrum analysis method)

Table EB-9 : Parameters defining the criteria for damage
limitation requirement by modal response spectrum analysis - Soft soil conditions

Table EB-10: Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Medium soil conditions

Table EB-11: Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Hard soil conditions

Table EB-12: Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Soft soil conditions

Table EB-13: Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Medium soil conditions

Table EB-14: Calculation of inter-storey drift sensitivity coefficient at each level of building B from modal response spectrum analysis – Hard soil condition

Table EC-1: Total seismic mass of building C
Table EC-2: Correction factor, $\lambda$ for building C
Table EC-3: Seismic base shear of building C
Table EC-4: Distribution of seismic base shear at each storey level - Building C
Table EC-5: Periods and effective modal mass participation of building C (Modal response spectrum analysis)
Table EC-6: Torsional moments at each horizontal direction
Table EC-7: Storey shear forces of building C (Modal response spectrum analysis method)
Table EC-8: Design displacement ($d_s$) of the test building at each storey level (Modal response spectrum analysis)
Table EC-9 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis - Soft soil conditions

Table EC-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Medium soil conditions

Table EC-11 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Hard soil conditions

Table EC-12 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Soft soil conditions.

Table EC-13 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Medium soil conditions

Table EC-14 : Calculation of inter-storey drift sensitivity coefficient at each level of building C from modal response spectrum analysis – Hard soil conditions

Table AA-1 : Total seismic weight of building A

Table AA-2 : Design seismic base shear of building A ($T_1$ from modal analysis)

Table AA-3 : Design seismic base shear of building A ($T_1$ from eq. 6.2(7) of AS 1170.4-2007)

Table AA-4 : Design seismic base shear of building A

Table AA-5 : Distribution of seismic base shear at each storey level

Table AA-6 : Periods and effective modal mass participation of building A (Modal response spectrum analysis)
Table AA-7 : Torsional moments - Building A  
Table AA-8 : Storey shear forces of building A (Modal response spectrum analysis method)  
Table AA-9 : Design displacement (d_s) of the test building at each storey level (Modal response spectrum analysis method)  
Table AA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building A  
Table AA-11 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Very soft soil conditions  
Table AA-12 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Shallow soil conditions  
Table AA-13 : Calculation of inter-storey stability coefficient at each level of building A from modal response spectrum analysis – Rock conditions  
Table AB-1 : Total seismic weight of building B  
Table AB-2 : Design seismic base shear of building B (T_1 from modal analysis)  
Table AB-3 : Design seismic base shear of building B (T_1 from eq. 6.2(7) of AS 1170.4-2007)  
Table AB-4 : Design seismic base shear of building B  
Table AB-5 : Distribution of seismic base shear at each storey level  
Table AB-6 : Periods and effective modal mass participation of building B (Modal response spectrum analysis)  
Table AB-7 : Torsional moments - Building B  
Table AB-8 : Storey shear forces of building B (Modal response spectrum analysis)
spectrum analysis method)

Table AB-9 : Design displacement \(d_i\) of the test building at each storey level (Modal response spectrum analysis method)

Table AB-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building B

Table AB-11 : Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Very soft soil conditions

Table AB-12 : Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Shallow soil conditions

Table AB-13 : Calculation of inter-storey stability coefficient at each level of building B from modal response spectrum analysis – Rock conditions

Table AC-1 : Total seismic weight of building C

Table AC-2 : Design seismic base shear of building C \(T_1\) from modal analysis

Table AC-3 : Design seismic base shear of building C \(T_1\) from eq. 6.2(7) of AS 1170.4-2007

Table AC-4 : Design seismic base shear of building C

Table AC-5 : Distribution of seismic base shear at each storey level

Table AC-6 : Periods and effective modal mass participation of building C (Modal response spectrum analysis)

Table AC-7 : Torsional moments - Building C

Table AC-8 : Storey shear forces of building C (Modal response spectrum analysis method)

Table AC-9 : Design displacement \(d_i\) of the test building at each
storey level (Modal response spectrum analysis method)

Table AC-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building C

Table AC-11 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Very soft soil conditions

Table AC-12 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Shallow soil conditions

Table AC-13 : Calculation of inter-storey stability coefficient at each level of building C from modal response spectrum analysis – Rock conditions

Table IA-1 : Seismic weight of building A

Table IA-2 : Design seismic base shear by static lateral force method - Building A

Table IA-3 : Distribution of design seismic base shear at each storey level - Building A

Table IA-4 : Periods and effective modal mass participation by modal response spectrum analysis - Building A

Table IA-5 : Torsional moments - Building A

Table IA-6 : Storey shear forces by modal response spectrum analysis method - Building A

Table IA-7 : Summary of base shear forces - Building A

Table IA-8 : Modified storey shear forces by modal response spectrum analysis method - Building A

Table IA-9 : Storey displacement (d) by modal response spectrum analysis method - Building A

Table IA-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis method - Building A
limitation requirement by modal response spectrum analysis – Building A

Table IA-11 : Modified storey displacements by modal response spectrum analysis method – Building A

Table IA-12 : Adjusted storey displacements by modal response spectrum analysis method – Building A

Table IB-1 : Seismic weight of building B

Table IB-2 : Design seismic base shear by static lateral force method - Building B

Table IB-3 : Distribution of design seismic base shear at each storey level - Building B

Table IB-4 : Periods and effective modal mass participation by modal response spectrum analysis - Building B

Table IB-5 : Torsional moments - Building B

Table IB-6 : Storey shear forces by modal response spectrum analysis method - Building B

Table IB-7 : Summary of base shear forces - Building B

Table IB-8 : Modified storey shear forces by modal response spectrum analysis method - Building B

Table IB-9 : Storey displacement (d) by modal response spectrum analysis method - Building B

Table IB-10 : Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building B

Table IB-11 : Modified storey displacements by modal response spectrum analysis method - Building B

Table IB-12 : Adjusted storey displacements by modal response spectrum analysis method - Building B

Table IC-1 : Seismic weight of building C
| Table IC-2 | Design seismic base shear by static lateral force method - Building C | 154 |
| Table IC-3 | Distribution of design seismic base shear at each storey level - Building C | 155 |
| Table IC-4 | Periods and effective modal mass participation by modal response spectrum analysis - Building C | 156 |
| Table IC-5 | Torsional moments - Building C | 157 |
| Table IC-6 | Storey shear forces by modal response spectrum analysis method - Building C | 157 |
| Table IC-7 | Summary of base shear forces - Building C | 158 |
| Table IC-8 | Modified storey shear forces by modal response spectrum analysis method - Building C | 158 |
| Table IC-9 | Storey displacement (d) by modal response spectrum analysis method - Building C | 159 |
| Table IC-10 | Parameters defining the criteria for damage limitation requirement by modal response spectrum analysis – Building C | 159 |
| Table IC-11 | Modified storey displacements by modal response spectrum analysis method - Building C | 160 |
| Table IC-12 | Adjusted storey displacements by modal response spectrum analysis method - Building A | 160 |
| Table 7.1.1 | Transient lateral drift at roof level of the three structures | 162 |
| Table 7.1.2 | Code of practice for highest and lowest drift ratio at roof level | 162 |
| Table 7.2.1 | Highest storey drift ratio at any storey level | 163 |
| Table 7.2.2 | Code of practice for maximum and minimum value of highest storey drift ratio at any storey level | 164 |
| Table 7.3.1 | Design base shear force of the three structures | 165 |
Table 7.3.2 : Code of practice for highest and lowest design base shear force 165

Table A1 : Material properties used in the analysis 176

Table A2 : Design loads used in the analysis 176

Table A3 : Approximate calculation of dead load on the test buildings 177

Table A4 : Approximate calculation of imposed load on the test buildings 179

Table A5 : Fundamental period of vibration obtained from modal analysis 179

Table A6 : Structural eccentricity, torsional radius and radii of gyration in each horizontal direction 181

Table A7 : Structural eccentricity in each horizontal direction 182

Table A8 : Torsional radii in each horizontal direction 183

Table A9 : Radius of gyration 184

Table B1 : Material properties used in the analysis 190

Table B2 : Design loads used in the analysis 191

Table B3 : Approximate calculation of dead load of the test building 192

Table B4 : Approximate calculation of imposed load of the test buildings 197

Table B5 : Fundamental period of vibration obtained from modal analysis 197

Table B6 : Structural eccentricity, torsional radius and radii of gyration in each horizontal direction 198

Table B7 : Structural eccentricity in each horizontal direction 199

Table B8 : Torsional radii in each horizontal direction 199

Table B9 : Radius of gyration 200
| Table C1 | Material properties used in the analysis | 202 |
| Table C2 | Design loads used in the analysis | 202 |
| Table C3 | Approximate calculation of dead load on the test building | 203 |
| Table C4 | Approximate calculation of imposed load on the test buildings | 205 |
| Table C5 | Fundamental period of vibration obtained from modal analysis | 205 |
| Table C6 | Structural eccentricity, torsional radius and radii of gyration in each horizontal direction | 206 |
| Table C7 | Structural eccentricity in each horizontal direction | 207 |
| Table C8 | Torsional radii in each horizontal direction | 207 |
| Table C9 | Radius of gyration | 208 |
LIST OF FIGURES

Figure EA-1 : Elastic response spectrum and design response spectrum - Building A 52
Figure EA-2 : Three dimensional (spatial) model of Building A 54
Figure EB-1 : Elastic response spectrum and design response spectrum - Building B 66
Figure EB-2 : Three dimensional (spatial) model of Building B 67
Figure EC-1 : Elastic response spectrum and design response spectrum - Building C 78
Figure EC-2 : Three dimensional (spatial) model of Building C 80
Figure AA-1 : Three dimensional (spatial) model of Building A 92
Figure AB-1 : Three dimensional (spatial) model of Building B 105
Figure AC-1 : Three dimensional (spatial) model of Building C 117
Figure IA-1 : Three dimensional (spatial) model of Building A 129
Figure IB-1 : Three dimensional (spatial) model of Building B 141
Figure IC-1 : Three dimensional (spatial) model of Building B 152
Figure A1 : Plan View - Ground floor 171
Figure A2 : Plan View - First floor 171
Figure A3 : Plan View – 2nd to 4th floor 172
Figure A4 : Plan View – 5th floor 172
Figure A5 : Plan View – 6th to 16th floor 173
Figure A6 : Plan View – 17th floor 173
Figure A7 : Plan View – Roof floor 174
Figure A8 : Cross section A-A of the buildings 175
Figure B1 : Plan View - Ground floor 186
Figure B2 : Plan View - First floor 187
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure B3</td>
<td>Plan View – 2nd to 13th floor</td>
<td>188</td>
</tr>
<tr>
<td>Figure B4</td>
<td>Plan View – Roof floor</td>
<td>189</td>
</tr>
<tr>
<td>Figure B5</td>
<td>Cross section A-A of the buildings</td>
<td>190</td>
</tr>
<tr>
<td>Figure C1</td>
<td>Plan View - First Floor</td>
<td>201</td>
</tr>
<tr>
<td>Figure C2</td>
<td>Plan View - Typical Floor</td>
<td>202</td>
</tr>
</tbody>
</table>