Adapting the structural design actions standard for the seismic design of new industrial plant

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ABSTRACT: There are overseas publications that have considered the differences in the typical structural systems necessary to support the equipment and distributive systems needed to process industrial feedstock. Current standards as ASCE 7 and FEMA 450 incorporate these in a specific manner relating to the design of industrial plant. The design engineer for industrial structures is required to develop a feel for how nonbuilding structures behave with a shortage of research into their earthquake performance. A degree of conservatism in the design approach for these structures is warranted until their behaviour is more fully documented and researched. This paper takes the opportunity to review AS/NZS 1170 and adapt these overseas guidelines for the seismic design of new industrial plant in New Zealand.

1 INTRODUCTION

The need to get overseas structural and mechanical design engineers to be familiar with the 1976 version of NZS 4203 with its preference for strength design for the impending “Think Big” projects led to the commissioning by the Ministry of Energy and subsequent publishing in 1981 of the document “Seismic Design of Petrochemical Plants” (SDPP). NZS 4203 was subsequently revised in 1984 and in 1992 moving progressively to a limit state based approach to the design of new buildings. This has continued with the new standards AS/NZS 1170 Parts 0, 1, 2 and 3 and NZS 1170.5.

ASCE (1997) outlines specific seismic design approaches for the nonbuilding-like structures encountered in petrochemical plants. Although aimed at petrochemical plants, the philosophies are able to be used for other industrial plants. The ASCE recommendations have been incorporated into other design codes used for the design of industrial facilities in North America such as ASCE 7-02 Section 9.14 “Nonbuilding Structures” and FEMA 450 Chapter 14 “Nonbuilding Structure Design Requirements”. In 2002, the American Lifelines Alliance (ALA) published their recommendations for the seismic design of new and seismic retrofitting of existing pressure piping. This included a proposed seismic design standard for the range of piping within the scope of the ASME B31 series of pressure piping codes.

This paper takes the ASCE guidelines (1997), uses NZS 4203:1992, AS/NZS 1170.0, NZS 1170.5, FEMA 450, the ALA guidelines (2002) and relevant legislative requirements to develop design methods for typical structures within an industrial or petrochemical plant.

2 RELEVANT LEGISLATION AND GUIDELINES

2.1 Legislation

In general, all work on New Zealand soil for industrial plant is subject to the consents and approvals granted by the appropriate authority empowered under the following Acts/Regulations:

- Resource Management Act.
- New Zealand Building Code (NZBC), a schedule to the Building Regulations made under the Building Act.
• Pressure Equipment, Cranes and Passenger Ropeways Regulations (PECPR) made under the Health and Safety in Employment (HSE) Act.
• Hazardous Substances and New Organisms (HSNO) Act.

2.2 Guidelines
Those items that come under the PECPR Regulations and the HSNO Act will also be subject to mechanical design considerations and the appropriate approvals and Design Verification. These requirements have been elaborated in approved code of practices (ACOP) or compliance guides written by either the Occupational Safety or Health Service for the HSE Act or the Environmental Risk Management Authority for the HSNO Act.

3 STRUCTURAL SYSTEMS

3.1 General
Structures found in industrial and petrochemical facilities support the process, mechanical and electrical items that are located above ground. Hence, they are the primary means that ground shaking from an earthquake is introduced to these non-structural items.

3.2 Types of Structures
Industrial structures can be separated into two main structural types:

1. Building structures.
2. Nonbuilding structures.

The “Nonbuilding structures” can be divided further into two sub-categories:

1. Building-like structures.
2. Nonbuilding-like structures.

3.3 Building Structures
These are buildings that the NZBC and associated standards apply directly to without modification. Typically for industrial sites, these are administration buildings, buildings providing weather and/or hygienic protection to people who produce, repair or store goods, substations, maintenance buildings, shelters, compressor houses etc. These structures will generally have a NZBC classification of either Industrial or Outbuilding and are not the subject of this paper.

3.4 Nonbuilding Structures
Other than actual buildings, all structures within an industrial/petrochemical facility are typically nonbuilding structures. Some of these have structural systems that resemble those of buildings such as multi-storey modules or pipe racks. Hence, these types of structures can be classified as building-like structures. Other structures whose structural systems do not resemble buildings are classified as nonbuilding-like structures. These structures will generally have a NZBC classification of Ancillary.

3.4.1 Building-like Structures
These are structures (generally unclad) such as pipe racks and multi-storey modules that have Lateral Force Resisting Systems (LFRS) similar to those of buildings and their analysis can be undertaken as per Section 4.

3.4.2 Nonbuilding-like Structures
These structures can be subdivided into four subcategories:

1. Rigid structures with a natural period of vibration $T_1 < 0.06$ secs such as pumps, compressors or squat horizontal vessels supported either by ground slab foundations or short stiff piers. A design seismic coefficient can be determined from Section 4.2 assuming system damping has
little effect and $\mu = 1.0$ or $1.25$ depending on whether any limited ductility can be utilised.


3. Combination structures. These support non-structural items (such as process related equipment, ducting or piping) whose weight exceeds 20% of the supporting structure’s weight. The supporting structure generally being building-like. Appropriate analysis methods are discussed below in Section 5.

4. Others. Examples include skirt supported vertical vessels, spheres, guyed structures and vertical fired heaters supported on braced legs. These are generally either slender or vertically irregular and require a modal response spectrum analysis as discussed below in Section 4.3.

3.5 Parts and Components

When a non-structural item’s combined weight is less than 20% of the total weight of the structure, it shall be considered as a part or as a component. The seismic analysis of these items is discussed in Section 6. Examples of non-structural items classed as either a part or a component typically found in an industrial facility include:

1. Components such as; pressure equipment e.g. horizontal vessels, exchangers and piping, tubing, cable tray/ladders, lights, conduit, instruments, pumps and ductwork.

2. Parts such as access platforms and ladders.

4 EARTHQUAKE ANALYSIS FOR NEW INDUSTRIAL PLANT

4.1 Design Actions

The general equation for seismic forces modifies the 5% damped elastic hazard curves to allow for the assumed level of ductility, actual building performance and damping. This is shown in the NZS 1170.5 equations 5.2(1), 5.2(3) and 5.2(4). These can be further modified to suit industrial structures:

$$C_d(T) = C(T) * S_p / k_{\mu} * C_f(\xi) * K$$ (1)

Where the factors are as per NZS 1170.5 and; $C_f(\xi)$ = damping scaling factor for the appropriate limit state; $K$ = scaling factor that accounts for a variety of ultimate limit state (ULS) effects that may need to be considered such as P-Delta effects, material standard seismic load modifiers, modal response spectrum method ULS scaling factor $k$ etc.

4.2 Equivalent Static Analysis Method (ESA)

4.2.1 Ultimate Limit State Horizontal Design Actions

Equation (1) is used where the factors are determined for the ULS where; $T = T_1$ the ULS fundamental translational period of vibration; and $K = k_1 * k_2$; where $k_1$ = ESA P-Delta scaling factor and $k_2$ = material standard earthquake actions modifier factor.

4.2.2 Serviceability Limit State Horizontal Actions

Equation (1) is used where the factors are determined for the appropriate serviceability limit state; SLS1 or SLS2 including $T_1$ determined for the appropriate serviceability limit state.

4.2.3 Ultimate Limit State Vertical Design Actions

The main ULS equation is set out in Equations 3.2(1) and 5.4(1) of NZS 1170.5:

$$C_v(T_v) = C_v(T_v) * S_p * C_f(\xi)$$ (2)

Where $T_v$ = the fundamental vertical period of the structure or element under consideration.

Clause 5.4.1 NZS 1170.5 sets $T_v = 0.0$ secs for buildings. For industrial structures, the mass
distribution may be such that significant masses for nonbuilding items may be not set over columns and a $T_p > 0.0$ secs may be more appropriate.

4.2.4 Serviceability Limit State Vertical Actions

Equation (2) is used where the factors are determined for the appropriate serviceability limit state; SLS1 or SLS2.

4.3 Modal Response Spectrum Analysis Method (MRSA)

4.3.1 Ultimate Limit State Equation for Horizontal Design Actions

Equation (1) is used where the factors are determined for the ULS where: $K = k_3 \times k_4 \times k_5$ where $k_3 =$ MRSA P-Delta scaling factor; $k_4 =$ MRSA effects scaling factor $k$ if base shear comparisons with ESA base shear are required to be considered; $k_5 =$ material standard earthquake actions modifier factor.

4.3.2 Serviceability Limit State Equation for Horizontal Design Actions

Equation (1) is used where the factors are determined for the appropriate serviceability limit state; SLS1 or SLS2.

4.3.3 Limit State Equations for Vertical Design Actions

Equation (2) is used where the factors are determined for the appropriate limit state; ULS, SLS1 or SLS2.

5 GUIDELINES FOR EARTHQUAKE ANALYSIS OF COMBINATION STRUCTURES

5.1 General

Combination structures generally will have difficulty meeting the horizontal and/or vertical regularity requirements of Section 4.5 of NZS 1170.5. Thus depending on the overall height and the fundamental period of the combined system, the equivalent static analysis method may not be applicable.

5.2 Method of Analysis

Section 4.4.3 and Appendix 4.B of the ASCE guidelines (1997) outlines their recommended analysis approach. The method of analysis differs depending on whether the nonbuilding item is flexible ($T_p > 0.06$ secs) or not ($T_p \leq 0.06$ secs). One aspect of the ASCE approach that has not been universally adopted is that the minimum value for the structural ductility factor for either the nonbuilding item or the supporting structure shall be used for the design of the entire system, i.e. $\mu = [\mu_p, \mu_s]_{\text{min}}$. FEMA 450 Clause 14.1.5 differs in that for rigid nonbuilding items, the combined system is designed using the structural ductility factor for the supporting structure, i.e. $\mu = \mu_s$. For flexible nonbuilding items, FEMA 450 restricts $\mu$ to being $\leq 3.0$.

For those supporting structures that are supporting pressure equipment covered by PECPR, the minimum seismic coefficients set out in NZS 1200 Appendix I often govern as required by OSH (2001). Unless the site has a specific seismic hazard study, the effect of the NZS 1200 Appendix I minimum values usually limits $\mu$ to a maximum value of 1.25.

5.2.1 Rigid Nonbuilding Items – Case 1

The actions on the supporting structure are determined using the procedures outlined above in Sections 4.2 or 4.3 with the overall heights adjusted for the masses of the rigid nonbuilding items.

The actions on the nonbuilding item are determined using the procedures outlined below in Section 6. These are based on Section 8 of NZS 1170.5 for parts and components. The chosen value for $\mu_p$ does have an effect on the magnitude of $F_{ph}$ and the designer needs to assess what is the maximum value that can be given to the structural ductility factor for the nonbuilding item. Suggested values for the part structural ductility factor have been given in Table C8.2 of NZS 1170.5 Supp 1. Note 4 to this
table states that the designer needs to consider when the nonbuilding item can start to sustain damage and whether continuity of operation is required after a ULS event. C8.6 of NZS 1170.5 Supp 1 states:

In many instances, especially with mechanical services plant, the design of the part is based on non-structural considerations, and proportioning is such that yielding is unlikely and $\mu_p$ should be taken as 1.0.

5.2.2 Flexible Nonbuilding Items – Case 2

The nonbuilding item is included in the analysis model as specific structural members. The masses of the nonbuilding items are kept separate from the rest of the supporting structure. The actions on the combined structure are determined using the procedures outlined above in Sections 4.2 or 4.3 with the overall heights including those to the masses of the flexible nonbuilding items. The actions on the nonbuilding item are determined also using the combined model.

To derive any benefit in providing a ductile support structure with $\mu > 3$ for a combination structure to reduce the earthquake forces on nonbuilding items, a special study involving non-linear time history analyses would be necessary.

5.2.3 Summary

Table 1 gives the two design cases, Case 1 and Case 2 and details how the seismic coefficients shall be derived for the ULS. Case 2 can always be used in lieu of undertaking a Case 1 analysis.

### Table 1. Analysis Methods for Combination Structures

<table>
<thead>
<tr>
<th>Description</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of supported nonbuilding item</td>
<td>$T_p \leq 0.06$ secs</td>
<td>$T_p &gt; 0.06$ secs</td>
</tr>
<tr>
<td>Fundamental horizontal period of system</td>
<td>$T_1$ determined for combined system</td>
<td>$T_1$ determined for combined system</td>
</tr>
<tr>
<td>Structural ductility factor</td>
<td>$\mu = \mu_s$</td>
<td>$\mu = [\mu_p, \mu_s]_{\text{min}}$ and $\mu \leq 3$</td>
</tr>
<tr>
<td>Structural performance factor</td>
<td>$S_p = S_{ps}$</td>
<td>$S_p = [S_{pe}, S_{ps}]_{\text{max}}$</td>
</tr>
<tr>
<td>System damping</td>
<td>$C_d(\xi) = C_d(\xi)_s$</td>
<td>$C_d(\xi) = [C_d(\xi)_p, C_d(\xi)<em>s]</em>{\text{max}}$</td>
</tr>
<tr>
<td>Seismic Weight</td>
<td>$W_t = W_n + W_s$</td>
<td>$W_t = W_n + W_s$</td>
</tr>
<tr>
<td>Heights to seismic masses</td>
<td>Heights to masses adjusted for mass of nonbuilding item</td>
<td>Floor heights include those to masses of nonbuilding items</td>
</tr>
<tr>
<td>ULS Inelastic Spectrum Scaling factor</td>
<td>$k_d$ determined for $T_1$ based on the site soil class and fundamental period (with $T_1$ taken not less than 0.4 secs)</td>
<td>$k_d$ determined for $T_1$ based on the site soil class and fundamental period (with $T_1$ taken not less than 0.4 secs)</td>
</tr>
<tr>
<td>Horizontal design action coefficient</td>
<td>$C_d(T_1)$ based on system’s period</td>
<td>$C_d(T)$ based on period of combined system</td>
</tr>
<tr>
<td>Base Shear</td>
<td>$V = C_d(T_1) W_t$ For structures supporting pressure equipment; $C_d(T_1) \geq$ applicable value from Table I1 of NZS 1200</td>
<td>$V = C_d(T_1) W_t$ For structures including modelled pressure equipment; $C_d(T_1) \geq$ applicable value from Table I1 of NZS 1200</td>
</tr>
<tr>
<td>Support structure’s member forces</td>
<td>Determined from model by either equivalent static analysis or modal response spectrum analysis</td>
<td>Determined from combined model by either equivalent static analysis or modal response spectrum analysis</td>
</tr>
</tbody>
</table>
### Description | Case 1 | Case 2
--- | --- | ---
Nonbuilding item’s member forces | Forces on nonbuilding item are determined from Section 8 of NZS 1170.5 using $T_p$, $\mu_p$, $R_p$, $C_{ph}$ and $C_i(\xi)$, applied through the centre of gravity of the nonbuilding item | Determined from combined model by either equivalent static analysis or modal response spectrum analysis

Where the factors are as per NZS 1170.5 and; $W_s =$ weight of support structure; $\mu_s =$ structural ductility factor for support structure; $S_{pe}$ = structural performance factor for nonbuilding item; $S_{ps}$ = structural performance factor for support structure; $C_f(\xi)$ = damping factor for support structure.

### 6 GUIDELINES FOR EARTHQUAKE ANALYSIS OF PARTS AND COMPONENTS

#### 6.1 General

The derivation of the applicable seismic forces shall be as per Section 8 of NZS 1170.5, “Requirements for Parts and Components” including any deflection induced forces as per NZS 1170.5 clause 8.5.3.

#### 6.2 Method of Analysis

Table 2 gives the design case, Case 3 for the ULS/SLS2/SLS1 limit states and details how the seismic actions shall be derived. In general, the method of calculating the response for the part or component is not dependent on whether the part or component is rigid or flexible. The value for the period of the part, $T_p$ only affects the value for the part spectral shape coefficient, $C_i(T_p)$.

The results for the horizontal design earthquake actions on a part or component as per a Section 8 analysis is also not dependent on the chosen or actual structural ductility factor, $\mu$, of the supporting structure. The only way to reduce the design action is to increase the $\mu_p$, the structural ductility factor for the part or component. For pressure retaining systems in an industrial plant, this is often not desirable and a $\mu_p = 1.25$ is the maximum level of ductility that can be tolerated by pressure equipment.

### Table 2. Inertia Force Analysis Method for Parts and Components

<table>
<thead>
<tr>
<th>Description</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of part or component $T_p$</td>
<td>any value</td>
</tr>
<tr>
<td>Vertical period of supporting structure $T_v$</td>
<td></td>
</tr>
<tr>
<td>ULS part category</td>
<td>P.1 through to P.4</td>
</tr>
<tr>
<td>SLS2 part category</td>
<td>P.5 For Importance Level 4 or 5 items only</td>
</tr>
<tr>
<td>SLS1 part category</td>
<td>P.6 or P.7</td>
</tr>
<tr>
<td>Structural ductility factor $\mu = \mu_p$</td>
<td></td>
</tr>
<tr>
<td>Support structure’s damping $C_f(\xi)$</td>
<td>$C_f(\xi)_s$</td>
</tr>
<tr>
<td>Site hazard coefficient for $T = 0$ secs, C(0)</td>
<td>Sections 3.1 and 8.2</td>
</tr>
<tr>
<td>Floor height coefficient $C_{Hi}$</td>
<td>Section 8.3</td>
</tr>
<tr>
<td>Part spectral shape coefficient $C_i(T_p)$</td>
<td>Section 8.4</td>
</tr>
<tr>
<td>Description</td>
<td>Case 3</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Horizontal design response coefficient $C_p(T_p)$</td>
<td>Equation 8.2(1)</td>
</tr>
<tr>
<td>$C_p(T_p) = C(0) C_{Hi} C_{i}(T_p)$</td>
<td></td>
</tr>
<tr>
<td>Vertical design action coefficient $C_{vd}$</td>
<td>Equations 3.1(1), 3.2(1) and 5.4(2)</td>
</tr>
<tr>
<td>$C_{vd} = C_v(T_v) = 0.7 C(T_v) = 0.7 C_{hi}(T_v) R Z N(T_v,D)$</td>
<td></td>
</tr>
<tr>
<td>Part risk factor $R_p$</td>
<td>Table 8.1</td>
</tr>
<tr>
<td>Part horizontal response factor $C_{ph}$</td>
<td>Table 8.2</td>
</tr>
<tr>
<td>Part vertical response factor $C_{pv}$</td>
<td>Table 8.2 usually $C_{pv} = 1.0$</td>
</tr>
<tr>
<td>Horizontal limit state design action $F_{ph}$</td>
<td>Equation 8.5(1)</td>
</tr>
<tr>
<td>$F_{ph} = C_p(T_p) C_{ph} R_p C_i(T_v) W_p \leq 3.6 W_p$</td>
<td>Item checked for $F_{ph}$ acting in two principal directions separately. Internal forces and moments = $M_x$ and $M_y$.</td>
</tr>
<tr>
<td>WSD horizontal design action = 0.8 $F_{ph}$</td>
<td>$F_{ph}$ calculated as above with $\mu_p \leq 1.25$</td>
</tr>
<tr>
<td>For item supported on same structure but at different levels, interstorey deflections $\delta_x$</td>
<td>Section 7.3</td>
</tr>
<tr>
<td>For item supported on different structures, design horizontal deflections $\delta_h$</td>
<td>Section 7.2</td>
</tr>
<tr>
<td>Internal limit state horizontal design actions $M_{hux}$ and $M_{hyu}$</td>
<td></td>
</tr>
<tr>
<td>$M_{hux} = (M_{ix}^2 + M_{ix}^2)^{0.5}$ and $M_{hyu} = (M_{iy}^2 + M_{iy}^2)^{0.5}$</td>
<td></td>
</tr>
<tr>
<td>Internal WSD horizontal design actions $M_{hwx}$ and $M_{hyw}$</td>
<td></td>
</tr>
<tr>
<td>$M_{hwx} = [(0.8 M_{ix})^2 + M_{ix}^2]^{0.5}$ and $M_{hyw} = [(0.8 M_{iy})^2 + M_{iy}^2]^{0.5}$</td>
<td></td>
</tr>
<tr>
<td>Vertical limit state design action $F_{pv}$</td>
<td>Equation 8.5(2)</td>
</tr>
<tr>
<td>$F_{pv} = C_{vd} C_{pv} R_p W_p \leq 2.5 W_p$</td>
<td>Internal forces and moments = $M_v$.</td>
</tr>
<tr>
<td>WSD vertical design action = 0.8 $F_{pv}$</td>
<td>$F_{pv}$ calculated as above with $\mu_p = 1.0$</td>
</tr>
<tr>
<td>Total limit state design actions</td>
<td></td>
</tr>
<tr>
<td>$M_{hux} + M_{iv}$ and $M_{hyu} + M_{iv}$</td>
<td></td>
</tr>
<tr>
<td>Total WSD design actions</td>
<td></td>
</tr>
<tr>
<td>$M_{hwx} + 0.8 M_{iv}$ and $M_{hyw} + 0.8 M_{iv}$</td>
<td></td>
</tr>
</tbody>
</table>

Where the factors that are not detailed in the table above are as per NZS 1170.5.

7
7 CONCLUSIONS

The prediction of earthquake performance for buildings, building-like and nonbuilding-like structures is an art as Jury (2004) highlights. The design engineer for industrial structures is required to develop a feel for how nonbuilding structures behave with a shortage of research into their earthquake performance. A degree of conservatism in the design approach for these structures is warranted until their behaviour is more fully documented and researched.

The lack of a specific section within NZS 1170.5 for the seismic design of nonbuilding structures has meant that there will continue to be a degree of uncertainty as to how the new standard should be applied to those structures commonly found in industrial plant.

This paper has attempted to integrate the recently completed set of structural design actions standards with guidelines incorporated into overseas standards for the determining of seismic actions and displacements for the nonbuilding-like structures commonly found in industrial and petrochemical plants.

REFERENCES:


