4 SEISMIC DESIGN

4.2 DEFINITIONS

Pile bent - Gravity and lateral load resisting substructure comprising piles that extend above grade, without an at-grade pile cap, connecting directly to a pier cap beam supporting the bridge superstructure.

4.4 EARTHQUAKE EFFECTS

4.4.1 General

Delete the third paragraph and replace with the following:

Design of lateral load resisting substructures in Seismic Performance Zone (SPZ) 3 and 4 shall use capacity design principles.   .

Earthquake load effects in Ductile Substructure Elements shall be determined from the inelastic action of members with which they connect.

Elastic design forces may be used for:

- structures in Seismic Performance Zone (SPZ) 1 or 2;
- bridges with seismic base isolation.
- abutments walls in the strong direction, and;
- wall piers in the strong direction.

Displacements shall be determined using a response modification factor of 1.0 and an importance factor of 1.0.

Commentary: *While clause 4.4.8.1 requires design and detailing for all lateral load-resisting sub-structures, it is recognized that stiff substructures may have significantly greater strength than required for seismic loads. In such cases elastic design forces may be appropriate. Detailing requirements referenced in Table 4.4.8.1 remain as in S6-00.*

For base isolated bridges the substructure and other elements in the seismic load path are to be designed as capacity protected elements, with force and deformation demands from the isolation devices being scaled up, analogous to over-strength demands on ductile substructures, with appropriate margins to avoid unintended failure modes.

4.4.2 Importance Categories

Add the following paragraph immediately before the last paragraph:

Lifeline bridges in SPZ 3 and SPZ 4 shall be explicitly designed to ensure the above performance requirements are met for the 10% in 50 year and 5% in 50 year seismic events unless directed otherwise by the Ministry.

Add the following sentences to the end of this clause:

The Ministry will designate the Importance Category for each bridge.

Structures classified as “lifeline” in project specific requirements in regions having PHA < 0.08 shall be designed as if they are “emergency route” bridges in SPZ 2.

Commentary: *It is appropriate to design lifeline structures in areas of low seismicity with an Importance Factor (I) of 1.5 instead of 3.*

Low Volume Road (LVR) bridges are typically designated as "other" bridges unless otherwise specified by the Ministry.

The following relationship is used to relate probabilities of exceedence and return periods:

$$R = [1 - (1 - p)^{1/t}]^{-1}$$

Where:

R = *return period*

p = *probability of exceedence in period t*

t = *duration consistent with p (e.g.1 year for an annual probability of exceedence)*

Dividing the period (t) by the annual probability of exceedence provides an approximation of the return period.

4.4.3 Zonal Acceleration Ratio

Delete the first paragraph and replace with the following:

The zonal acceleration ratio, A, to be used in the application of these provisions shall be determined from the most current site specific 10% in 50 year PHA values obtained from the Geological Survey of Canada (GSC) either directly, through their Pacific Geoscience Centre (PGC) in Sidney, BC or from their on-line web page at:

http://earthquakescanada.nrcan.gc.ca/hazard/interpolator/index_e.php

Commentary: *The GSC site may refer to the PGA rather than the PHA. The Pacific Geoscience Centre in Sidney, B.C. can be contacted at:*

www.pgc.nrcan.gc.ca/index_e.html

Phone: (250) 363-6500 Fax : (250) 363-6565.

4.4.4 Seismic Performance Zones

Delete the first paragraph and replace with the following:

Bridges shall be assigned to one of the four seismic performance zones in accordance with Table 4.4.4.1 using the zonal acceleration ratio, A, obtained from the site specific values obtained from Clause 4.4.3.

4.4.5 Analysis for Earthquake Loads

4.4.5.1 General

Delete the second paragraph and replace with the following:

For modal methods of analysis specified in Clause 4.4.5.3, the elastic design spectrum shall be that given by the equations in Clause 4.4.7.

4.4.6 Site Effects

Commentary: *Soil profile classifications are relatively broad and generic in S6-00, and Clause 4.4.6.6 allows for engineering judgment. Additional guidance may be found in technical references supporting the proposed NBCC2005 code, ATC-32, and ATC – 49. Comparison of soil classifications considering soil types, thicknesses, and shear wave velocities are useful.*

4.4.8 Response Modification Factors

4.4.8.1 General

Commentary: *This clause outlines the use of R factors for the design of ductile substructures and provides simplifying assumptions for the design of superstructures having concrete decks.*

Table 4.4.8.1 includes R factors for 'pile bents'. (See Definitions in this Supplement, Clause 4.2).. S6.1-00 clarifies that inelastic hinges below grade in such bents are acceptable at '"reasonably accessible" locations, described as, "….. less than two metres below ground or mean water or tide level". This is regarded by the Ministry as a reasonable guideline for "reasonably accessible".

For the purposes of this clause, R factors identified for "pile bents" may also be applied to ductile piles, i.e. appropriately detailed steel, concrete or composite piles, used as part of integral abutments.

S6-00 and the Commentary are clear that R factors are used to modify bending moments in ductile sub-structure elements. S6-00 Clause 4.4.10 relates to the design forces and detailing as part of a 'capacity design' approach, and allows axial loads from either the elastic analyses or as found from the plastic mechanism. For the initial sizing of yielding ductile *substructure elements, typically the columns, neither document is explicit on the appropriate axial loads to adopt. The designer must use engineering judgment. Some commonly considered options for axial loads for this purpose include:*

i) *Those obtained from the elastic analyses, unreduced by the R factor. A designer might assume the seismic axial loads should be taken as either positive or negative to achieve the most conservative design.*

ii) *Those consistent with the plastic mechanism at probable member resistances. Axial loads in columns of multi-column bents will vary, and the maximum and / or minimum axial load may be inferred.*

iii) *Those consistent with the plastic mechanism at nominal member resistances.*

iv) *Those consistent with the plastic mechanism at factored member resistances.*

v) *Those associated with dead loads only, i.e. changes in axial loads from seismic demands being neglected during column sizing.*

It is less important which axial loads are adopted for member sizing than for the subsequent derivation of demands on capacity-protected elements. Minor variations in overall system ductility capacity may be expected for the range of assumptions noted above. Axial loads based on (i) or (ii) above could result in un-necessary conservatism. Care should be taken to ensure that the benefits of capacity design are not made economically or otherwise impractical as a result of sizing columns using unreasonably conservative assumptions regarding column axial loads.

4.4.10 Design Forces and Support Lengths

4.4.10.4 Seismic Performance Zones 3 and 4

4.4.10.4.2 Modified Seismic Design Forces

Delete the second paragraph and replace with the following:

Capacity-Protected Elements shall be designed to have factored resistances equal to or greater than the maximum force effect that can be developed by the ductile substructure element(s) attaining their probable resistance.

4.4.10.4.3 Yielding mechanisms and design forces in ductile substructures

Delete the third paragraph and replace with the following:

Shear and axial design forces for columns, piers, and pile bents due to earthquake effects shall be the following:

(a) Shear Force – the shear corresponding to inelastic hinging of the column as determined from static analysis considering the flexural probable resistance of the member and its effective height. For flared columns and columns adjacent to partial height walls, the top and bottom flares and the height of the walls shall be considered in determining the effective column height. If the column foundation is significantly below ground level, consideration shall be given to the possibility of the hinge forming above the foundation. This is acceptable as long as the inelastic hinges are at reasonably accessible locations.

(b) Axial Force – the axial force corresponding to inelastic hinging of the column in a bent at its probable resistance.

For cases of structures where elastic design forces may be used for capacity-protected elements in accordance with Clause 4.4.10.4.2, shear and axial design forces for ductile substructure elements may be taken as the unreduced elastic design forces in accordance with Clause 4.4.9 with R=1.0.

Commentary: *The Ministry considers "reasonably accessible" to mean less than 2 metres below ground or below mean water or below tide level*.

4.5 ANALYSIS

4.5.1 General

Delete the third paragraph and replace with:

In modelling reinforced concrete sections of ductile substructures the effects of cracking may be taken into account in calculating periods, force effects, and force distributions. The effects of cracking shall be taken into account when calculating deflections.

Sway effects shall be considered where appropriate in all bridge substructures.

Commentary: *S6-00 currently specifies that uncracked member properties be used in calculating periods and elastic seismic demands in all lateral load-resisting substructures. Common practice is to adopt cracked section properties. This approach is believed to be reasonable based on the state of practice internationally, and on a comparison to other modern seismic design standards or guidelines.*

Guidance on when and how to incorporate P-Delta effects can be found in ATC – 32 Clause 3.21.15.

4.5.3 Multispan Bridges

4.5.3.4 Time-History Method

Delete the first paragraph and replace with the following:

The time-histories of input acceleration used to describe the earthquake loads shall be selected by the designer and subject to Approval. Three or more sets of time history records shall be used, each set comprising three orthogonal records. The design response quantities will be taken as the maximum from the three analyses. If five or more record sets are used, the design quantities may be taken as the mean from the five or more analyses. If site specific time-histories are used, then they shall include the site soil profile effects and be modified by the importance factor, I.

Commentary: *Time history methods are not required for the design of most new highway bridges in B.C. Where time history methods are proposed, the design benefits should be clearly outlined, and the number and characteristics of the records should be developed in consultation with the Ministry. The above shall be fully described in a project specific design criteria developed by the designer.*

4.5.3.5 Static Pushover Analysis

Commentary: *Static push-over analyses are used to define the sequence of development of inelastic action in ductile structures, to develop member design forces for ductile substructures, and to assist in defining deformation capacity. They may also be used to assist in defining stiffness and hysteretic properties for use in inelastic dynamic analyses.*

Guidance is available in Priestley and Calvi, SSRP91/03 (UC San Diego), and ATC – 32, ATC - 49. The use of push-over analyses should also be considered to confirm the expected performance of important new or existing bridges under long return period events.

4.6 FOUNDATIONS

4.6.5 Soil-Structure Interaction

Delete and replace with the following:

Soil-structure interaction analysis is required for lifeline and emergency route bridges in SPZ 2 and for all bridges in SPZ 3 and SPZ 4. For bridge designs that include soil-structure interaction, geotechnical input shall be obtained.

Dynamic soil-structure interaction shall be performed for retaining walls supporting 5 m or more of soil. Analysis software shall be used that is capable of taking into consideration non-linear soil and structure behavior and the input ground motions.

Upper and lower bound values shall be considered in soil-structure interaction analysis to account for uncertainties in soil properties and analysis methodologies.

Commentary: *Soil-structure interaction should be included unless the merit or values of such analyses are expected to be minor. Among the potential benefits from such analyses would be an improved estimate of seismic deformations, a reduction of effective seismic input motion, and improved estimates of demand distributions among piers and abutments.*

4.6.6 Fill Settlement and Approach Slabs

Delete the first sentence in the first paragraph and replace with the following:

Approach slabs shall be provided in accordance with Clause 1.8.2.

Commentary: *Project specific design criteria developed by the Ministry may specify settlement slabs (6 m long, measured normal to the abutment) as part of the structural design criteria. In general approach slabs improve post-seismic performance and vehicle access.*

4.7 CONCRETE STRUCTURES

4.7.3 Seismic Performance Zone 2

Delete the second sentence and replace with the following:

The transverse reinforcement at potential plastic hinge zones of beams and columns shall be as specified in Clauses 4.7.4.1.4 and 4.7.4.1.5.

4.7.4 Seismic Performance Zones 3 and 4

4.7.4.1 Column Requirements

4.7.4.1.1 Longitudinal Reinforcement

Delete and replace with the following:

The area of longitudinal reinforcement shall not be less than 0.008 (0.8%) nor more than 0.06 (6%) times the gross cross sectional area, Ag, of the column. The centre to centre spacing of longitudinal bars shall not exceed 200 mm.

4.7.4.1.2 Flexural Resistance

Delete the second paragraph of this clause.

4.7.4.1.6 Splices

Delete the second paragraph and replace with the following:

Lap splices in longitudinal reinforcement shall not be permitted in plastic hinge regions. Where practical, such lap splices shall be located within the centre half of column height. For tall piers, rational analysis considering potential plastic hinging mechanism shall be performed to determine the location and extent of plastic hinge regions. The plastic hinge region shall be taken as the greater of the region calculated in accordance with Clause 4.7.4.1.3(b) and the region over which the moment exceeds 70% of the maximum moment. The splice length shall not be less than the greater of 60 bar diameters or 400 mm. The centre-to-centre spacing of the transverse reinforcement over the length of the splice shall not exceed the smaller of 0.25 times the minimum cross-section dimensions of the component or 100 mm.

Commentary: *Splices should be limited to the centre half of columns where standard bar lengths can be accommodated without adding unnecessary extra splice cost.*

4.7.4.3 Column Connections

Delete the second paragraph and replace with the following:

For lifeline and emergency route bridges in SPZ 3 and SPZ 4, the design of column connections, including member proportions, details, and reinforcement, shall be based on beam-column joint design methodologies as described in either:

- ATC-32 Section 8.34
- Seismic Design and Retrofit of Bridges, Priestley and Calvi (1996).
- Caltrans Seismic Design Criteria (latest version, currently 1999)
- ATC-49 Section 8.8.4

For bridges in SPZ 2, or for “other ’bridges’ in SPZ 3 and SPZ 4, column transverse reinforcement as specified in Clause 4.7.4.1.4, shall be continued full depth through the adjoining component, unless designed as specified above.

Commentary: *Rational design of beam- column joints is required for important bridges in high seismic zones. In the absence of an explicit design, other bridges are to have beam-column joints reinforcing extend the full depth of the joint.*

4.7.5 Requirement for Piles

4.7.5.1 General

For bridges in SPZ 3 and 4 and where plastic hinging may reasonably be expected to form, concrete piles shall be designed and detailed as ductile components so as to ensure performance similar to concrete columns designed to Section 4.7.

4.8 STEEL STRUCTURES

4.8.3 Sway Stability Effects

Commentary: *Guidance on incorporating P-Delta effects can be found in ATC – 32 Clause 3.21.15.*

4.10 SEISMIC BASE ISOLATION

4.10.1 General

For designs using base isolation, the Designer shall submit to the Ministry for review and acceptance, a seismic design criteria document outlining methodology, including key aspects and assumptions upon which the design is based. This shall include bearing types, properties, potential suppliers, recommended test requirements and acceptance criteria. Information on soil profiles, design response spectra, firm ground and soft soil time history records as required, and how displacements are accommodated at expansion joints, shall also be provided.

Testing of the isolation systems shall be in accordance with the 1999 edition (including 2000 interim) of the AASHTO Guide Specifications for Seismic Isolation Design.

Commentary: *Clause 4.10 "Seismic Base Isolation" of S6-00 is mainly based on the 1991 edition of the AASHTO Guide Specifications for Seismic Isolation Design. Significant changes have been made in the 1999 edition (including 2000 interim edition) of the AASHTO Guide Specifications for Seismic Isolation Design. The testing requirements in the 1999 AASHTO Guide Specifications are more stringent than those in the 1991 edition. Therefore, the more stringent testing requirements of the 1999 AASHTO Guide Specifications are adopted here.*

In the 1999 AASHTO Guide Specifications, three types of tests are clearly identified and required: (a) system characterization tests; (b) prototype tests; and (c) quality control tests. For example, for quality control tests of elastomeric bearings, Clause 4.10 of S6-00 (or the 1991 AASHTO Guide Specifications) requires combined compression and shear tests on 20% of the bearings whereas the 1999 AASHTO Guide Specifications requires such testing on all bearings

The more stringent testing requirements in the 1999 AASHTO Guide Specifications are intended to ensure that all fabricated isolation bearings meet the specified design properties, and the isolated systems will perform as designed in the event of a major earthquake. After test set-up, the additional cost of testing all bearings versus 20% of the bearings for the combined compression and shear test would not be significant. This is because the combined compression and shear test for each bearing is relatively fast. Both

S6-00 (or the 1991 AASHTO Guide Specifications) and the 1999 AASHTO Guide Specifications require sustained proof load test on each bearing under 1.5 times the maximum dead plus live loads as part of the quality control tests.

S6-00 (or the 1991 AASHTO Guide Specifications) requires a duration of 12 hours for each sustained proof load test whereas the duration is reduced to 5 minutes in the 1999 AASHTO Guide Specifications. Previous experience indicates that any bulging suggesting poor laminate bond will show up almost immediately after application of the vertical load, and the requirement of 12 hours is not necessary.

Bearing suppliers and contractors like this trade off between reduction in time for the sustained proof load test and increase in number of bearings for the combined compression and shear test. This is because the time required for quality control test is reduced significantly.

4.10.4 Site Effects and Site Coefficient

Delete the asterisked sentence under Table 4.10.4 and replace with the following:

Site specific studies shall be performed for bridges for which isolation systems are proposed on Type IV soils.

Commentary: *Site specific spectra for soft soils may show that isolation is not effective. A realistic assessment of non-linear deformations of the isolated system, and the potential for unintended inelastic deformations in sub-structures, requires realistic soil spectra and analysis of soil-structure interaction.*

4.10.6 Analysis Procedures

Foundation flexibility and other relevant soil-structure interaction effects shall be considered in analyses, and shall be included for structures founded on Soil Profile Types III and IV.

4.10.7 Clearance and Design Displacement of Seismic and Other Loads

Allowance shall be made for thermal deformation demands in combination with seismic isolation deformation demands on joint, bearing and railing details unless otherwise Approved. 40% of the thermal deformation demands shall be combined with deformation demands from the base isolation system.

4.10.11 Required Tests of Isolation Systems

4.10.11.2 Prototype Test

For Item (d), change cross-reference from clause 4.10.11.3 to 4.10.10.3.

4.11 SEISMIC EVALUATION OF EXISTING BRIDGES

Clause 4.11 and all subsections shall be deleted. The Ministry “Seismic Retrofit Design Criteria (2005) shall be used for seismic rehabilitation of existing structures.

4.12 SEISMIC REHABILITATION

Clause 4.12 and all subsections shall be deleted. Seismic rehabilitation (retrofit) design shall be in accordance with the Ministry “Seismic Retrofit Design Criteria (2005).”