SEISMIC DESIGN CRITERIA FOR CRITICAL FACILITIES IN CANADA

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ABSTRACT. Seismic design criteria for a range of critical structures are reviewed and design philosophies compared. These include: liquid natural gas facilities, nuclear power plants, offshore platforms, major dams, mining operations and pipelines.

1. INTRODUCTION.

Seismic design requirements for the majority of engineered structures in Canada are specified by the National Building Code of Canada (NBCC)(1), which applies to "normal" buildings. For structures outside the scope of the NBCC, seismic design requirements, if any, are generally defined by a regulatory authority, or codes or standards for specific types of installations. Hence liquefied natural gas (LNG) facilities, offshore petroleum platforms, nuclear power plants, and large hydro-electric dams are designed under a different set of design guidelines.

The structures discussed are the so-called "critical facilities". Such facilities are either: key components in public utility and transportation services, "lifeline systems"(9) items which pose a major potential hazard to populations; installations which would cause severe economic penalties through loss of investment, supply, employment, etc; or facilities which would pose a potentially major environmental impact.

Our review of the seismic design of these "critical facilities" is from a "safety systems analysis" point of view. Our analysis and conclusions regarding safety and economics and design are limited to comparisons between current practice and identification of topics under active development. A more comprehensive version is to be published separately.

2. TRENDS IN SEISMIC DESIGN PHILOSOPHY

2.1 Systems Safety Analysis.

During the last 10 years or so, "System Safety Analysis" methods(28) have begun to be applied in Canada to certain "critical facilities", initially nuclear power plants,(19) more recently to LNG plants and proposals for offshore petroleum platforms, hazardous waste storage and disposal facilities. These analyses require a step-by-step procedure involving failure modes and effects analysis, hazards and consequences analysis, etc. These analyses contribute two new aspects: first, and probably of most present benefit, they provide a formal logical framework for the safety analysis; secondly, they provide a basis for computing accident and failure probabilities which are somewhat unreliable at this time but do give useful order of magnitude estimates. In the institutional facility field "Lifeline Earthquake Engineering"(9) has emerged as a framework.

In such analyses, earthquakes are frequently an important initiating event, made more so by the fact that they can potentially cause a "common mode" failure(15) in which they tend to short-circuit otherwise redundant or independent safety systems.

2.2 Codes and Standards.

Traditional seismic design methods for buildings(1,2) have used working or yield stress levels, load factors and static or dynamic analysis procedures in conjunction with an earthquake level with a reasonably high probability of occurrence. No explicit attempt is made to examine the ultimate strength of the structure or system against collapse, and the specific consequences for human safety, environmental impact, or economic loss. However, the use of conservative procedures and assumptions implicitly connected with the specified "design earthquake", based mainly on experience in California, has ensured that an extra measure of strength will be available to accommodate earthquakes more severe than the specified "design earthquake". Thus the NBCC design procedure is somewhat indirect and the provision for a less likely "extreme earthquake" is implicit in the approach to some degree.

Recent codes and standards for certain critical facilities have responded to the need to rationalize the basis for seismic design criteria. Frequently a "two-tier" approach is used: (i) design or Operating Level Earthquake (OLE); and (ii) Safety Level Earthquake (SLE). The OLE is principally an engineering design approach using reasonably low stress levels and high factors of safety. The SLE is principally a seismological statement of an extreme event(47). To carry out overall risk analyses, it is necessary to go further, and consider the ultimate strength of key components.

2.3 **Decision Analysis.** The decision process for critical facilities may be either more or less formalized. There are trends to quantify the seismicity components of risk analysis and make explicit definitions and cost-benefit analyses of a set of design alternatives. Decision analysis(10,11) provides a logical framework within which all such relevant facts about seismicity, system behaviour, costs and benefits, etc. can, theoretically, be optimized.(11) This approach was attempted for nuclear power plants(45) and has been recommended for offshore petroleum platforms(27).

The acceptable probability levels for design ground motions derived by seismicity alone are based on intuitive estimates of the reliability of the structural and mechanical systems, implicit estimates of reserve or ultimate strength, and some recognition of the severity of the potential consequences. Opinions range between probabilities of exceedence of 10^{-2} to 10^{-4} per annum.

One recent logical improvement in the assignment of probability levels to ground motions has been the explicit statement of seismic exposure duration, or facility lifetime.

The acceptable public risk level is sometimes(24) suggested as being less than 10^{-6} per annum. The reconciliation between this very low probability and the design earthquake probability is usually not addressed explicitly. This is sometimes addressed through "event-free" methods of analysis(15), "fault-free" safety systems analysis(19) or reliability assessments.(20)

In the past the practice of specifying a "Maximum Credible Earthquake" was frequently accepted as a means of circumventing the risk analysis issue. More recently, attempts have been made to make more specific statements in that vein, e.g. "Maximum Capable Earthquakes". However, such upper bounding attempts are now being recognized as being unavoidably subjective in the sense that there are essentially no fixed upper bounds and that such estimates are in fact based on the proponents' unstated degree of conservatism. For rational design of critical structures, it would therefore appear desirable to at least associate a probability level with conservative design criteria.

2.4 **Seismicity.** Several interesting variants of the site seismicity probability calculation have been developed which attempt to improve the statistical reliability of these. Baysian Methods appear to show considerable promise in logic but at additional mathematical complexity. (13,14)

In addition, major improvements in reliability of local seismicity assessments may be possible at certain sites using micro-seismic data, fault analyses based on Quaternary geology,(45) fault mechanism models, wave propagation analysis, etc.(41).

The use of seismic ground motion attenuation formulae for critical structures requires careful selection. Recently, proposed attenuation formulae for use in Canada have been shown to be mainly applicable to moderate magnitudes, say 5.0 to 6.0, and high probabilities, of the order of 10^{-2}.(22,23,25) They can be seriously misleading if applied to major earthquakes or the low probabilities of interest for critical facilities. The treatment of uncertainty in assigning ground motion parameters and design response spectra needs to be consistent and clarified(21,47).

3. **PRESENT PRACTICE AND DESIGN CODES.** Table 1 provides a simplified comparison of seismic hazards and design strategies for a wide range of critical facilities. The table summarizes the key potential seismically initiated system failure modes and effects in terms of safety, economics, environmental or supply consequences, identifies the duration and spatial exposure of the facility, comments on the existence or lack of multiple redundant safety systems and indicates the principal thrust of present design strategies in terms of structural system, design methods and rigour, and provision of reserve capacity. (Unavoidably, many simplifications have been introduced to arrive at such a general summary.)

Table 2 provides a summary of the existing Canadian Code seismic design criteria. The design criteria have been classified, where possible, into "design" or "operating" level and "safety" or "extreme" level checks. This separation is intended to exhibit the trend to more explicit limit states or two-tier design methods. Comments are added regarding the status of Codes.

A brief discussion of each type of critical facility is given below.

a) Important Buildings. It has been shown(3) that the NBCC pseudo-static design procedure using an "Importance Factor" I = 1.0 for "normal" buildings, will result in yield stresses being exceeded in steel buildings at return periods ranging from 50 to 350 years, depending on the natural period of the structure. The NBCC dynamic analysis procedure results in return periods of about 200 years. The seismic loading level at which structural collapse would occur is not required to be identified, nor are major damage or structural collapse probability estimates required.(4)

For critical institutional buildings, e.g. hospitals, the NBCC suggests the use of an "importance factor", "I" of up to 1.3. This factor would increase the return periods for exceedence of yield stresses by a ratio of about 2, say from 200 to 400 years for a building designed by dynamic analysis.

The use of a more explicit design procedure would no doubt help. The proposals in ATC-3(26) in which design levels are based on ground motions with a 10% probability of exceedence in a 50-year lifetime with correspondingly adjusted factors, is a move in this direction.

b) **LNG Plants.** Recent Canadian regulations for LNG plants(5) involve a limit state design approach and have aimed to quantify part of the reserve strength implied by traditional design methods in order that adequate ultimate resistance against catastrophic failure and vapour release can be assured(28).

A typical LNG storage facility involves a double containment system comprising an inner tank and outer dyke of some form. This system redundancy improves safety with respect to certain failure modes but may be "short-circuited" by a major earthquake.

CSA Z276-1981M(5) requires a "two-tier" design approach using the following criteria: (1) OBE - The Operating Basis Earthquake has a 10% chance of being exceeded in 50 years (A475). Critical structures should remain sound and operational during the OBE. This implies effectively elastic behaviour and stress levels less than yield; and (2) SSE - The Safe Shut-down Earthquake is the maximum credible motion or that which has an annual probability of exceedence of 10^{-4} or less. This requirement implies specific dynamic analysis of the ultimate capacity of the containment system.

CSA Z276 is currently under revision. It may be possible to tie final selection of the SSE design level to the risk analysis. This would allow the criteria to be site dependent and provide a rational basis for selection of SSE to meet public safety requirements, and OBE for economic design.

c) **LPG or Oil Storage.** Standard procedure in Canada to date appears to involve the use of an NBCC A100 seismic design level and API design standards. The low temperature conditions of the LPG storage are provided for in API 620 and oil storage tanks requirements are specified in API 650.

The need for greater protection depends on the location of the tanks, the secondary containment provisions provided and potential consequences to the environment from oil release or to the public from LPG vapour releases.

d) **Hydro-Electric Water Supply Dams.** Various types of major hydroelectric and water supply dams exist in seismically active regions of Canada. These include major concrete gravity dams, earthfill dams, and concrete arch dams.

Several such dams may well be operating for 100 or more years within a seismic region. The impoundment system rarely has a backup, or redundant system and thus safety depends on one structure in which failure of any one weak link could initiate a problem. The severity of the problem depends on the downstream exposure. Consequently, conservative design procedures have been used on major dams. In the past USBR(31) and U.S. Army Corps(46) criteria have frequently been used. The U.S. Army inspection program for existing dams(30) uses a simplified but systematic overall safety classification system.

The justification for use of coefficients is based on detailed dynamic analyses and case histories, as reported by Seed(32), for instance, for earth and rockfill dams.

The USBR(31) recommendations for concrete arch and gravity dams require use of a "maximum credible" earthquake but allow a factor of safety as low as 1.0 for the "extreme load condition". Thus, this design approach is essentially a limit state or ultimate strength approach.

In Canada, present practice tends to favour an "ultimate strength" approach using "maximum credible" earthquake loads, careful in situ materials testing, dynamic analysis and low factors of safety. A probabilistic definition of MCE has also been used in some cases as a ground motion with an annual probability of exceedence less than 10^{-3} for certain earthfill dams. The required reserve strength is provided for through the use of factors of safety greater than 1.0, displacement calculations and stable construction materials.

e) **Thermal-Electric Generating Stations.** Thermal-electric generating stations, whether oil, gas or coal fired, require prevention of structural collapse during earthquakes. The consequences of failure are primarily economic and energy supply related, in addition to worker safety. It has been suggested(35) that it is appropriate to apply building code seismic design levels to this design, and use a dynamic analysis method which recognizes the unique structural systems.

In Canada, such an approach may also be possible using NBCC procedures with an "importance factor" I ¨ 1.0 depending on the economics of the plant and its role in the general power grid. This could be addressed through cost-benefit analysis of seismic design levels.

f) **Nuclear Power Plants.** Nuclear power plant seismic design is required to prevent loss of operation and major radioactive releases. CANDU reactor design has recognized these issues and produced a system with three or more redundant safety systems.

Nuclear power plant structures, mechanical piping and components, and electrical and control systems are required to be subject to detailed seismic qualification analyses and/or dynamic testing, according to CSA-N289(6) and other standards(36). CSA-N289 specifies the required seismicity assessment, dynamic analysis methods, key parameters, etc. in more detail than required for any other critical facility in Canada.

Two design earthquakes are specified for nuclear systems: (1) DBE - Design Basis Earthquake - defined as an artificial representative of the combined effects in the free-field at the site of a set of possible earthquakes having a sufficiently low probability of exceedence during the life of the plant; and (2) SDE - Site Design Earthquake - defined as an event with an annual probability of exceedence less than 0.01 and with a peak ground motion acceleration not less than 0.03 g.

In practice in Canada, DBE probabilities have been less than 10^{-3} per annum. Preliminary seismic safety risk analyses(15,16,17,18,44) have shown that the effect of the redundant safety systems is to reduce the release probability to values in the range of 10^{-6} per annum; the analyses were based on event-free analysis models including common mode failures and estimates of reserve strength.

g) Electrical Transmission Systems. Electrical transmission lines may be subject to structural collapse of towers from vibratory ground motions or landslides arising from earthquakes. The consequences of a major line break or substation damage may be quite modest in terms of repair cost, but possibly serious if the line or substation is the sole feed to a major consumer or community.

The Canadian Code CSA C22-3 does not require a seismic design check for transmission towers. Certain utilities require seismic qualification of key substation components. The seismic design strategy relies on aseismic route selection to avoid potential landslide areas, seismic design of key components, quick repair of line breaks, and redundancy in the power grid.

h) Mines - Open Pit and Underground. Earthquakes could affect large mines through major slope failures in open pits, damage to shafts, hoists, ventilation systems in underground mines and surface process plants. Major damage to these could cause extended shutdown of the mine with its associated economic penalty, plus repair costs. Worker safety is a key issue in underground workings and therefore protection of worker egress routes is vital.

Current practice in Canada appears to involve the use of NBCC seismic criteria for buildings and some consideration for seismicity in setting pit slopes. Underground workings have a good seismic performance record to date.

i) Mine Tailings Impoundments. Mine tailings impoundments differ from water retaining dams in terms of both the nature of material behind the dam and the exposure time during which impoundment is required.

The seismic resistance of tailings dams depends critically on the construction method and response analyses must recognize this.(38) Present practice for seismic design criteria for environmentally sensitive major tailings dams normally uses a "maximum credible earthquake" and an "ultimate" strength check. This limit states approach supercedes previous USBR dam design methods(31) using large factors of safety and a more indirect design check. This extreme loading has been required in view of the indefinite future exposure time during which environmental damage could occur. It may be possible to argue in some cases that seismic resistance of the tailings may increase with time due to drainage in which case a lesser design earthquake may be permissible.

j) Oil and Gas Pipelines. Oil and gas pipelines are potentially vulnerable to earthquakes through landslides or possibly through overstressing of the pipe wall by large vibratory ground motions(39). The consequences of pipeline rupture would be mainly environmental impact in the case of oil pipelines and loss of supply in the case of gas or oil lines. The extent of economic impact will depend on the existence of network redundancy and repair time.

Normally, careful routing can minimize exposure to landslides and liquefaction problems. However, the proposed Canadian Arctic pipelines may pass through seismically active zones, with expensive repair due to remoteness and no alternative routing. In these cases, seismic risk assessment and design become important and design criteria ranging between 10^{-2} per annum probability level and a maximum credible value have been considered. In carrying out seismic risk analyses for long pipelines, it is necessary to recognize the effect of linear extent in increasing exposure.(39,40)

k) Offshore Petroleum Structures. In Canada to date, fixed offshore petroleum structures have only been constructed in the Arctic for exploration drilling. Various steel and concrete deep water platforms are under consideration for the east coast, and possibly the west coast. The expected lifetime for these production platforms should be in the region of 30 years.

Such facilities may be vulnerable to earthquake loads depending on the relative magnitude of earthquake loads to other environmental loads, for instance ice or waves. Particular failure modes peculiar to earthquakes, such as foundation liquefaction, will need to be carefully assessed(42).

Seismic design of fixed offshore platforms is a subject of API RP2A(27). This contains a recommendation that environmental loading design decisions to which platforms are designed is the prerogative of the owner and should involve a "two-tier" design approach: (i) design level for "strength requirements"; and (ii) safety level for "ductility requirements". The design level is an event which would have a reasonable likelihood of not being exceeded in the life of the structure and should prevent significant damage. The safety level is an extreme event and should prevent collapse. The earthquake criteria for the design or strength level can be based either on an overall risk analysis or a coefficient method.

In the absence of seismic data and risk studies, the coefficient method involves the use of design accelerations approximately equal to those with a 10% probability of occurrence in 50 years as proposed in ATC-3 for buildings in the United States(26).

Ductile design of steel platforms to ensure sufficient energy absorption capacity to prevent collapse should consider "rare intense earthquake motions". The actual level is not quoted, but an event with probability of exceedence in the range 10^{-3} to 10^{-4} per annum may be appropriate.

Heavy concrete gravity platforms are covered in ACI-357(48), and would require special detailing and also recognition of their long fundamental period. Conventional criteria in terms of peak ground acceleration are not relevant for setting design response spectra in the long period range.

Beaufort Sea exploration islands will have a short operating lifetime and therefore a short exposure to seismic hazards. Economic considerations would suggest a relatively low return period for design. For example, if design is based on an earthquake with a 25-year return period, the probability of the design earthquake being exceeded during a 2-year operating life is only 0.08. This risk level is thus consistent with API-RP2A.

l) Transportation Systems (Marine, Highways and Railways). Aseismic design of major transportation systems, highways, railroads, marine terminals, bridges and tunnels are important in terms of public safety, economic loss and possible loss of communication in the event of a major earthquake disaster. Their normal operating lifetime may be 1-200 years. Redundancy through alternative routes may alleviate the indirect effects in most cases, although major export terminals are probably critical. Current design practice for bridges and docks is to adopt NBCC design procedures.

m) Hazardous Waste Disposal Facilities. Current thinking on design concepts for disposal of hazardous wastes tends to favour geological disposal vaults for radioactive waste, or secure land burial for chemical wastes. In the meantime, such materials are being stored in surface facilities.

The assignment of design criteria and risk assessment for seismic events is still in the early stage of development since basic design concepts have yet to be established.(43)

4. **CONCLUSIONS.** A brief review of seismic design criteria for critical structures indicates an increasing trend towards more specific and direct design approaches, generally using a "two-tier" philosophy. This is consistent with the general trend towards limit states design. Specific discussion of the potential failure modes of critical structures is recommended in order to focus the attention of the seismic designers on the key issues. Such an assessment should recognize human safety (both worker and public), environmental impact and cost benefit relations. The trend towards integration of design decisions in overall risk analyses should improve the economics and safety of critical facilities.

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Table 1 - Summary Comparison of Seismic Hazards and Design Criteria

STRUCTURE TYPE	FAILURE MODE EFFECT (SAFE/ECONOM./ENV./ SUPPLY)	SEISMIC EXPOSURE (TIME/SPATIAL)	SAFETY SYSTEM (SINGLE OR REDUNDANT)	SEISMIC DESIGN STRATEGY(SYSTEMS/ DESIGN/RESERVE)
Important Buildings & Plants	Structural collapse/ Occupant safety, Economic penalty	50 year lifetime	Usually single structural system	Redundant frames/ Dynamic analyses/ Ductile frames & members
LNG Storage	LNG vapour release/ Public safety, Economic penalty	50 year lifetime/ isolated sites	Multiple containment	Avoid common mode failure/Detailed dynamic analysis/ Ensure reserve strengths
LPG or Oil Storage	LPG or oil release/ Public safety (LPG), Environmental impact (Oil)	50 year lifetime/ multiple sites	Multiple containment	Avoid common mode failure/Dynamic analysis/Ductile connections
Hydro-Electric & Water Supply Dams	Loss of impoundment/ Public safety, Economic penalty, Energy shortage	100 year lifetime/ multiple sites	Single structural system	Provide freeboard/ Conservative design/ and detailed dynamic analysis/Ensure reserve strength
Thermal-Electric Power Plant	Structural collapse/ Economic penalty, Energy shortage	50 year lifetime/ multiple sites	Single structural system	Redundant frames/ Dynamic analysis/ Ductile frames & members
Nuclear Power Plant	Loss of containment/ Public safety, Economic impact, Environ. impact Energy shortage	50 year lifetime/ multiple sites	Multiple safety systems	Avoid common mode failure/Detailed dynamic analysis of all key systems/Ensure reserve strength
Elect'l Transmission Systems	Structural collapse/ Energy shortage	50 year lifetime/ 500-2000 km long grid system	Network redundancy	Aseismic route selection/Seismic design of key lines Ensure quick repair
Mines	Pit slope failure or underground collapse/ Worker safety	20 year lifetime/ multiple sites	Work area separation, separate egress routes	Ensure separation/ Check slopes and egress faces/Check safety equipment
Mine Tailings Impoundment	Loss of impoundment/ Public safety/ Environmental impact	Indefinite future/ multiple sites	Single init'l containment improves with time	Site selection/ Dynamic analysis if necessary/ Construction methods
Pipelines (Oil & Gas)	Pipeline rupture/ Environmental impact (oil) Loss of fuel supply	50 year lifetime/ 500-5000 km long network system	Network redundancy	Route selection/ Geotechnical checks/ Ensure quick repair
Offshore Petroleum Struct's	Structural collapse/ Worker safety, Economic penalty, Environmental impact (oil)	Expl^n: 2 yr life Prod^n: 30 years/ multiple sites	Single structural system	Redundant frames/ Detailed dynamic analyses/Ductile frames & members
Transpor. (Highways Rail or Marine Terminal)	Structural collapse/ Public safety, Economic penalty, Loss of communications	100 yr lifetime/ 100-500 km long, network system	Network redundancy	Route selection/ Geotechnical checks/Ensure quick repair
Hazardous Materials Storage & Disps'l	Loss of containment/ Public safety, Environmental impact	Storage: 50 year life; Disposal: Indef. future/ isolated or multiple sites	Multiple containment	Avoid common mode failure/Check all key systems/ Aseismic site selection

Table 2 - Summary Comparison of Present Code Seismic Design Criteria

FACILITY (CODE)	"OPERATING OR "DESIGN" LEVEL"	"EXTREME" OR SAFETY LEVEL	CODE STATUS
Important Buildings (NBCC, 1980)	A ≥ A100 - design for allowable stresses in the elastic range using pseudo-static method or elastic dynamic analysis	Reserve strength implied through design formulae	Usually owner's decision to use NBCC. Use I=1.3 for key structures such as hospitals. Need consistent design for foundations. NBCC under development for 1985.
LNG Storage (CSA Z276)	OBE = A475 - allowable stresses in in elastic range - dynamic analysis using DRS	SSE = A10,000 - yield strength - buckling limit - dynamic analyses using DRS	CSA Standard seismic criteria under review. Possibly overall risk analysis related. Also use API 620.
LPG or Oil Storage	A = A100 Working stress design	Reserve strength implied through design formulae	Possible need for CSA standard with seismic criteria. Presently use API 620 or 650.
Hydro-Electric and Water Supply Dams	A = empirical seismic coefficient, -psuedo-static stability analyses and factors of safety	- Generally MCE or equivalent for ultimate strength check	Presently based on USBR & US Army Corps Methods plus expert review
Thermal-Electric Power Plants	A = A100 - allowable stresses in elastic range - pseudo-static method or dynamic analysis	Not required	Presently based on NBCC. Could use cost/benefit analysis to set seismic design levels.
Nuclear Power Plants (CSA N289)	SDE > A100 - allowable stresses in elastic range - elastic dynamic analysis	DBE ≥ A1000 - yield strength - elastic/plastic dynam. analysis	Ssubject to very comprehensive CSA Code and AECB review.
Electrical Transmission Systems CSA-C22.3	A = A100 for substations	Not required	No seismic design required in CSA Standard. Could be appropriate on long key lines.
Mines	Check pit slope stability and buildings using A ≥ A100	Not required	Mainly based on precedent. Subject to Prov. Reg. Agency review. NBCC used for buildings.
Mine Tailings Impoundments	A = empirical seismic coefficient - pseudo-static stability analysis and factors of safety	MCE used for ultimate strength check	Need to evaluate environmental & safety consequences for particular mineral.
Pipelines	A = A100 for compressor stations and slope stability checks	MCE used for major continental pipelines	Subject to review by NEB and Prov. regulatory agencies.
Offshore Petroleum Structures	OLE A25 for exploration islands or platforms OLE A475 for production facilities - Strength design	SLE = extreme event - Ductile design	Presently uses API-RP2A which recommends risk analysis based design levels and owner's decision.
Transportation (Marine & Railways)	A100 where applicable to buildings, bridges, and docks. Tunnel designs checked for fault displacements.	Not required	Usually owner's decision.
Hazardous Materials Storage & Disposal	May use A100 for buildings.	Needs specific risk assessment and design check	Subject to Fed. & Prov. regulatory review and EIS review.