RATIONAL SEISMIC DESIGN CRITERIA FOR CRITICAL STRUCTURES: SOME CONCEPTS AND COMPARISONS

G.M. Atkinson (I)
R.G. Charlwood (II)
Presenting Author: G.M. Atkinson

SUMMARY

This paper compares the objectives and evaluation of risk-based seismic design criteria for critical structures with more traditional deterministic criteria. Differences between the approaches are of a political or public relations, as opposed to a scientific nature. Overall risk analysis provides a rational basis for design of critical facilities.

INTRODUCTION

Seismic design requirements for the majority of engineered structures in North America are provided by building codes (1, 2) which apply to "normal" buildings. In Canada and many parts of the United States, there is a legal requirement to conform to building code standards. For structures outside the scope of building codes, seismic design requirements, if any, are defined by a regulatory authority, or by 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 each designed under a different set of guidelines.

The purpose of this paper is to discuss the design objectives for facilities outside the scope of normal building codes, and how these relate to the philosphical objectives of applicable codes or regulatory standards. Canadian seismic design requirements are used to illustrate certain points, due to the authors' familiarity with these, but the discussion is intended to be general in nature.

The structures discussed are the so-called "critical facilities". This category includes items that pose a major potential hazard to populations or the environment, installations the loss of which would cause severe economic penalties through loss of investment, supply, employment, etc., or key components in public utility and transportation services. For such facilities, there has been a shift away from

(I) Klohn Leonoff Ltd., Richmond, British Columbia, Canada, currently Visiting Fellow , Earth Physics Branch, Ottawa, Canada

(II) Klohn Leonoff Ltd., Richmond, British Columbia, Canada

traditional "factor of safety" design methods, towards approaches involving the (explicit or implicit) analysis of risk and consequences. Such procedures require a quantitative evaluation of not only the potential ground motions for a site or system, but also of their possible effects on various key components and the subsequent impacts on public and worker safety, the environment, and economics. This paper will provide an overview of this process, as a framework for comparing the merits of risk-based design approaches with the more traditional approaches, which still persist for many applications.

OVERVIEW OF SEISMIC DESIGN PHILOSPHY

Recent codes and standards for certain critical facilities have responded to the need to rationalize the basis for seismic design levels. For example, regulations for LNG facilities (3), nuclear power plants (4) and offshore platforms (5) involve a limit state design approach. The aim is to quantify the reserve strength available for certain key failure modes.

Frequently a "two-tier" approach is used. A structure is "designed" for an operating level earthquake (OLE), using working stress levels and high acceptable factors of safety; the OLE has a reasonable probability of occurrence during the life of the facility. In addition, the structure is "checked" for a safety level earthquake (SLE), allowing materials to go to yield stresses or beyond based on the estimated ultimate strength against collapse; the SLE has an acceptably low or negligible probability of exceedence.

To make design decisions on the basis of acceptable levels of risk, it is necessary to go further, and evaluate the probability of various failure modes or scenarios, in the event that the design level is exceeded.

The alternative to risk based procedures for seismic design of critical facilities is the more traditional "maximum credible earthquake" (MCE) approach, in which a structure is designed to withstand what are believed to be the maximum possible motions at the site. The MCE is principally a seismological and/or geological statement of an extreme event. Its probability of occurrence is very low, but is generally unstated.

Table 1 reviews applicable codes and standards used for various facilities in Canada (6), and identifies those which are currently based on risk analysis, at least to some degree, and those which are more traditional in nature. The following sections review risk-based and traditional or "deterministic" design approaches.

RISK-BASED SEISMIC DESIGN CRITERIA

The assessment of overall seismic rosk levels associated with an engineered structure requires the following probability estimates:

(i) P(≥E)

The first sdtep is the traditional seismic risk assessment, which focusses on the probability (P) of exceeding various levels of ground motion due to all potential earthquakes (E). Probabilities of interest generally range from 10^{-2} tp 10^{-4} per annum.

Various methods of estimating P(E) are employed, all of which share the assumption that knowledge of past seismicity will enable the modelling of future seismicity. Methods differ (sometimes radically) in the manner in which seismic processes are modelled. The results of the seismic risk analysis may be in terms of expected ground motion or structural response parameters.

One recent logical improvement in the assignment of probability levels to earthquake motion parameters has been the explicit statement of seismic exposure duration, or facility lifetime. This would replace the statement, for example, of the building design earthquake having an exceedence probability of 10^{-2} per annum (or 100 year return period), with a statement that the design earthquake has a 30% probability of exceedence during a 50 year lifetime. This highlights the fact that such a risk level is relatively high, and should help to avoid a false sense of security associates with the "100 year return period" concept.

This first step of the total risk analysis is well-defined compared to those that follow, and can be performed with a relatively high degree of confidence in many parts of North America. In general, the earthquake data of the past 100 or 200 years, supplemented by geologic data concerning the nature of longer term processes, form a good basis for projecting the seismicity since most critical facilities which have a relatively short lifetime, say 100 years or less. Even when long statistical records of seismicity are available (eg. several thousand years in China), the near future is still predicted better by the near past than by the longer record (7).

(ii) $P(F/\geq E)$ Calculate $P(F)=P(\geq E)\cdot P(F/\geq E)$

The second step in the overall risk analysis is to estimate the probability of a failure generally defined in terms of specific failure modes, given that the design earthquake conditions are exceeded ($P(F/\geq E)$). This enables the calculation of the overall probability of seismically induced failure ($P(F)$). The evaluation can be a complicated problem in inelastic behaviour, and may be dependent on the amount by which the design earthquake has been exceeded. In the inelastic range, $P(F/\geq E)$ may be largely a function of the duration of shaking. It may be necessary to make many simplfying assumptions, or sum over several failure possibilities.

(iii) P(Scenario/F) {Calculate $P(\text{Scenario}) = P(\geq E)\cdot P(F/\geq E)\cdot P(\text{Scenario}/F)$}

For each identified failure mode, the probability of certain consequent scenarios needs to be estimated. This could be based on operating conditions and environmental factors, an example problem would be the estimation of the probability that a large plume of spilled LNG would ignite. On the other hand, this step may be very simple if the consequences of a failure can be readily predicted.

(iv) (\$/Scenario) {Calculate expected damage cost = $P(\geq E)\cdot P(F/\geq E)\cdot P(\text{Scenario}/F)\cdot(\$/\text{Scenario})$}

If the failure scenarios of concern would cause only economic losses, the expected damage costs under various design options can be calculated and compared. However, in situations where human safety or grave encironmental impact are at stake, the risk analysis would generally end at the conclusion of step (iii), leaving the public and regulatory authorities to assess the acceptability of P(Scenario).

In reviewing the schematic development of a risk analysis presented above, it is apparent that large uncertainties will exist in most steps of the procedure. It may not even be possible to establish an order of magnitude definition of the probability of given failure scenarios. This lack of precision, although regrettable, may not be all that serious a limitation to the usefullness of the exercise, for two reasons. First, the definition of what level of risk is acceptable to the public is highly variable, depending on the perceived nature of the threat, the number of people potentially threatened, and the economic benefits to the public of the proposed project. Provided that this can be achieved, uncertainties of several orders of magnitude in the risk estimate may not be problematic. Second, despite their imprecision, they provide a basis for comparing different design options.

Often, relative levels of risk are of more interest than absolute levels. In such cases a lack of percision may be unimportant, and the risk estimates may aid greatly in making design judgement.

DETERMINISTIC SEISMIC DESIGN CRITERIA

Deterministic seismic design philosophy is based on the premise that critical facilities should be designed to withstand the largest earthquake motions to which they may be subjected. It is assumed that the maximum credible earthquake (MCE) loading can be determined objectively on the basis of seismology and geology. The validity of the method depends heavily on this assumption.

The deterministic methodology has proved very valuable in areas where the seismic potential can be directly related to well known geologic structures, the physics of which are understood well enough to enable bounds to be placed on possible site motions. In many parts of California, for example, the seismic hazards to a site derive from surface faults with a well documented geologic history of past earthquake activity. With the many recent advances in techniques of interpretting past and present fault activity, the nature of maximum ground motions at a site can be assessed with reasonable confidence.

In active areas, the associated probabilities of the maximum ground motions may be irrelevant. For example, the recurrence interval of great earthquakes along the San Andreas fault is of the order of hundreds of years. As a result, expected ground motions for return periods of hundreds of years would not differ greatly from those for return periods of thousands of years. In such a case, probabilistic analyses appear to offer little insight for the design of critical structures.

The main drawback to the deterministic philosophy centres around the often subjective nature of the MCE. In most parts of the world, there are in fact no fixed upper limits on earthquake potential, and estimates of such limits are actually based on the proponents' unstated degree of conservation. The final risk level achieved will depend on subjective judgements by the proponents and any regulatory authorities as to an appropriate degree of conservatism for the supposedly seismological and/or geological MCE. Deterministic design criteria may or may not be more conservative than their probabilistic counterparts.

A very conservative estimate of the MCE for a critical structure may not carry a significant economic penalty on design for some cases, but in others it may be prohibitive. For rational design of critical structures, it would appear desirable to at least associate a probability level with conservative design criteria.

DISCUSSION

From a scientific point of view there is no conflict between the probabilistic and deterministic seismic design philosophies. The probabilistic concepts can be considered an extension to deterministic ideas, in which the probabilities of various "deterministic" events are evaluated. Deterministic data can be wholly contained within the probabilistic framework. In this light, information can only be gained by performing a risk analysis. Whether deterministic data are input to a risk analysis, or a risk analysis is performed to supplement a deterministic analysis is simply a matter of convenience.

There is, however, a conflict between deterministic and probabilistic ideologies from a political or public relations point of view. Designing a structure to the MCE implies, to the layman, that a seismically induced failure will not be possible; this type of statement is more acceptable to most people than a statement regarding the low probability of failure. From the public viewpoint, deterministic vs probabilistic philosophies might be perceived as "safety" vs "statistics". The proponents of a critical facility may prefer to have a seismologically given MCE, rather than have to deal with the issue of risk to the public. For these reasons, it would seem more desirable to have a deterministic statement of the MCE. Nevertheless, the fact remains that the MCE, regardless of how it is derived, is associated with some (known or unknown) probability level.

A rational analysis of risk serves several useful functions. Risk analysis forces the designers to address safety issues, and also helps ensure that acceptable low risk levels will be achieved, thus protecting the public. The interests of proponents are also served, since risk analysis should prevent overly conservative design in areas where large events may be considered possible but very unlikely.

CONCLUSIONS

1. Based on Table 1, it appears that there is a need for more specific, consistent guidelines, in either deterministic or probabilistic terms, for the seismic design of many types of critical facilities in Canada, such as LPG or oil storage, dams, some mining operations and major transportation networks. By contrast, much attention has been focussed on the high profile nuclear and LNG facilities, using more rational risk-based criteria.

2. The unstated probability level associated with deterministic seismic design criteria depends on the designers degree of conservatism, which is also unstated. In some cases, this may lead to a level of risk that is much greater than that perceived by the designers or the public. In other cases, overly conservative design criteria, possible with significant economic penalties, may result.

3. Seismic design criteria for critical facilities should be based on acceptable levels of risk. To this end, probabilistic statements of seismological events are preferable to strictly deterministic statements.

REFERENCES

1. Uniform Building Code, 1976. International Conference of Building Officials, Whittier, California.

2. National Building Code of Canada, 1980. National Research Council of Canada, Ottawa.

3. CSA Standard Z276-M1981. Liquefied Natural Gas (LNG) - Production, Storage and Handling. Canadian Standards Association, Rexdale, Ontario.

4. CSA Standard N289. CANDU Nuclear Power Plants. Canadian Standards Association, Rexdale, Ontario.

5. API RP2A, 1981. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Structures, American Petroleum Institute, Dallas, Texas.

6. Charlwood, R.G. and Atkinson, G.M., Senior Design Criteria for Critical Facilities in Canada, 4th Canadian Conference on Earthquake Engineering, Vancouver, June 1983.

7. McGuire, R.K. and Barnhard, T.P., 1981. Effects of Temporal Variations in Seismicity on Seismic Hazard. Bull. Seism. Soc. Am., 71, 321-334.

FACILITY (CODE)	"OPERATING OR "DESIGN" LEVEL"	"EXTREME" OR SAFETY LEVEL	CODE STATUS	BASED ON RISK LEVELS AS OPPOSED TO TRADITIONAL METHODS
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.	No
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.	Yes
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.	No
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	No
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.	No
Nuclear Power Plants (CSA N289)	SDE > A100 - allowable stresses in elastic range - elastic dynamic analysis	DBE > A1000 - yield strength - elastic/plastic dynam. analysis	Subject to very comprehensive CSA Code and AECB review.	Yes
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.	No
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.	No
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.	No
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.	No
Offshore Petroleum Structures	OLE $\hat{=}$ A25 for exploration islands or platforms OLE $\hat{=}$ 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.	Yes
Transportation (Marine & Railways)	A100 where applicable to buildings, bridges, and docks. Tunnel designs checked for fault displacements.	Not required	Usually owner's decision.	No
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.	Yes

Table 1. Summary Comparison of Present Code Seismic Design Criteria in Canada