Paper No. 41. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3
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DEVELOPMENT OF A SEISMIC CODE FOR AN INTRAPLATE AREA; CASE STUDY: NORWAY

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ABSTRACT

This paper presents the efforts involved in developing a new seismic code for an intraplate area. Emphasis is put on reducing uncertainties in seismic hazard estimation through careful research and study work, including data collection, collation and analysis. A case study related to the development of the Norwegian seismic code and its relation to international standards will be given.

The Norwegian case can be used as an example of a low cost effort to develop an optimized code, where the authorities and the industry have cooperated closely together.

In order to promote safety and protect investments Norwegian authorities have determined, in cooperation with oil companies operating on the Norwegian Continental Shelf (NCS), that major offshore structures be designed to resist progressive collapse in earthquakes with probabilities of exceedance of 10^{-4} per year, and to behave elastically without significant loss of functionality in earthquakes with probabilities of exceedance of 10^{-2} per year. Site specific earthquake hazard analyses are therefore conducted in the design phase of such installations.

The development of regulations and guidelines for earthquake resistant design of fixed installations offshore Norway has taken place over more that 20 years in parallel with a significant development also within seismological and earthquake engineering research during the same time period. A noticeable result from this work is that recommended earthquake loading levels have been reduced significantly along with a reduction of uncertainties.

KEYWORDS

Seismic Codes; Intraplate Area; Norwegian Continental Shelf; Data Collection; Seismicity; Ground Motion Relations; Soil Response; Earthquake Hazard and Loading.

INTRODUCTION

Norway and the Norwegian Continental Shelf are located in an intraplate area. In the North Sea and further north along the Norwegian coast the seismicity ranges from low to moderate, with earthquake of magnitudes larger than 5 occurring not too infrequently (Ambraseys, 1984, Bungum *et al.*, 1991). However, since the loading impacts from earthquakes at low probabilities can be high even in such areas it was recognized, when the exploitation of petroleum resources started in the North Sea in the 1970's, that one should also look closer at the risks from earthquakes, in addition to other environmental factors.

It was soon recognized by both Norwegian authorities and the oil companies that the earthquake loads implied both an economical risk to industrial structures, a potential for pollution, and a safety risk for personnel. Consequently it was decided to develop a set of regulations for the purpose of earthquake resistant design of fixed installations offshore, and in parallel with this is was decided also to support an improvement in earthquake surveillance capabilities along with research within both seismology and earthquake engineering. This effort has resulted in regularly updated guidelines for earthquake resistant design on the Norwegian Continental Shelf during the past 20 years.

The purpose of this paper is to review this development, with emphasis on the process and the progress of the work such that others could apply the methodology to other intraplate areas. Furthermore, a short outline of existing earthquake design criteria for the Norwegian Continental Shelf is presented.

RELEVANT NORWEGIAN STANDARDS AND CODES

When the first major offshore installation was being planned for the Norwegian sector of the North Sea in the early 1970's there were no specific regulations with respect to earthquake resistant design. In 1977, however, the Norwegian Petroleum Directorate issued a set of regulations (NPD, 1977) which specified earthquake loading to be of the accidental type. These regulations were supplemented with a set of guidelines in 1981 (NPD, 1981) which required that the platforms should be designed to resist total collapse for an earthquake load with probability of exceedance of 10^{-4} per year.

In a new set of regulations for load bearing structures issued in 1984 (NPD, 1984), earthquake loads were eventually regarded as environmental loads. According to these new regulations, fixed platforms should withstand elastically the ultimate limit state (ULS) earthquake load with an annual exceedance probability of 10^{-2}, while at the 10^{-4} per year probability, the installation should resist progressive collapse represented by the progressive collapse limit state (PLS) earthquake load. The regulations furthermore required seismic response analysis to be based on excitation described by a response spectrum and/or relevant time histories, and also that soil response effects and soil-structure interaction should be considered.

The 1984 regulations were later supplemented with guidelines for the seismic design requirements, issued in draft versions in 1985 and in final form in 1987 (NPD, 1987). The 1987 guidelines presented zoning maps, design spectra, etc., that could be used in the initial design of a platform, while a site specific earthquake hazard analysis would be required in the detailed design phase.

Later in the 1980's it was realized, as more seismological results became available, that the existing guidelines probably were unduly conservative, in particular with respect to the design spectra. Following new draft versions of both regulations and guidelines in 1991, final updated versions were issued in 1993 (NPD, 1993).

In the 1987 (NPD, 1987) guidelines, recommended PGA (peak ground acceleration) zoning maps and PSV (pseudo-relative velocity) design spectra were assumed to be applicable to sites with average soil conditions on the Norwegian Continental Shelf. In the new guidelines (NPD, 1993) this approach has been changed in that the recommended PGA values now are tied to a bedrock outcrop level, with additional suggestions for average soil amplification factors.

The 1993 guidelines are primarily concerned with avoiding progressive collapse for exceedance probabilities of 10^{-4}/year, with input motions defined either from spectra or from time histories.

With the development of an international (ISO) code for design of offshore structures (Craig . 1996), North Sea structures will be designed according to the principles laid down in this code. It is, however, important that spectra developed for the North Sea region and seismic input parameters as found for specific sites be used in the analysis.

EARLIER SEISMIC HAZARD ASSESSMENTS IN NORWAY

The first earthquake hazard related studies in Norway were conducted in 1975 for nuclear power plant sites (Dames and Moore, 1975). For several reasons, however, the development of nuclear energy in Norway never got beyond the pre-feasibility study stage. On the other side, the need for improved knowledge and understanding of earthquake occurrence and earthquake loads soon emerged within the fast growing petroleum sector, partly because the main oil and gas fields coincide in location with the main seismic zones offshore Norway. This is clearly seen in Fig. 1, showing the historical seismicity (1800-1964), greater than or equal to magnitude 4, and the instrumentally recorded seismicity (1965-1995), greater than or equal to magnitude 3.

EARTHQUAKE HAZARD RESEARCH, 1975 - 1995

In the following, some of the more important developments within earthquake engineering in Norway will be reviewed.

The Safety Offshore Program

Following the disastrous capsizing of a semi-submersible platform in the North Sea in 1980, with 123 casualties, a comprehensive evaluation of the offshore design practice and risk was initiated by the Norwegian authorities through a broadly based research project called the "Safety Offshore Program" (SOP), conducted during the years 1980-1983.

By this time it had been recognized that earthquakes were part of the necessary design basis for fixed offshore structures, and the zoning maps and the design spectra developed during the SOP project (Ringdal *et al.*, 1982; Selnes *et al.*, 1983) were therefore eventually implemented in the 1987 guidelines (NPD, 1987)

Earthquake Loading on the Norwegian Continental Shelf

The needs for improved earthquake loading assessments to reduce the uncertainties in the seismic hazard assessments resulted in a broadly based research project termed "Earthquake Loading on the Norwegian Continental Shelf" (ELOCS), conducted during the years 1986-1988. Fifteen different project reports from this study covered geological topics, earthquake data bases, source and wave propagation problems, local site response, and earthquake loading (Bungum and Selnes, 1988). The projects contributed significantly not only to more specific earthquake engineering problems, but also to a better understanding in general of the seismotectonic conditions in Norway and surrounding areas (Bungum *et al.*, 1991).

The ELOCS project was aimed in particular at recommending improved procedures for future site specific engineering seismology projects on the Norwegian Continental Shelf, including methods and models for the computation of earthquake loads (Woo *et al.*, 1988). Peak ground acceleration (PGA) zonation maps (see Fig. 2) and design spectra for the Norwegian continental shelf were therefore developed, for annual probabilities 10^{-2} and 10^{-4} under the ELOCS project. These results eventually found their way into the Norwegian offshore regulations in the form of revised criteria (NPD,1993).

Ground Motions From Earthquakes on the Norwegian Continental Shelf

The ground motion (attenuation) model, in particular for lower frequencies, was identified under the ELOCS project as one of the main sources of uncertainty in earthquake hazard analyses for the NCS. Another research project, "Ground Motions from Earthquakes on the Norwegian Continental Shelf", sponsored by oil companies with operating responsibilities north of 62^{o}N (OKN), was therefore established and conducted during the years 1988-1991 (NORSAR and Risk Engineering Inc., 1991). Using high quality seismological data for developing and calibrating a random vibration (RV) model for stochastic predictions of strong ground motions, combined with empirical data and models from Norway and geologically similar areas, led to the development of a set of new ground motion attenuation relations through this project (Dahle *et al.*, 1991). A multiple relation was finally recommended for future use in this area.

The result of this study was more or less a confirmation of the 10^{-4}/year loading levels but a lowering by about a factor of two of the 10^{-2}/year loading levels. Part of the reason for this result was tied to the development of a new ML magnitude scale for Norway, made possible through the abundance of data from many new seismic stations and networks installed in Norway since 1970 (Alsaker *et al.*, 1991).

Site Specific Studies

A large number of site specific studies have during the last 20 years been carried out for oil and gas facilities on the NCS and for terminals along the Norwegian coast. Many of these studies have included some components of earthquake hazard research and development and have thus contributed to an improved basis for further studies. A soil response study is normally carried out as a separate task in the earthquake hazard evaluation at the NCS.

All together, significant efforts have been directed into the field of earthquake hazard analysis, both in terms of methodologies and computational techniques. For example, the Logic Tree approach is now regularly applied, thereby providing a flexible and realistic treatment of uncertainties. Important achievements have also been made within soil response analysis (which was an important topic in the ELOCS study), particularly with respect to integration of uncertainties in soil parameters through a simplified Monte Carlo technique (Nadim *et al.*, 1989).

TRENDS IN EARTHQUAKE HAZARD LEVELS

Over the years, uncertainties and levels of conservatism in input parameters to earthquake hazard analyses for the NCS have been systematically reduced, thereby also resulting in lowering the average expected hazard levels. This is most easily demonstrated by comparing the mean normalized spectra applied over the years as shown in Fig. 3, for the 10^{-4} and 10^{-2} per year probability levels, respectively.

The PGA has simultaneously maintained its level for the 10^{-4}/year probability while the 10^{-2}/year level has been lowered, resulting in an effective reduction in spectral levels at low and intermediate frequencies for the 10^{-4}/year probability and even more so for the 10^{-2}/year probability. While the first guidelines included a conventional fixed design spectrum, later updates have invoked the principle of using an equal hazard spectrum for design.

Through this work, earthquake loading has been reduced from being a key design factor to a level normally below the sea wave load for North Sea structures.

APPLICATION OF INFORMATION TO THE DEVELOPMENT OF A SEISMIC CODE

The cost of the research and development work described above have been about $3 millions. The savings for only one of the large fixed platforms installed have been considerably larger. It is therefore recommended, also for intraplate areas, to carry out seismic hazard assessments supported by research on seismicity and related topics, in order to obtain more accurate seismic loading criteria against which structures be designed. The seismic research would include:

- Data collection from a network of seismograph stations over at least 20 years.
- Review and use of older data and information about historical earthquakes.
- Review and development of appropriate attenuation ground motion models.
- Inclusion of available geologic and (neo)tectonic data and results.
- Use of the logic tree approach to handle uncertainties.

This work should be carried out by the industry in cooperation with research institutions and legislative bodies in order to promote safety and reduce costs.

CONCLUSIONS

Research work and data collection have successfully been carried out with the effect of reducing the earthquake design levels for fixed structures on the Norwegian Continental Shelf. This effort has resulted in considerable savings compared with early estimates of the seismic loading in this area.

It is recommended to carry out such studies in intraplate areas rather than to increase the strength of (offshore) structures by designing unnecessarily conservatively in order to resist the estimated earthquake loading.

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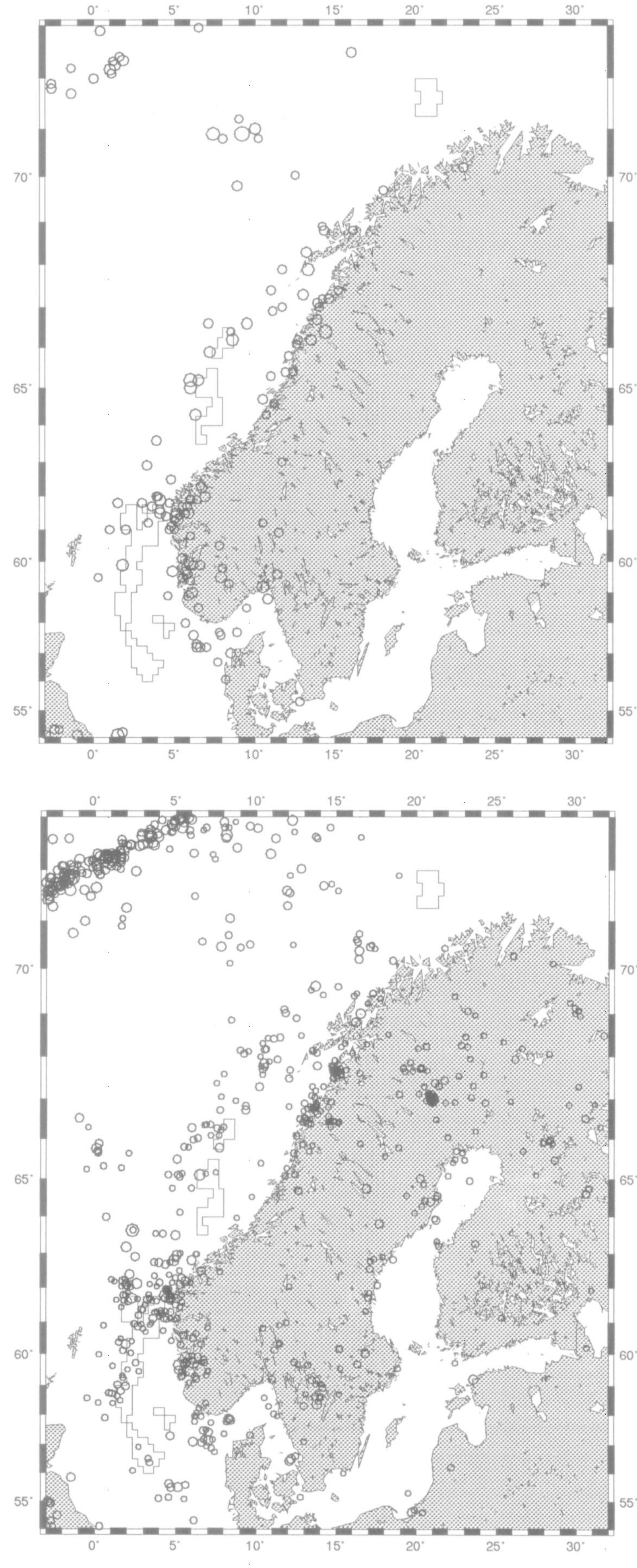

Fig. 1. Historical earthquakes (1800-1964) greater than or equal to magnitude 4 seen in relation to the main producing oil and gas provinces on the Norwegian Continental Shelf (upper), and instrumentally recorded earthquakes (1965-1995) greater than or equal to magnitude 3 (lower).

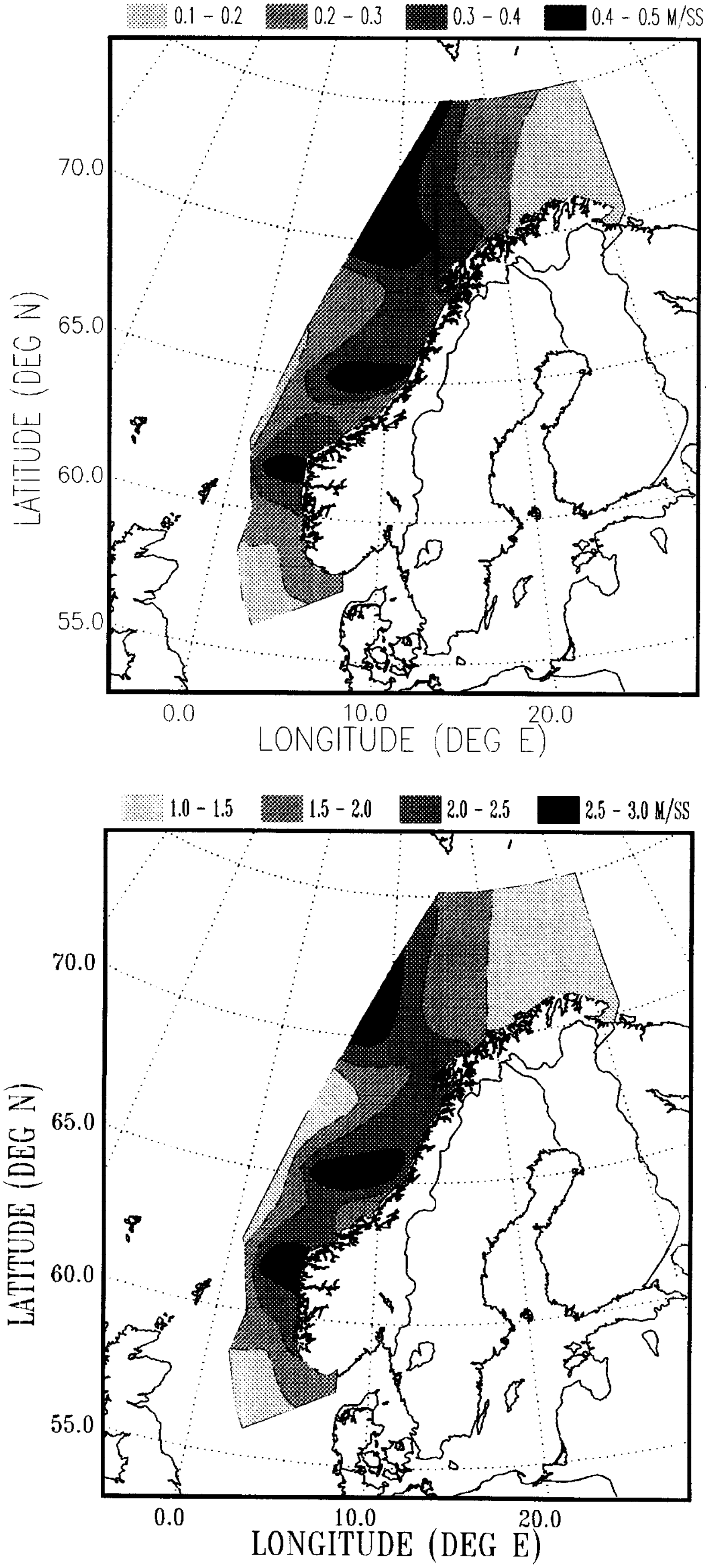

Fig. 2. PGA zoning maps for the Norwegian continental shelf with probability of exceedance 10^{-2}/year (upper) and 10^{-4}/year (lower).

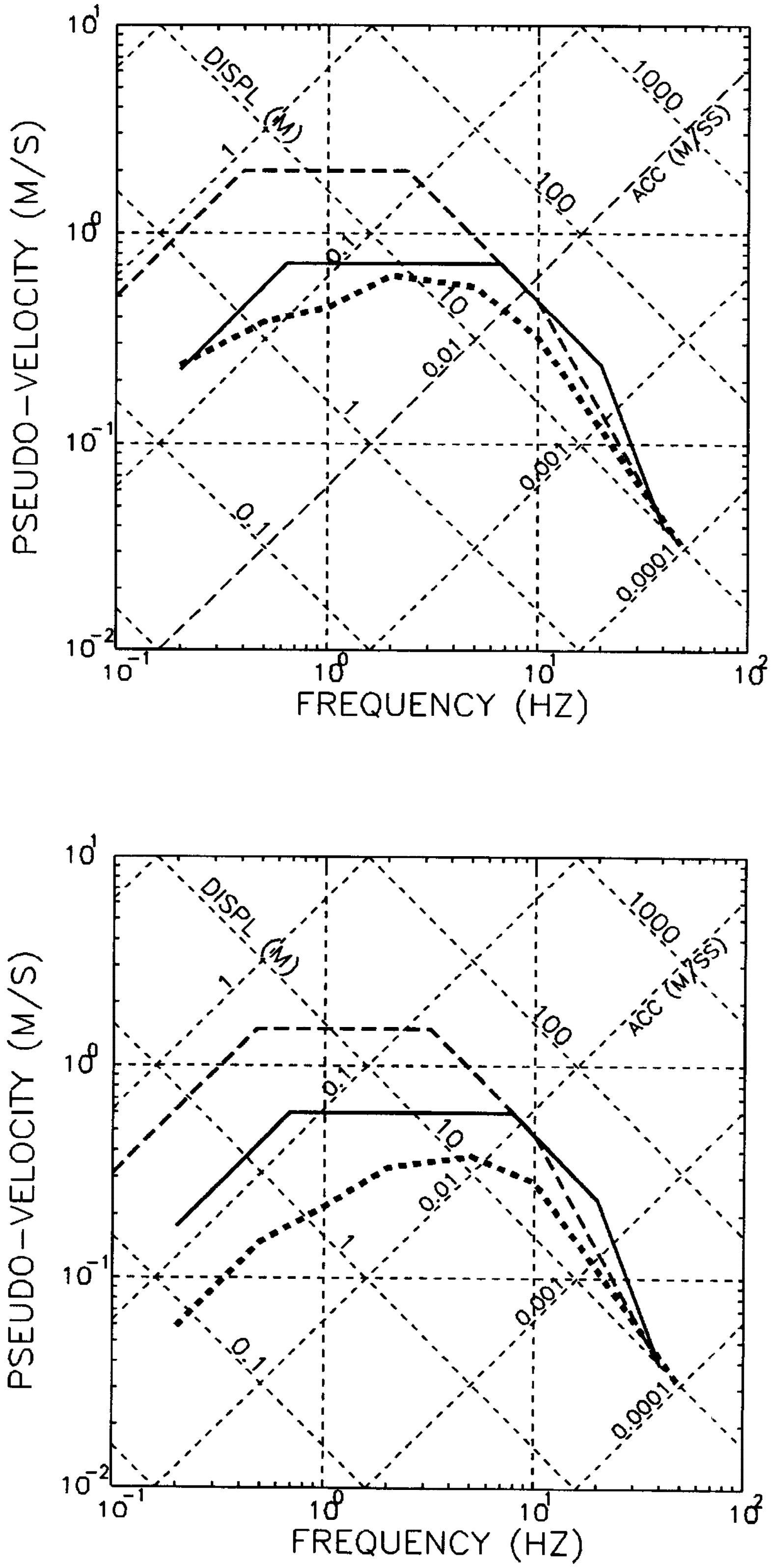

Fig. 3. Normalized 5% damped NCS bedrock outcrop spectra for annual probability of 10^{-4} (upper) and 10^{-2} (lower): NPD(1987) spectrum (dashed line), NPD (1993) (solid line) and OKN (dotted line).