Probabilistic Seismic Hazard Analysis Using Physical Constraints

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A. Gürpinar, IAEA

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International Atomic Energy Agency

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Introduction

PSHA already has a prominent place in the assessment of the seismic safety of NPPs. It has been used as a tool to derive design basis values, in seismic re-evaluation studies and also as input to seismic PSAs. Its role in the future is likely to increase further because of the recent emphasis on 'risk-informed' decision making.

Introduction (Cont’d)

PSHA has been an IAEA requirement since 2000. This is because a Probabilistic safety assessment (PSA) is a requirement for all NPPs (IAEA Design Safety Requirements). As seismic events may trigger initiators to sequences in the PSA, the definition of the hazard curve becomes necessary.

The IAEA Safety Guide on Evaluation of Seismic Hazards for NPPs

- The IAEA Safety Guide related to PSHA is called “Evaluation of Seismic Hazards for NPPs NS-G-3.3”. It was published in 2002. This is the second revision of the Guide; previous versions were dated 1979 and 1991.

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The IAEA Safety Guide on Evaluation of Seismic Hazards for NPPs (Cont'd)

- The basis for the second revision involved the following aspects:
  - Feedback from IAEA Seismic Safety Review Services
  - New developments
    - Regulatory approach
    - External event PSA for new and existing NPPs
    - New data from significant recent earthquakes
    - New approaches in methods of analysis

The IAEA Safety Guide on Evaluation of Seismic Hazards for NPPs (Cont'd)

- Major changes that were made in this revision are as follows:
  - Provide more guidance on new topics of data generation such as paleoseismology
  - Provide guidance on methods for PSHA
  - Provide further guidance on the development of ground motion response spectra – decouple this from the 'design response spectrum' issue

The IAEA Safety Guide on Evaluation of Seismic Hazards for NPPs (Cont'd)

- Recommended scales of study for all types of data (from Rev. 1, 1991):
  - Regional: a minimum radius of about 150 km and at a scale of 1 : 500000
  - Near regional: a minimum radius of about 25 km and at a scale of 1 : 50000
  - Site vicinity: a minimum radius of 5 km and a scale of 1 : 5000
  - Site area: fenced in area, at a scale of 1 : 500

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The IAEA Safety Guide on Evaluation of Seismic Hazards for NPPs (Cont'd)

- Data and uncertainty

  One of the general recommendations of the Safety Guide (Para 2.7) is as follows:

"The general approach to seismic hazard evaluation should be directed towards reducing the uncertainties at various stages of the process. Experience shows that the most effective way of achieving this is to collect a sufficient amount of reliable and relevant data. There is generally a trade-off between the effort needed to compile a detailed, reliable and relevant database and the degree of uncertainty that the analyst should take into consideration at each step of the process."

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TYPE OF DATA	TIME FRAME (approx.)	LOWER MAGNITUDE THRESHOLD (approx.)	TIME RESOLUTION
Local networks	10- 20 years	_ -1	second
Modern instruments	30-40 years	_ 2	second
Early instruments	100 years	_ 4	second/minute
Historical	from few centuries to few millennia (*)	_ 3(**)	from minute to year
Archaeological	from few centuries to a few millennia (*)	_ 5	year
Paleoseismological	10,000 years	_ 6	century
Neotectonics	100,000 years		millennium

(*) depending on history of the Country
(**) depending on time period, seismic activity of region and according to cultural and socio-economic historic context.

Table 1

Type of data for the reconstruction of long term seismic history

IAEA Review Services on Seismic Safety of Nuclear Facilities

In the following slides, a brief overview of the sites/plants that have been reviewed is presented.

Overview of the Reviewed Sites

- Gorki (USSR): New name of the city is Nizni Novgorod. Heat Generating Plant. The seismic hazard review was done within the scope of a design safety review of the plant. AEP Leningrad was the designer. (1989)
- Crimea (USSR): WWER 1000 under construction (never completed). Detailed review of seismic hazard including geological hazards (e.g. mud volcanoes)

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Overview of the Reviewed Sites (Cont'd)

The seismic hazard studies were done by AEP Moscow with Ismes (Italy) as consultants. MEQ network operatied for several years. Many geophysical profiles and historical earthquake catalogues were reviewed. (1991)

- Smolensk NPP (RF): RBMK under operation. The seismic hazard review was part of the design safety review for the plant. The adequacy of the 0.1g minimum requirement was checked. (1993)

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Overview of the Reviewed Sites (Cont'd)

- Leningrad NPP (RF): RBMK under operation. The seismic hazard review was done within the scope of a general study of external hazards. The adequacy of the 0.1g requirement was checked. The work was performed by Russian consultants.(1999)

- Temelin NPP (Czechoslovakia): WWER 1000 at the time under construction. The seismic hazard review was done within the scope of a site safety review. Potential for geological hazards was considered. MEQ network operated for several years. The work was done by Czech consultants. The final study was PSHA. (1992 with a follow up in 2003)

Overview of the Reviewed Sites (Cont'd)

- Mochovce NPP (Slovakia): WWER 440/213. Started operation in The seismic hazard was reviewed during three missions, the last one in 2003. The work was done by Slovak, Czech and US consultants. Geological hazards (surface faulting issue) was considered. MEQ network operating. The final study was PSHA. (1994 – 2003)

Overview of the Reviewed Sites (Cont'd)

- Bohunice NPP (Slovakia): WWER 440/ 230 and 213. The process was similar to Mochovce except the final review was in 2000. Slovak and US consultants performed the work. Geological hazards were considered. MEQ network operating. PSHA was used throughout. (1994 – 2000)

Overview of the Reviewed Sites (Cont'd)

- Paks NPP (Hungary): WWER 440/213. Several interim missions were conducted to review the seismic hazard. Extensive work on geophysics (for fault identification) as well as a permanent MEQ network. A PSHA was performed and later extended for a seismic PSA. Geological hazards (surface faulting and liquefaction) were considered. Hungarian, UK and US consultants were involved. IAEA involvement in the review process was intensive. (1993 – 1995)

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Overview of the Reviewed Sites (Cont'd)

- Cernavoda NPP (Romania): PHWR. The review of the PSHA (to be used in the seismic PSA) is presently (2003) ongoing. The work is performed by Romanian and US consultants .

- Pitesti RR (Romania): The seismic hazard review was done as part of the safety review of the research reactor. (2001)

Overview of the Reviewed Sites (Cont'd)

- Kozloduy NPP (Bulgaria): WWER 440/230 and WWER 1000. The review of the seismic hazard was an intensive process with several interim and topical reviews. Geophysical studies were performed (for surface faulting) and a MEQ network was procured. The seismic hazard studies used both deterministic and probabilistic methods. Bulgarian and Macedonian consultants performed the work. (1991 – 1995)

Overview of the Reviewed Sites (Cont'd)

- Belene NPP (Bulgaria): WWER 1000. At the time of the review the NPP was under construction. The seismic hazard review was performed as part of the site safety review. Several missions were made. MEQ network for a short period. The work was done mainly by Bulgarian consultants. Independent review was made by US consultants. IAEA involvement was from 1990 to 1994.

Overview of the Reviewed Sites (Cont'd)

- Krsko NPP (Slovenia): PWR Westinghouse. The PSHA was reviewed as part of the review of external events PSA for the plant. Geophysical work for identification of surface faulting. MEQ network. (1998)

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Overview of the Reviewed Sites (Cont’d)

- Medzamor NPP (Armenia): WWER 440/230. Several missions were conducted specifically for the seismic hazard review. Geophysical work was performed by Ismes. MEQ network deployed. Volcano hazard addressed. IAEA involvement started in 1991 and a final review mission for seismic safety (including hazard assessment) will be conducted this year (2003). A new PSHA study was initiated in 2003.

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Overview of the Reviewed Sites (Cont'd)

- Cekmece RR (Turkey): The IAEA involvement was mostly related to seismic re-evaluation of the facility and upgrading. Seismic hazard was evaluated by Turkish consultants. The strong motion instrumant at the site recorded ~0.2g during the 1999 Izmit Earthquake. (1999)

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Overview of the Reviewed Sites (Cont'd)

- Bushehr NPP (Iran): WWER 1000 (original plant was a German Konvoi). Several missions were performed specifically to review the seismic hazard. Very detailed geological, geophysical and seismological studies were performed by Russian and Iranian contractors. MEQ network. Surface faulting investigations. (1994 – 2000)

Overview of the Reviewed Sites (Cont'd)

- Ulken (Kazakstan): NPP site near Lake Balkash. The review of seismic hazard was within the scope of site safety review. Work was performed by Russian and Kazak consultants. MEQ network. (1998)

- Alatau (Kazakstan): RR near Almati under operation. Main concern was surface faulting and extensive trenching was performed. (1997)

Overview of the Reviewed Sites (Cont’d)

- Ulugbek (Uzbeksitan): RR near Tashkent in operation. The seismic hazard review was part of the general seismic safety review of the RR. (1996)

- Rooppur (Bangladesh): NPP Site. The seismic hazard review was part of the general site safety review. (2000)

Overview of the Reviewed Sites (Cont'd)

- Chashma NPP (Pakistan): PWR 300MW Chinese design (now in operation). The seismic hazard studies were reviewed as part of the site safety review. Site vicinity field geological was reviewed in detail. The wok was performed by Pakistani consultants and Ismes (Italy). MEQ monitoring for a limited period. The review was completed before construction started in 1992.

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Overview of the Reviewed Sites (Cont’d)

- Kanupp NPP (Pakistan): PHWR in operation near Karachi. Seismic hazard was reviewed as part of the seismic safety program for the plant. The work was performed by Pakistani consultants. Several missions were conducted. (1997 – 1999)

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Overview of the Reviewed Sites (Cont'd)

- Muria (Indonesia): NPP Site North Central Java. The seismic hazard was reviewed as part of the site safety review during a period of about eight years. The studies are still not completely finalized. Volcanic hazard was also of concern. The work was performed by Indonesian and Japanese consultants. (1991 – 1999)

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Overview of the Reviewed Sites (Cont'd)

- Madura (Indonesia): Site for a nuclear desalination plant. The first review was performed as part of the site survey review. (2002)
- Bangkok (Thailand): Site for a RR. The review was done as part of a site safety review. (1997)

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Overview of the Reviewed Sites (Cont'd)

- Ulchin NPP (Korea): PWR Korean design. The review was done as part of the external events PSA for the plant. Soil stability was also addressed. The work was done by Korean and US consultants. (1997)
- Sinpo (N. Korea): Site for a PWR Korean design to be built by KEDO. The review was done as part of the design review of the plant. The work was done by North and South Korean consultants. (2001)

Overview of the Reviewed Sites (Cont'd)

- Tianwan NPP (China): Site for a WWER 1000 (now under construction). Work was done by Chinese consultants. Some surface geology work and use of historical earthquake data. Limited MEQ monitoring. (1998)

Overview of the Reviewed Sites (Cont'd)

- Sidi Boulbra (Morocco): Site for NPP. Seismic hazard review was part of a site safety review which went on for almost ten years. The work was done by French and Moroccan consultants. Tsunami effects considered. MEQ monitoring and use of historical earthquake data. (1985 – 1993)

Overview of the Reviewed Sites (Cont’d)

- Maamora (Morocco): Site for a RR. The seismic hazard review was done as part of design safety review of the facility. The work was done by French, US and Moroccan consultants. (2001)
- Tantan (Morocco): Site for a desalination plant. The review was done as part of the feasibility study. The work was done by Chinese and Moroccan organizations. (1998)

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Overview of the Reviewed Sites (Cont'd)

- Inshas (Egypt): Site of an operating and a future RR. The review of the existing reactor site was done within the scope of a seismic safety review including surface faulting considerations. For the future RR (now constructed) the review was done as part of design safety review. (1993, 1997)

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Overview of the Reviewed Sites (Cont'd)

- Koeberg (South Africa): Site of a new NPP (PBMR). The review was conducted as part of the EIR review for the new facility. There is already an existing NPP (PWR) at the site with a unique sesimic isolation feature. (2000)

Overview of the Reviewed Sites (Cont’d)

- Lucas Heights (Australia): Site of a RR (now under construction). The seismic hazard review was done as part of design review of the facility. Consultants from Australia and New Zealand performed the work for PSHA. Surface faulting was also considered. (2001 – 2002)

Overview of the Reviewed Sites (Cont'd)

- Santiago (Chile): RR in operation. The seismic hazard review was part of an integrated safety review of the RR. The main emphasis of the seismic part of the review was related to seismic vulnerabilities of the RR. (2002)

Comparison of Design/Reevaluated Values for PGA

Name of Installation	Design Value of PGA	Re-evaluated value (Deterministic or corresponding to 10^{-4} annual frequency
Leningrad NPP	< 0.1g	0.1g
Temelin NPP	< 0.1g	0.1g
Mochovce NPP	< 0.1g	~ 0.2g
Bohunice NPP	< 0.1g	0.28g

Comparison of Design/Reevaluated Values for PGA

Name of Installation	Design Value of PGA	Re-evaluated value (Deterministic or corresponding to 10^{-4} annual frequency
Paks NPP	< 0.1g	0.35g → 0.28g
Cernavoda NPP	0.2g	> 0.3g
Kozloduy NPP	< 0.1g	0.1g → 0.2g
Belene NPP	0.1g	0.25g

Comparison of Design/Reevaluated Values for PGA

Name of Installation	Design Value of PGA	Re-evaluated value (Deterministic or corresponding to 10^{-4} annual frequency
Krsko NPP	0.3g	0.4g
Medzamor NPP	0.1g	0.2g → 0.35g
Çekmece RR	0.1g	0.4g
Bushehr NPP	0.4g	0.4g

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Comparison of Design/Reevaluated Values for PGA

Name of Installation	Design Value of PGA	Re-evaluated value (Deterministic or corresponding to 10^{-4} annual frequency
Alatau RR	0.3g	0.7g
Kanupp NPP	0.1g	~ 0.25g
Wolsung NPP	0.2g	> 0.3g
Lucas Heights RR	0.1g	0.35g

Paks NPP

Paks NPP is located in Hungary on the Danube about 100 kms south of Budapest. There are four WWER 440/213 units in operation. The original design did not include seismic loads explicitly.

A ‘preliminary’ seismic hazard study was performed in 1992 by an international consulting company that recommended a ZPA value of 0.35g associated with a site specific RS. This study was commissioned by the plant.

Paks NPP (Cont'd)

The Hungarian regulatory body commissioned a review of this study by a national committee headed by a professor of geology from the Hungarian Academy of Sciences. This committee confirmed that the hazard values proposed by the international consultant company were appropriate for the Paks NPP site.

The Hungarian regulatory body asked the IAEA to review the seismic hazard in 1993.

Paks NPP (Cont'd)

The same international company was contracted to perform the study in detail and with much more new local data. The new data included:

- MEQ monitoring
- Geophysical profiles including across the Danube
- Site vicinity geological mapping
- Large number of boreholes
- Trenches

Paks NPP (Cont'd)

The aim of these investigations was to clarify the uncertainties related to the potential of faulting in the near region and the site vicinity.

After these investigations a PSHA was performed in which a number of alternative seismotectonic models were considered with different weights.

The IAEA monitored all the investigations and reviewed the final PSHA and agreed with the final results (the 10^{-4}/yr value of the ZPA was 0.25g).

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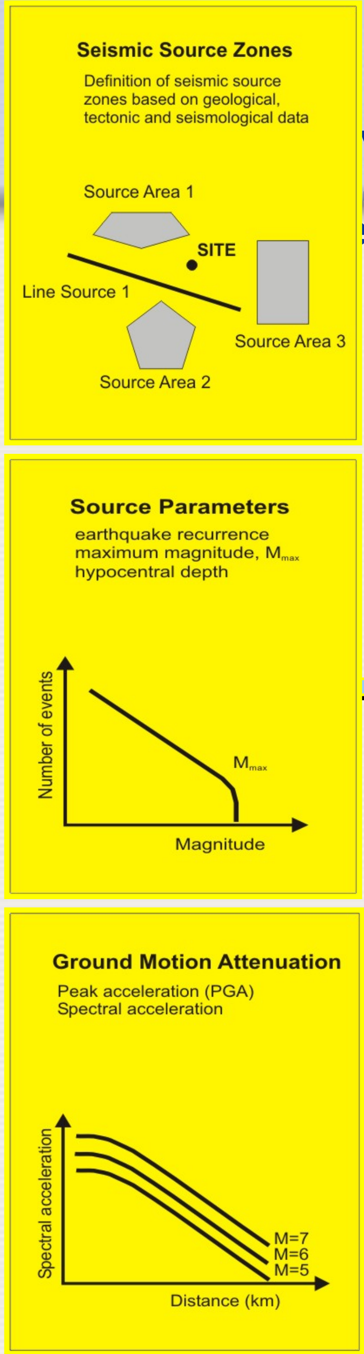
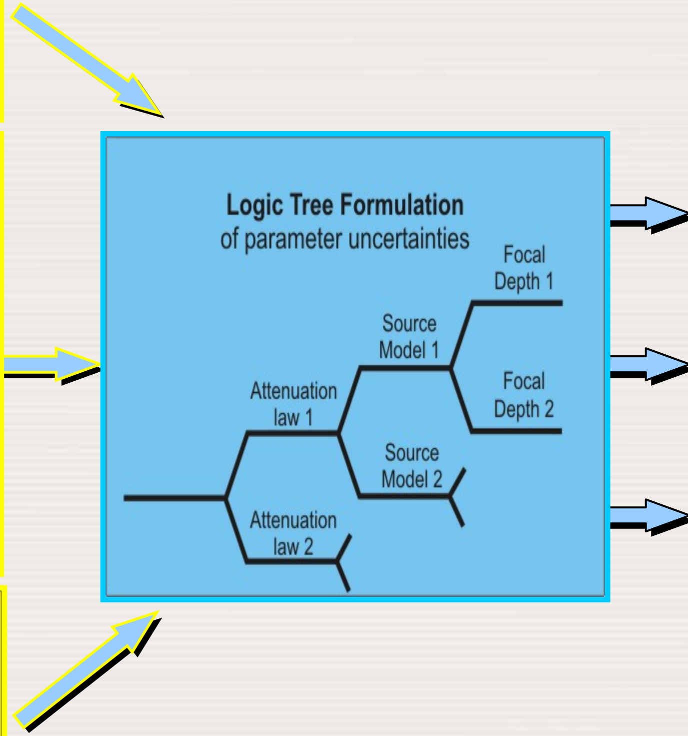
Paks NPP (Cont'd)

More recently an extended PSHA was performed for the external events Probabilistic safety Assessment of the Plant using the same seismotectonic models. The following slides are from this study. The study was commissioned by the Paks NPP and conducted by Messrs. L. Toth and Györi.

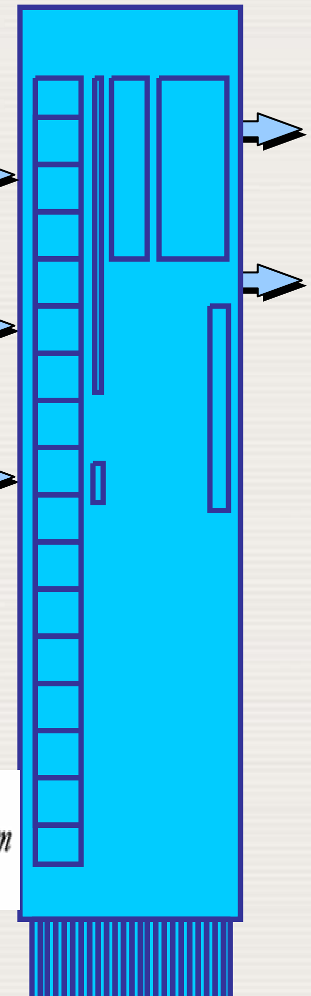
ystematic process

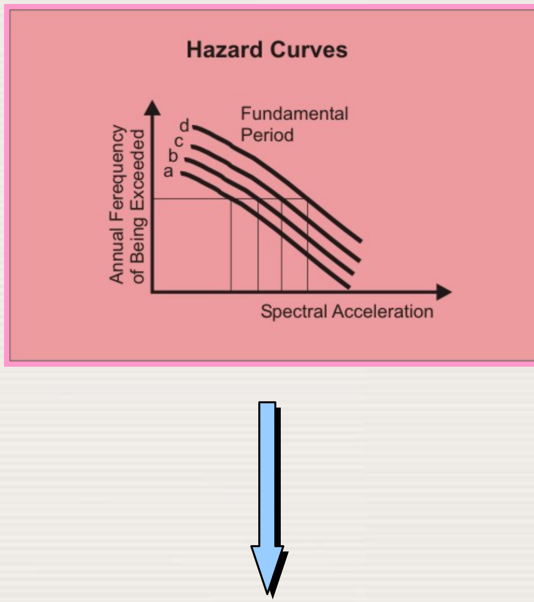
e steps are involved in the assessment of seismic hazard

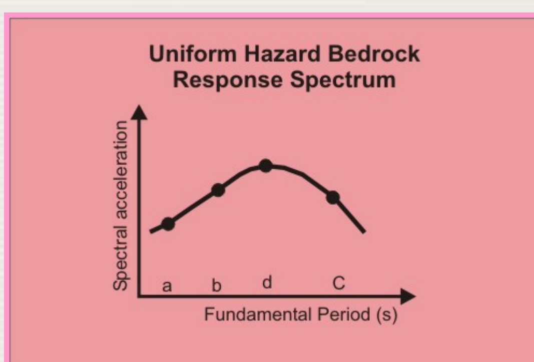


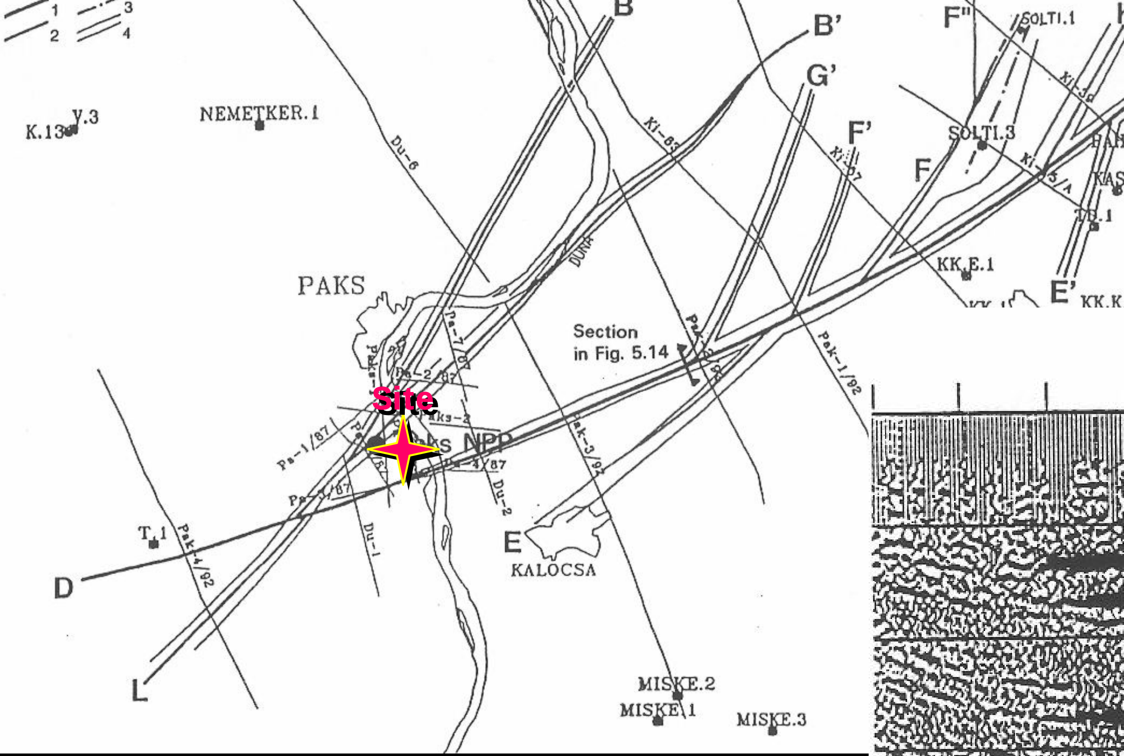


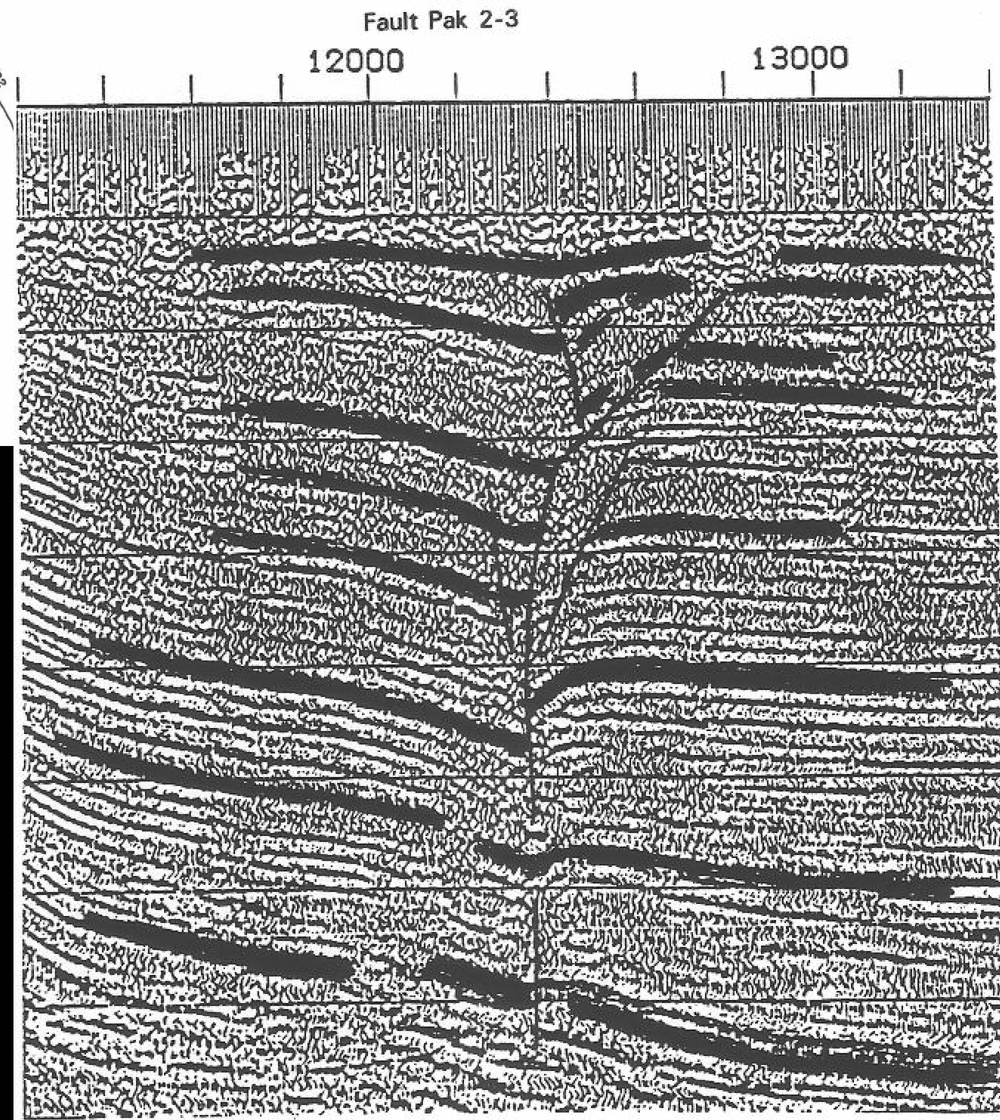
$$\nu(z)=\sum_{n=1}^{N} a_n(m^0)\int_{m=m^0}^{m^u}\int_{r=0}^{\infty} f_n(m)\, f_n(r|m)\, P(Z>z|m,r)\,dr\,dm$$



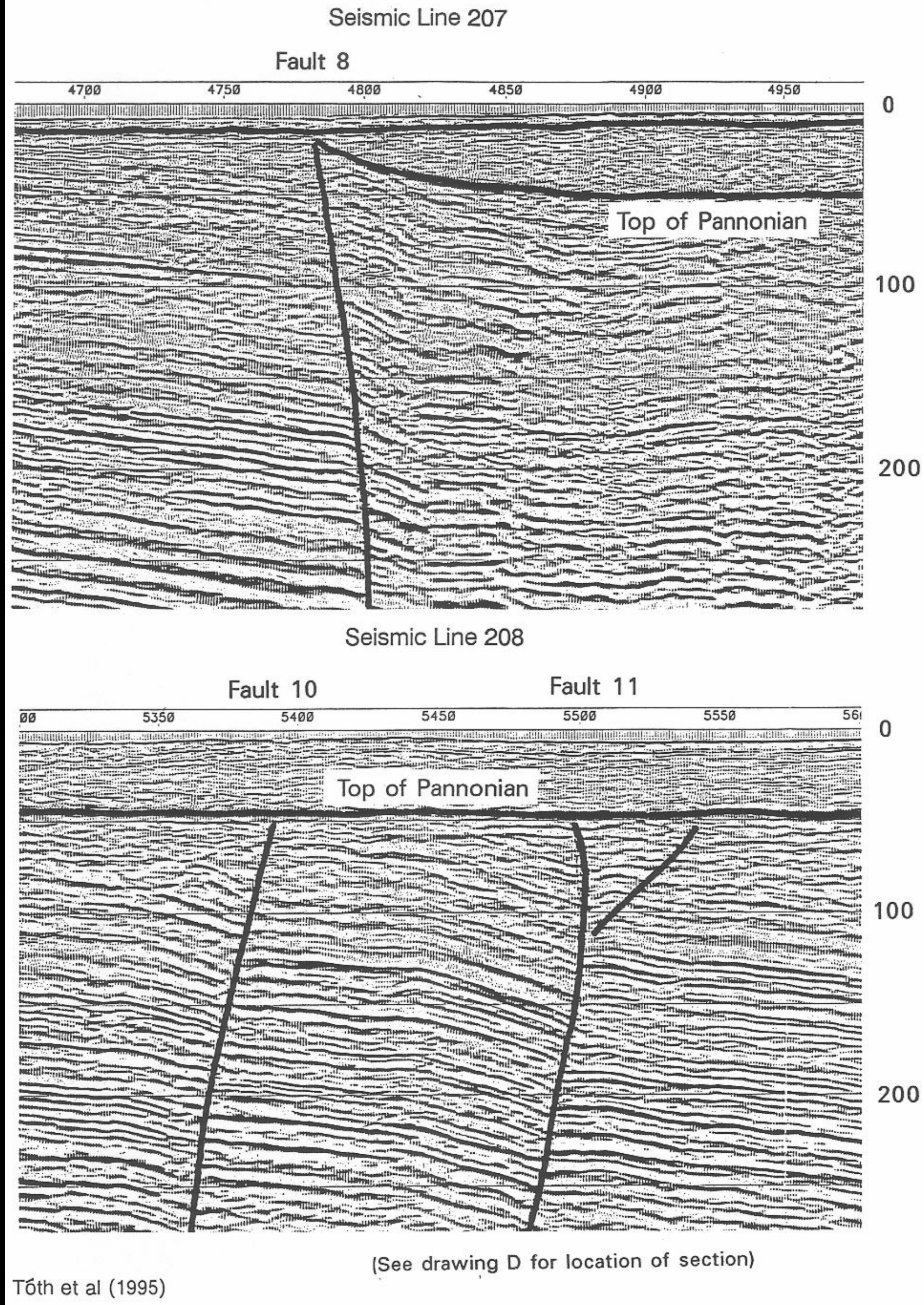








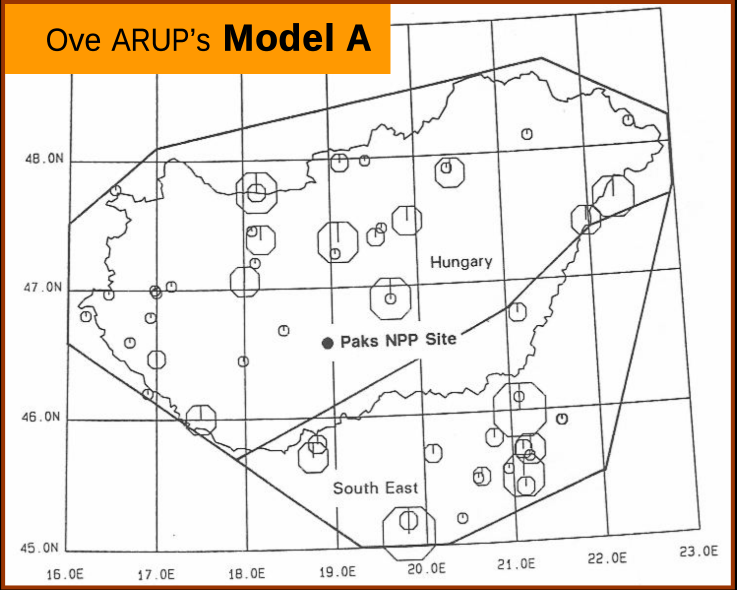
Geophysical profile
PAK-2



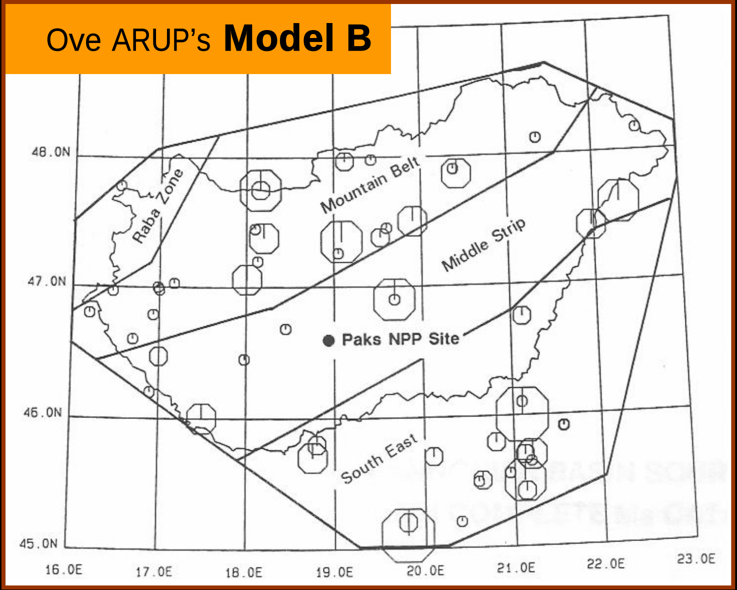
- ✓Geological
- ✓Geotechnical
- ✓Hydrogeological
- ✓Boreholes
- ✓Excavations
- ✓…

Examples of Danube shallow seismic lines

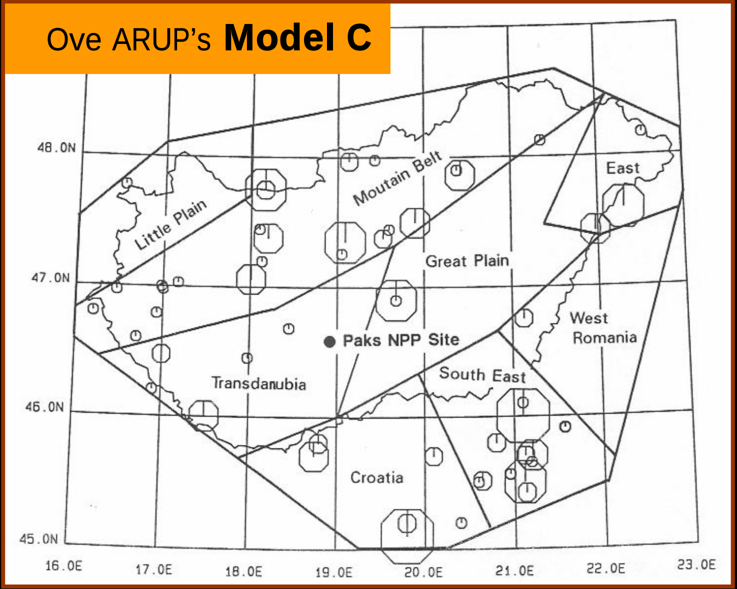
Ove ARUP's **Model A**



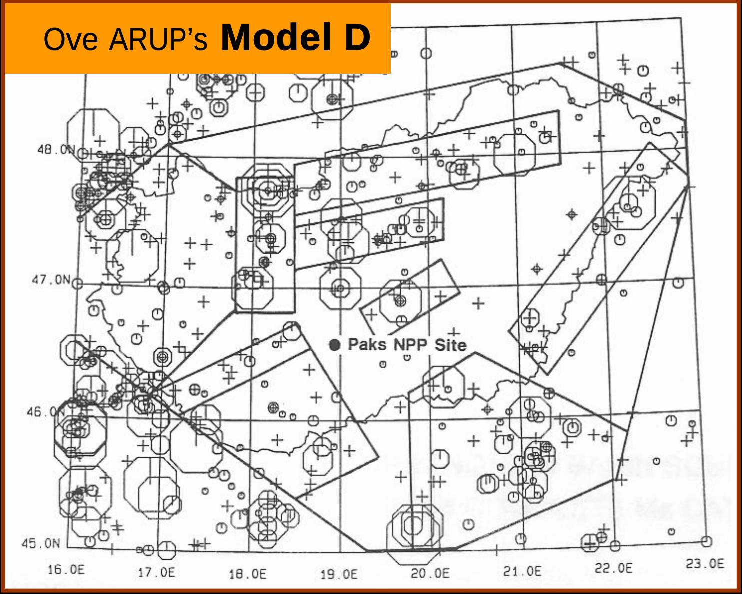
Ove ARUP's **Model B**



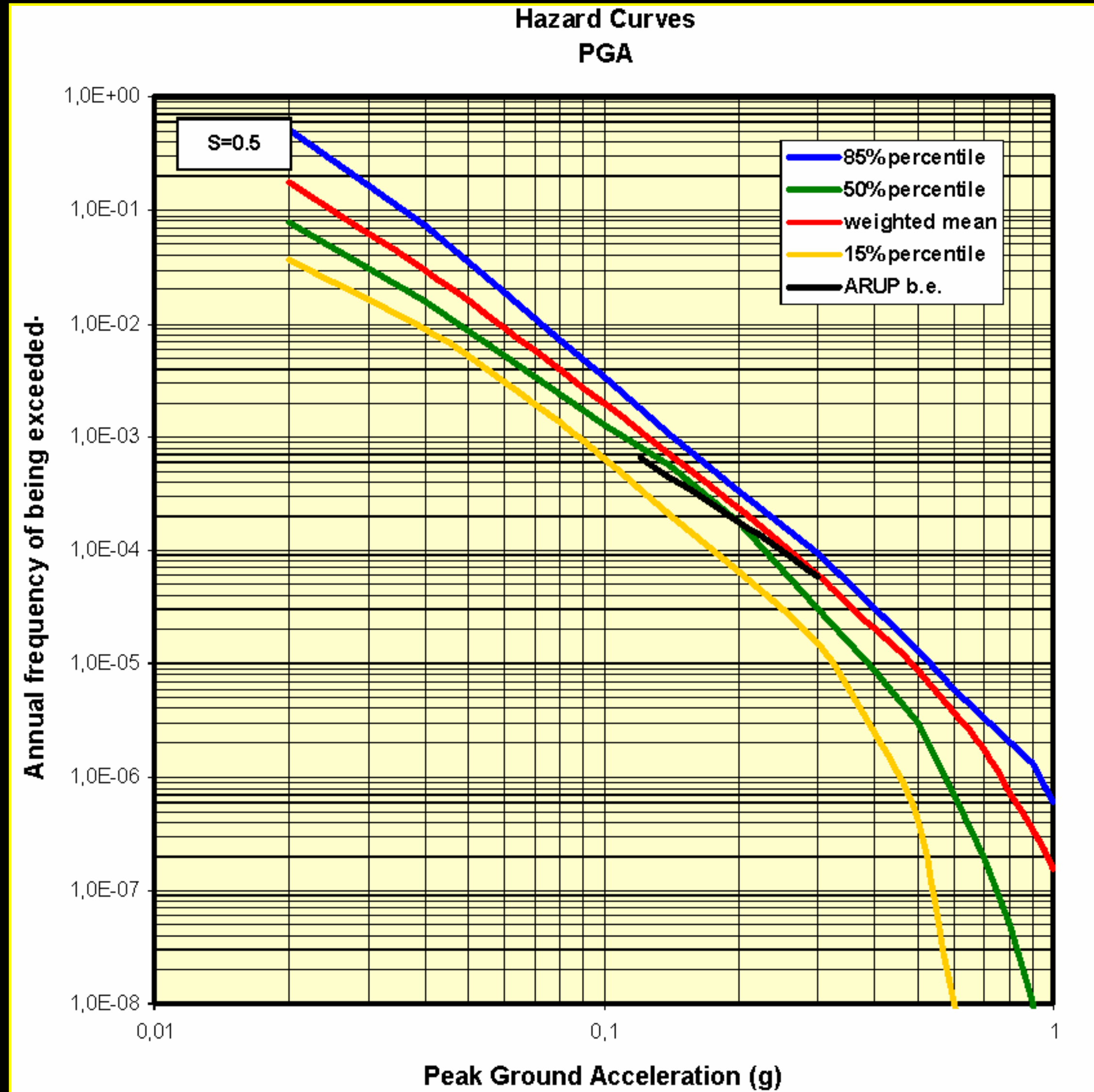
Ove ARUP's **Model C**

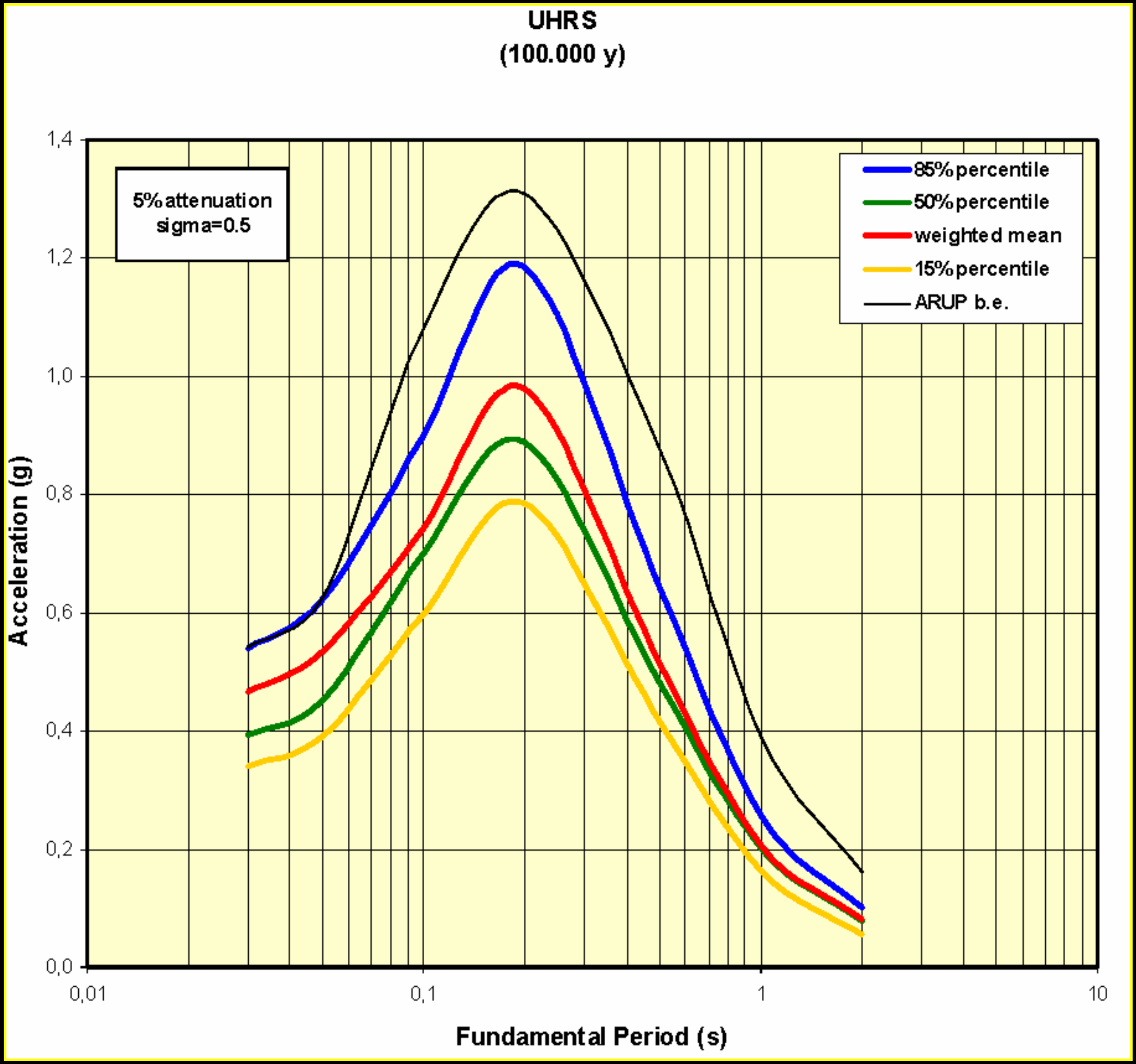


Ove ARUP's **Model D**



Results


Hazard Curves
PGA
S=0.5
85%percentile
50%percentile
weighted mean
15%percentile
ARUP b.e.
Annual frequency of being exceeded·
1,0E+00
1,0E-01
1,0E-02
1,0E-03
1,0E-04
1,0E-05
1,0E-06
1,0E-07
1,0E-08
0,01
0,1
1
Peak Ground Acceleration (g)


UHRS
(100.000 y)
5% attenuation
sigma=0.5
85% percentile
50% percentile
weighted mean
15% percentile
ARUP b.e.
Acceleration (g)
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0,01
0,1
1
10
Fundamental Period (s)

Cernavoda NPP

Two separate studies are being performed for the PSHA of the Cernavoda NPP site. The IAEA was invited to review both of these studies.

The seismic sources that affect the site are the Vrancea intermediate, Vrancea crustal and other crustal sources including some active faults in Bulgaria and Romania as well as zone(s) of diffuse seismicity. The original design of the plant was for a RS anchored to a pga of 0.2g.

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Cernavoda NPP (Cont'd)

The first study was conducted by a local engineering company (CITON). The review of this study together with its follow up was completed in September 2004. The study used existing geological, geophysical and seismological data. A group of experts was set up by the project team and the methodology of NUREG/CR 6372 was generally followed.

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Cernavoda NPP (Cont'd)

The final results took appropriate account for both aleatory and epistemic uncertainties relating to various parameters as well as the modelling of the seismic sources. The mean pga for a 10^{-4} annual frequency was approximately 0.36g.

Cernavoda NPP (Cont'd)

The second study was performed by an American consulting company (Paul Rizzo & Associates) in collaboration with a Romanian consulting company again following generally the approach of NUREG/CR 6372. The experts in various areas were chosen from Romanian institutes. Two experts were common to both studies. Again, similar to the first (CITON) study, the PSHA relied on existing data.

Cernavoda NPP (Cont'd)

Recommendations that were made involved mainly the uncertainties resulting from the lack of data especially related to the shallow sources (not related to Vrancea). The mean hazard curve for pga corresponds to a value of 0.3g at 10^{-4} annual frequency. The follow up of the review will be performed in the spring of 2005 after the implementation of the recommendations is completed.

Lessons Learned and Conclusions

- In countries where the original site evaluation did not involve adequate data collection (e.g. comparable to the recommendations of NS-G-3.3), it is very important to compile a reliable and relevant database focusing on significant features prior to the work on the PSHA. This will limit the uncertainties that will be encountered during the analysis.

Lessons Learned and Conclusions

- Several issues have been observed in the use of expert opinion in addressing epistemic uncertainties. These may be grouped under several headings:
  - In small countries, when expert groups are selected only within the country, there is considerable interaction amongst these.
  - In some countries there are well established, almost official positions on technical issues so that expert opinion (which merely reflects this position) has little added value.

Lessons Learned and Conclusions (Cont'd)

- The project management does not provide a coherent set of data and guidance to the process and the expert opinions are consequently divergent.
- National boundaries present major obstacles in the homogeneity of the investigations and data.
- Offshore areas present a particular challenge to experts if additional data is lacking.

Lessons Learned and Conclusions (Cont'd)

- One of the recurring key issues in the PSHA's that the IAEA has reviewed is the problem of the so called "near field" earthquake. The summary of the issue (with minor variations from case to case) is as follows:

Lessons Learned and Conclusions (Cont'd)

The site for the NPP has been chosen at a relatively 'aseismic' part of the country. This generally means that well known seismogenic sources are more than at least 50 - 100 kms from the site. Consequently the seismic source that contains the site is a 'zone of diffuse seismicity' (to use the terminology of the IAEA Safety Guide). Because there are few dispersed epicentres and that these are not well correlated with tectonic structures, these areas generally do not attract the interest of researchers and therefore contain the least amount of both geological and seismicity data that is available prior to the selection of the site.

Lessons Learned and Conclusions (Cont'd)

. In the process of site evaluation and contrary to what the IAEA Safety Guide recommends the largest efforts are again concentrated on the well established seismogenic structures and the site area, mainly for geotechnical studies (i.e. in the regional and site area scales). This leaves open questions in the near region and the site vicinity and therefore both the seismic source modelling (or absence of a model) and the parameters needed for the PSHA contain large uncertainties, both epistemic and aleatory. Eventually the contribution of this zone of diffuse seismicity is very significant and sometimes dominating. Then the analyst is stuck with the situation that the hazard is driven not by what he knows but what he does not know (in fact what he neglected to learn).