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NEA Kappa Workshop on Earthquake Ground Motions on Rock Sites

25-28 May 2021

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Foreword and acknowledgements

The members of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (WGIAGE) acknowledge the significant contributions of those individuals who had a key role in the preparation of the summary report, and those who had a leadership role in the conduct and success of the NEA Kappa Workshop, such as Mr Nebojsa Orbovic (the leader of the Organising Committee of the Kappa Workshop) and Dr Olga-Joan Ktenidou. Additional thanks are extended to Dr Keiko Chitose, Dr Norman A. Abrahamson, Dr Philippe Renault and Mr Emmanuel Viallet for supporting the workshop and contributing to the preparation of this summary. This report was approved by the CSNI at its 73rd Session on 6-7 June 2023 (NEA/SEN/SIN(2023)1, not publicly available).

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In memoriam: Neb Orbovic

Nebojsa “Neb” Orbovic was the Chair of the Seismic Engineering subgroup at the time when the Kappa Workshop was held. In addition, he was the leader of the organisation of this workshop, from the beginning of the NEA CSNI activity development until the workshop of which he was the Chair.

He sadly and suddenly passed away on 14 June 2021 and the community unanimously acknowledges a great loss.

Neb was passionate, detail-oriented and consistently aspiring to inspire excellence and innovation in any task. Through his multi-cultural background, he had accumulated a wide range of competences (in the field of civil and earthquake engineering and in impact analyses) in combination with an open-minded spirit, which made him an unavoidable partner in international collaboration. He made a strong contribution to the safety of nuclear structures through multiple national and international organisations, including the NEA, the International Atomic Energy Agency, the American Concrete Institute, the American Society of Mechanical Engineers, the American Society of Civil Engineers and the International Association for Structural Mechanics in Reactor Technology.

Moreover, Neb was always available to help and always strived for perfection in helping others.

We will all remember Neb for his smiling face, biting wit, frank opinions, and above all his technical and academic integrity, which was *par excellence*. For all these reasons, and many others that are not mentioned above, our community would like to thank him again and dedicate this Kappa Workshop report to his memory.

List of abbreviations and acronyms

ACI	American Concrete Institute
ASME	American Society of Mechanical Engineers
ASCE	American Society of Civil Engineers
BC Hydro	British Columbia Hydro and Power Authority
CAPS	CSNI activity proposal sheet
CENA	Central-Eastern North America
CNSC	Canadian Nuclear Safety Commission
CNSN	Canadian National Seismograph Network
CSNI	Committee on the Safety of Nuclear Installations (NEA)
EDF	Electricité de France
EPRI	Electric Power Research Institute
FAS	Fourier amplitude spectrum
GIT	Generalised inversion techniques
GMM	Ground motion models
GMPE	Ground motion prediction equations
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HF	High-frequency
IAEA	International Atomic Energy Agency
IASMiRT	International Association for Structural Mechanics in Reactor Technology
NEA	Nuclear Energy Agency
NGA	Next generation attenuation (relationships)
OECD	Organisation for Economic Co-operation and Development
PEER	Pacific Earthquake Engineering Research Center, Berkeley, United States
PGA	Peak ground acceleration
PSA	Pseudo-acceleration spectrum
PSD	Power spectral density
PSHA	Probabilistic seismic hazard analysis
RGMM	Reference ground-motion model
SA	Spectral acceleration
SCR	Stable continental region
SNR	Signal-to-noise ratio
SSI	Soil-structure interaction
UCLA	University of California, Los Angeles
WGIAGE	Working Group on Integrity and Ageing of Components and Structures (NEA)

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Executive summary

The nuclear community (including both licensees and regulators) is seeking to define a reliable framework with which to evaluate the characteristics of earthquake ground motions for rock sites, especially at high frequencies (>10 Hz). Kappa (denoted κ) is a measure of the slope of amplitude decay at high frequencies in the spectral domain; it expresses energy dissipation that reduces ground motion amplitudes, especially at f>10 Hz. Kappa exerts a major influence on the results of probabilistic seismic hazard analysis for nuclear plant components that are sensitive to high frequencies. It is believed to be correlated with site conditions – harder rock has lower kappa (thus less attenuation of high-frequency energy). This issue is of critical importance in defining input ground motions for earthquake safety assessments of nuclear facilities worldwide. The rock characteristics may vary significantly among rock sites. In practice, all sites with shear wave velocity values within a range of about 1 000 m/s and 4 000 m/s have simply been classed together as "hard rock". But even for similar velocity (i.e. stiffness) rock sites, high-frequency attenuation and amplification can vary considerably, thus affecting the ground shaking characteristics.

The objective of this "Kappa Workshop on Earthquake Ground Motions on Rock Sites" (held remotely from 25-28 May 2021), organised by the NEA Working Group on Integrity and Ageing of Components and Structures (WGIAGE), was to gather international know-how and experience on how to analyse high-frequency spectral decay (kappa) using earthquakes recorded preferably at <100 km at seismograph or strong-motion sites, as well as to provide guidance on selecting kappa values for rock sites and their relationship with site characteristics. The results of the current research programmes – namely, by the CNSC and Western University Ontario in Canada, as well as two other major international projects, the PEER/EPRI/UCLA/EDF Kappa project in the United States and the Seismic Ground Motion Assessment project (SIGMA2) led by France – were presented and discussed at the workshop.

The objectives of the workshop were:

- to share results from current research programmes on kappa and site characterisation;
- to discuss existing and new data sets and methodologies;
- to compare results across different regions, especially stable continental ones; and
- to reach a consensus through discussion and to provide conclusions and/or recommendations.

This report includes the one-page abstracts of each of the twelve presentations delivered during the first three days of the workshop, along with a compilation of the main discussion points and consensus conclusions reached during the Q&A sessions and the final day discussions.

During the workshop, it was agreed that the availability of on-site seismic data recording and monitoring is important to improving the ground motion prediction models used in safety assessment studies. Detailed technical recommendations on the required instrumentation, installation/layout and data processing method were discussed and formulated for the consideration of regulatory bodies or operating utilities, as appropriate, and are summarised below.

1. Overall, it was agreed that on-site seismic data recording is needed at nuclear installation sites to constrain site κ_0 values. Instruments should be installed as soon as possible, as data compilation takes time, especially at stable continental

regions (SCRs), and as loss of data cannot be compensated. The proposed recording systems are completely different to those already in place for safe shutdown/alarm monitoring purposes. The latter operate on a triggering basis with high thresholds, yielding too few or low-quality recordings, incapable of eventually refining κ_0 uncertainties. Guidelines are needed on how and where to implement sensors and how to process their outputs to get reliable signals at high-enough frequencies.

2. In terms of instrumentation, modern state-of-the-art equipment with a high sampling rate (at least 200 Hz) is needed, with due consideration to in-sensor anti-alias filters. Low self-noise broadband sensors (seismometers) should ideally be collocated with strong-motion sensors (accelerometers), both on continuous recording mode. Based on modern technological capabilities, triggered-mode recording is now considered obsolete in most cases and should be reconsidered. The United Kingdom's first borehole array on a nuclear power plant at Bradwell B is a forward-looking example.

3. In terms of sensor installation and layout, data should generally be recorded at free-field conditions. It is still not clear whether a nuclear installation is a free-field site itself, and at what distance its sensors should be installed. Minimising the distance of the sensor from the nuclear installation maximises the representativeness of site conditions (considering spatial variability), but also the level of noise. Site conditions across the nuclear installation site should not be assumed to be homogeneous, even if classified as rock. It is deemed best to install at least two sensors per site. A true free-field, more distant sensor could also serve as a reference station, as could a downhole station (the latter also avoiding noise). Several factors may generate high-frequency resonances or "site" effects that will in turn influence the recorded data. These may include crustal amplification from deeper layers, site-specific amplification from shallow layers including weathered rock, 2D or 3D layering effects and lateral discontinuities, surface topography, resonance of the sensor or its housing, and soil-structure interaction with buildings. Site metadata should be carefully assembled, with particular attention to features affecting high frequencies.

4. In terms of sensor output (data) and considering that nuclear installation datasets are often severely restricted, it is encouraged to perform all processing (including filtering, corrections, downsampling, etc.) after saving the raw data first, so that the unprocessed data always remain retrievable. New methods can eventually render previously rejected data exploitable, thus expanding and enhancing the available nuclear power plant datasets, as in the case of the new noise-modelling technique of Pikoulis et al. (2020). If analysis of existing nuclear installation data is planned, this approach may be a future research topic.

5. In terms of host-to-target (soft-to-hard rock) GMM adjustments, applying κ_0 corrections assuming that κ_0 is only due to pure attenuation/damping – which has been a widely used approach in ground motion characterisation for the last 25 years – leads to a large overestimation of high-frequency ground motion not supported so far by any data. The use of κ_0 in such adjustments should be applied carefully and all steps should be internally consistent with the underlying method and the other seismological parameters.

6. In terms of selecting κ_0 values, using κ_0-V_{s30} empirical correlations from literature is not recommended, as those are dated and lack both empirical and theoretical justification at high Vs. These data are sparse and scattered, and the

monotonic downward κ_0 trend implies too strong a diminution in damping on hard rock to be physically meaningful. Also, surface Vs is not the only parameter affecting κ_0: to assume so may lead to higher aleatory variability estimates, which could be refined into epistemic uncertainty if the profile dissimilarities at greater depth were also considered. The above outcomes support the conceptual model of regional asymptotic minimum κ_0 values (Ktenidou et al., 2015), where the extent of a “region” depends on spatial variability of its characteristics both near-surface and at depth.

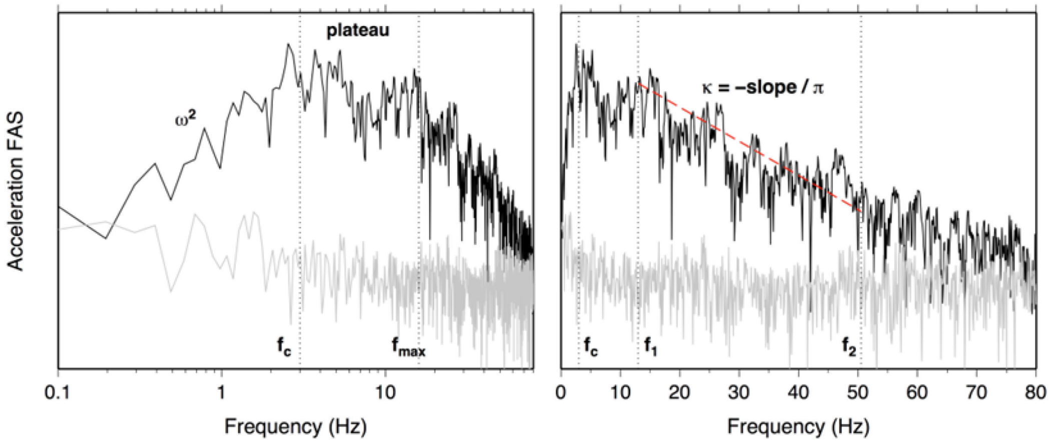
1. Introduction

1.1. Background

In the aftermath of the Fukushima Daiichi Nuclear Power Plant accident, the nuclear community has been re-evaluating seismic hazards at nuclear facilities worldwide. One of the major challenges in this effort is realistically quantifying epistemic uncertainties. An inappropriate assessment of uncertainty can result in higher or lower hazard estimates and have significant implications for seismic safety. To this end, licensees and regulators need a reliable framework to evaluate the characteristics of earthquake ground motions at rock sites, especially at high frequencies. Ground motions at high frequencies are driven by the combination of amplification and attenuation on rock sites.

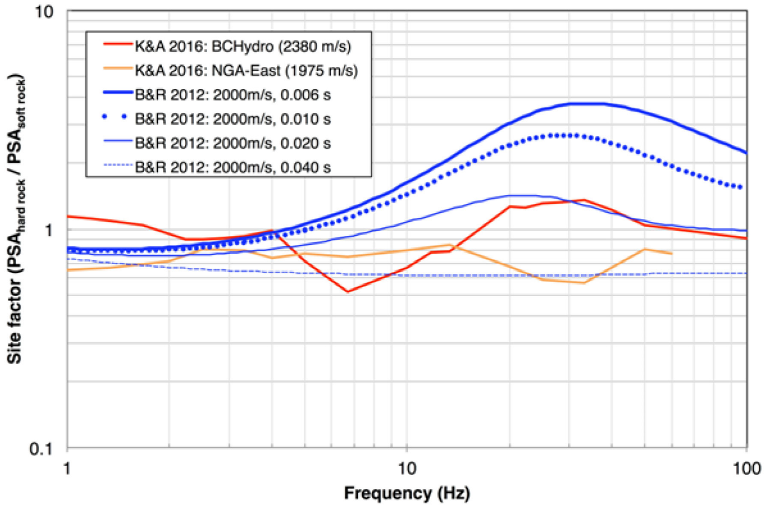
Energy dissipation effects are often characterised by the high-frequency attenuation parameter kappa (κ), which describes the slope of the Fourier amplitude spectrum (FAS) at high frequencies. Figure 1.1 shows an acceleration Fourier amplitude spectrum (black line) in log-log space, where the Brune (1970) ω^2 increase up to the source-related corner frequency f_c, which marks the onset of the plateau, and the site-related frequency f_{max}, which marks the onset of the rapid decay, are all labelled. Figure 1b shows the same spectrum in log-linear space, where the estimation of the slope, i.e. the rate of the decay, is related to κ, within a selected frequency band f_1-f_2 which must well exceed f_c and be well above the noise level (grey line).

Figure 1.1. Acceleration Fourier amplitude spectrum (FAS) in log-log and log-linear space



κ exerts a major influence on the results of probabilistic seismic hazard analysis (PSHA) – making it very consequential at low probabilities for nuclear plant components that are sensitive to high frequencies. Typically, κ is believed to be correlated with site conditions – harder rock exhibiting lower κ and thus less attenuation of high-frequency energy. However, the understanding of the physics behind κ, its trade-offs with other parameters and its estimation are still open issues in the scientific community. And while scientific issues are debated, uncertainties in κ between values of, say, 5 to 40 ms, may result in amplification of short-period (say, at 30 Hz) spectral acceleration (SA) up to factors of two or more when adjusting ground motion from soft rock to less attenuating hard rock. Figure 1.2 shows such soft-to-hard-rock amplification in the response spectral domain for theoretical modelling with varying κ values (Biro and Renault, 2012) and for recorded data (Ktenidou and Abrahamson, 2016). This issue is of critical importance in defining input ground motions for earthquake safety assessments of nuclear facilities worldwide, and especially in cases where no regional attenuation model is available and global attenuation models have to be adjusted to the target site of interest.

Figure 1.2. Large amplification factors near 30 Hz when adjusting ground motion from soft to hard rock, i.e. from large to small values of κ₀, are evident in theoretical PSA ratios but not in empirical ones



1.2. Objectives and scope

For this purpose, the NEA organised an online workshop in collaboration with the CNSC to discuss the current state of the practice of evaluating the characteristics of ground motions at rock sites. The workshop brought together experts in this area from academia, regulatory bodies, international organisations and industry representatives involved in seismic hazard analysis and seismic design and assessment of nuclear facilities. During the four-day workshop, participants exchanged recent research results and worked towards consensus conclusions and recommendations on how to realistically quantify epistemic uncertainties in high-frequency ground motions based on the analysis of seismic records. The structure of the workshop was strongly discussion-based, allocating time for presentations and discussions almost in equal measure, allowing not only the dissemination of results but also the active exchange of opinions in pursuit of consensus.

The scientific disciplines interested in the topic of κ are numerous. They include seismologists working on the emission of high frequencies by the seismic source and studying fault rupture features; engineering seismologists studying site and path attenuation features; geotechnical engineers interested in material attenuation in the sense of damping; and structural engineers interested in the definition of input ground motions for the structures, systems and components. Moreover, the scientific disciplines involved in the exploitation of high-frequency content of seismic recordings also include sensor technology and signal processing. Hence, the group of participants in the workshop was diverse and multidisciplinary.

The scope and objective of the workshop was to:

- share results from current research programmes on κ and site characterisation;
- discuss existing and new data sets and methodologies;

- compare results across different regions, with emphasis on stable continental regions; and
- reach a consensus through discussion and provide conclusions and/or recommendations.

1.3. Organisation of the report

Chapter 2 presents the main findings and conclusions regarding kappa definition, the estimation method and interpretations.

Chapter 3 presents the main recommendations regarding instrumentation type, installation and data processing.

The list of participants, the agenda of the workshop and the presentation abstracts are provided in the appendices.

2. Findings and conclusions regarding Kappa

This chapter provides a brief compilation of the main discussion points made during the workshop regarding the κ parameter, its definition, estimation methods, interpretation and open questions.

2.1. Definition

κ_0 is the slope of the high-frequency FAS after removing the effects of the source, path and site from the FAS. Therefore, κ_0 is the deviation of the observed spectrum from a theoretical model. The κ_0 is usually interpreted as representing attenuation due to damping in the near-surface geological layers beneath the site. Unlike physical quantities such as velocity, κ_0 is not a single straightforward quantity per se but is affected by the misfit of all aspects of the chosen theoretical model from reality. So, the validity of the source model (depending on the assumption of ω^2, etc.), the crustal and site amplification (depending on the Vs structure, the method of computation, deviation from 1D assumption, etc.), and the path attenuation (depending on the Q(f), the geometric spreading, regional variability, etc.) among other factors can bias the measured κ_0. The κ_0 is assumed to represent the effects of only attenuation (which in turn comprises anelastic material damping/absorption and frequency-dependent scattering from small-scale profile fluctuations and inhomogeneities). The case of hard rock-site attenuation in particular causing bias to κ has been made several times in the past for the CENA region. Although the response spectrum is less sensitive to this than the Fourier spectrum due to its nonlinear nature, evidence of clear resonance has been observed on both types of spectra.

2.2. Estimation methods

It is encouraged to continue testing new methods for κ_0 estimation, κ_0 relations with other parameters, or other ground motion adjustment schemes, such as those presented in this workshop. The IAEA guidelines endorse considering different available methods and models for site response estimation. Some new approaches were suggested in this workshop:

- Deconvolved GMMs (presentation 1.2: Hollender et al.)
  The deconvolved GMMs consist in estimating, for each host station, the site effect, either by 1D numerical simulation (when Vs is available) or by generalised inversion techniques (GIT) if enough data exist from enough stations. These site terms are then deconvolved within the Fourier domain from each surface recording, before deriving the GMMs. GIT requires an assumption about the reference site selection, and such a selection is in turn best constrained by in situ investigations.
- $T_{amp1.5}$ (presentation 1.3: Abrahamson)
  Rather than use the slope of the Fourier amplitude spectrum (FAS) to quantify κ as an indicator of high-frequency ground motion, which is sensitive to various trade-offs and leads to large high-frequency amplifications (as seen in this workshop), this method proposes to use the shortest oscillator period at which the normalised spectral acceleration (SA) equals 1.5 times the PGA. This method yields an estimate of κ that can be related purely to site attenuation (κ_{damp}). The result is not biased by crustal parameters, as it is based on short-distance data.
- Noise-modelling method (presentation 1.4: Pikoulis and Ktenidou)
  Increasing the sampling rate may reach higher frequencies but does not lower the noise level per se (due to sensor/site/machinery). But by stochastically modelling

the pre-event noise, the FAS of the seismic signal can be corrected and rendered exploitable up to higher frequencies. These yields improved estimates of high-frequency spectral characteristics and more usable recordings than before. A demonstration was made for κ but the proposition is made for any spectral analysis. The frequency-independence assumption implicit in the existing κ model can also be explored with this method. Existing κ values are likely subject to underestimation from spectral "flattening" due to noise.

- Zeta model (presentation 3.2: Haendel et al.)
  This model accounts for frequency dependency of the Fourier amplitude spectrum with a shape consistent to that due to path attenuation (quality factor $Q(f)=Q0f\eta$). It can be aided by the noise-modelling approach. It requires distances larger than a certain threshold, so it cannot yield κ_0 directly, which is the main goal for application. The spectral flattening consistent with Q(f) can also be due to noise.

In the framework of the IAEA, a plurality of methods and alternative approaches are encouraged, as they contribute towards the exploration of epistemic uncertainty. The methods and models should be backed by empirical data (in this case, seismic recordings); if there are discrepancies, the cause of those discrepancies should be investigated and prediction models rejected by observations should not be used. On-site data that are accessible and accompanied by appropriate metadata can be coupled with regional data and advanced metrics for exploring variability. Consideration of alternative models and uncertainties can be made through a logic tree in a PSHA context. It is also agreed that seismological parameters in each approach are computed to be consistent and correlated as groups of parameters. Hence, they should not be taken in isolation or mixed with other values or models that they are not consistent with.

2.3. Concerns and questions

The concern was expressed as to alternative models of the seismic source spectrum, namely divergence from the Brune (1970) ω^2 model above the corner frequency f_c, impacting κ estimates. The acceleration FAS is invariably considered flat above f_c to compute κ in the classical sense, namely using the κAS method as per the taxonomy of Ktenidou et al. (2014). However, theoretically, there is more confidence below f_c, where the displacement FAS is flat regardless. One method that does not depend on the Brune assumption is κDS (as per the taxonomy), which is applied below f_c. This method is of interest to nuclear installations as it targets small events, which are likely to constitute most data recorded at those sites. The possible effects of the seismic source on κ_0 were not represented in detail in this workshop. More work on the shape of the source spectrum and its effect on κ_0 is encouraged.

Concern was expressed as to the effect of crustal Q(f) and geometric spreading on κ_0 estimation, and as to the consistency of such estimates, as even within the same region, such estimates trade off heavily and may vary between studies. There is need for consistency among seismological parameters and corroboration with data if available. The key solution proposed is to seek short-distance data that is less affected by the Q(f) model, although the definition of "short distance" depends on the region, being shorter in active regions than in SCRs. The selection of appropriate distances also depends on the seismotectonics of a region, as crossing a geotectonic boundary may result in sharp differences in attenuation within short distances, as was shown in this workshop for Quebec.

The concern was expressed as to the large soft-to-hard-rock correction factors currently used when adopting analytical models with typical hard-rock values of the order of 6 ms (if κ reflects only damping). It was agreed that these should be checked against empirical data, checking amplitude scaling as well as the FAS slope per se. At least for active regions, soft-rock ground motion is typically more reliable than hard-rock ground motion, because more seismic recordings are available in the former than in the latter kind of site. Reference ground motions should be well constrained by recordings and not extrapolated. Most very low κ values of 5-6 ms are theoretical rather than empirical[1]. The hard-rock data from NGA-East and BCHydro do not show these large factors (lower by a factor of two at 20 Hz, see Figure 1.2), and there are no known empirical data sets at this time that support the current large-scale factors of high-frequency ground motion for low κ values. If at least some data showed such an effect, it should be made part of the logic tree.

κ is most often analysed in the Fourier domain for quantification and physical understanding. But from the structural engineering point of view, which is currently the representation towards the goal of seismic safety, the response spectral acceleration is the input for design. The concern was expressed that the PSA tool may not be appropriate, as it relates to maximum response of SDOFs, while structural damage is often not related to maximum acceleration values. It is suggested that the power spectral density (PSD) or Fourier amplitude spectrum (FAS) may be preferable as a seismology-engineering communication tool. A lesser concern regards the use of the entire recorded signal (standard practice for PSA) as opposed to the S-wave window (standard practice in seismology), as well as the use of broadband data in addition to strong-motion (accelerometric) data: in current approaches to κ estimation, the S-wave window is favoured, while the inclusion of broadband data is encouraged, although it was shown that the two types of collocated sensors can have different high-frequency effects that are not easily predictable.

Simulations and sensitivity studies were proposed as possible methods to systematically investigate trade-offs in κ estimation to reveal the relative importance and bias of each factor. One key concern expressed is that models should use internally consistent input parameters appropriate to high-frequency ranges. The user should also be aware of the intended frequency band of the methods used and not extrapolate the input values or implied assumptions blindly. Another concern relates to empirical checks on simulations. Multidisciplinary approaches combining empirical and physics-based-simulations are encouraged for this purpose.

2.4. Interpretation

Many consider κ_0 as the misfit parameter rather than a fundamental seismological parameter that can be measured. In the discussions at the workshop, κ_0 was not necessarily considered to be a physical parameter but rather a descriptive empirical parameter for the high-frequency decay rate. It is complicated to decouple the effect of κ_0 from other high-frequency physical mechanisms. It cannot be used outside the suite of assumed source, path and site parameters used to describe the ground motion at a site. The existence of near-surface attenuation due to damping and scattering at every site is irrefutable, but it is difficult to directly relate κ_0 to the near-surface attenuation. It is also important to always be precise in distinguishing between κ and κ_0, the former being measured from the slope of the FAS and the latter being misfit from a model.

As part of the workshop, existing V_{S30}-κ_0 relationships were also revisited. It was concluded by the participants that κ_0 does not correlate well with V_{S30} (here the Vs of the hard rock at depth is meant, and not the usual quantity evaluated 30 m from the top of the soil surface),

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[1] Noting some recent very low values estimated for microearthquake recordings from Olkiluoto hard rock, see abstract 3.3.

especially above e.g. 1 000 m/s, as neither is a good standalone site proxy. κ_0 has been shown to correlate somewhat to V_{S30}, resonant frequency f_0, and depth to bedrock, but this holds only over a wide Vs range and with a poor level of correlation. There is also demonstrated variability in κ_0 among rock sites of similar shear-wave velocities, e.g. potentially due to weathered hard rock, or other geological factors. It is incorrect to assume that rock sites all behave homogeneously, and it has been shown that their high-frequency response is not easy to predict. Simulations can help constrain rock amplification, provided they are empirically checked in the frequency range used.

κ_0 as attenuation has been shown to include both intrinsic damping/absorption and scattering effects from small-scale heterogeneities in the Vs profile. To account for the latter, it is necessary to have not the smoothed site profiles, but the near-raw, detailed profiles without any further loss of small-scale fluctuation/variability information, down to 1-m scale or even less. Similarly, the effect of thin layers and Vs reversals has also been reiterated as a factor of high-frequency dissipation.

Rock and reference site classification can be made according to several different criteria, such as engineering or seismological bedrock assumptions on rock type or shear-wave velocity. For example, Eurocode 8 considers as rock sites profiles with a time averaged Vs_{30} of more than 800 m/s (CEN, 2004), while NEHRP defines rock at 760 m/s and hard rock at 1 500 m/s (BSSC, 2004). EPRI (1993) established reference very hard rock conditions for NIs with a surface Vs of 2 830 m/s (Midcontinent region), while in the post-Fukushima Daiichi era, EPRI (2013) suggested that site-specific amplification functions should be computed if a top layer of more than 7.5 m thickness with a mean Vs of less than 2 590 m/s is over hard rock. For the other cases the amplification functions are unity. Later, Hashash et al. (2014) argued for using 3 000 m/s as the reference Vs for very hard rock conditions in CENA.

In terms of ground motion adjustment in the context of NIs, it is important to clarify the differences in what are considered soft, hard, or even very hard rock and the properties that are of interest. It was suggested that hard rock κ_0 values should be accompanied by the Vs they correspond to, but this is not recommended as a solution due to the poor correlation of κ_0 with Vs. In addition, the κ_0 stabilisation (regional asymptotic model) has been observed in several regions starting at different Vs thresholds. These thresholds could in themselves be region-dependent, although it has been shown that the definition of a region is not distance-bound but tectonically bound. Another problem when attempting to correlate κ_0 to values such as Vs_{30} is that these do not predict any potential site-specific amplification patterns due to impedance contrasts in the rock profile. It may be useful in this respect to qualify rock profiles by the lack or presence of impedance contrasts, as these have a demonstrated effect on spectral shape. It is also noted that many rock sites can be very heterogeneous with depth, e.g. due to glaciation and interbedding, or exhibit strong spatial variability, e.g. due to local fractures or meteor impacts, rendering the representativeness of a site an important issue. In such cases, it is complex to define the competent rock level and effects on high frequencies, and Vs_{30} has little value or meaning.

While the scientific questions are refined and investigated, there is a need for short-term solutions and guidelines that can be put into practice. This is especially the case when it comes to adjustments of ground motion attenuation models to target regions with very hard rock and with a lack of empirical data to compare with.

3. Consensus and recommendations for nuclear installations

This chapter provides a brief overview of the main recommendations reached through consensus during the workshop, focusing on the impact on nuclear installation instrumentation and recordings.

It is agreed that on-site data are needed at all sites to be able to constrain the site κ_0 values. These data are completely different from the data used for the safe shutdown/alarm monitoring system operating on a triggering basis, which has much higher thresholds and is not considered capable of providing high-quality data, or enough data to eventually better quantify uncertainties in a statistically robust manner. Observations are critical, and it can take years to collect enough data. Therefore, instruments should be installed as soon as possible, as earthquake record loss cannot be compensated.

Guidelines are needed on how to implement and install sensors, and possibly on how to process outputs, to get reliable, high-quality signals in the high-frequency domain. This workshop discussed what is implied by “high-quality” data, although the following are not to be taken as directives.

3.1. Instrumentation

Modern, state-of-the-art equipment with a high sampling rate (200 Hz or above) is needed, with due consideration to in-sensor anti-alias filters (e.g. nearer to 80% of the Nyquist rather than 30%, as in KiK-net; Aoi et al., 2004).

A low self-noise broadband sensor (seismometer) should ideally be collocated with a strong-motion sensor (accelerometer) to safeguard against clipping, both being always operative.

The continuous recording mode is best, as it will allow the use of data from low-magnitude events (weak or very weak shaking), which are more abundant.

Past practical limitations (bandwidth, telecommunications) are improving exponentially with time, rendering triggered-mode recording obsolete in most cases. Dual-sample rate digitisers can stream lower rate data real-time, allowing for recovery of higher-rate data later.

Examples of instrumented nuclear installations in SCRs were mentioned as good practice cases, particularly Bradwell B in the United Kingdom, which is effectively the United Kingdom’s first nuclear power plant borehole array (Ktenidou et al., 2023).[2]

3.2. Installation/layout

Data should generally be recorded at free-field conditions to avoid soil-structure interaction (SSI). There are several selection/installation guidelines for reference stations (e.g. COSMOS, 2001), but it is an outstanding issue whether a nuclear installation is a free-field station per se, and at what distance around it one can install the instrumentation. Nearer is more representative to the site, considering lateral variations, but it is noisier. In practice, a distance more than once (United States) or twice (France) the structure height is used if possible, and if not impacted by other structures nearby. Sensor installation on the intended nuclear installation foundation rock would be useful, but noisy due to operation.

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[2] Other borehole arrays worth mentioning, even if not presented in detail during the workshop, are Point Lepreau in Canada (unreferenced) and the Erbium project in Switzerland with surface and downhole sensors at three nuclear power plant sites (Renault 2022; Dalguer et al. 2018).

For proposed sites, unlike existing ones, it is also possible to select the location after investigating site response and its variability. Site conditions across the nuclear installation property should not be assumed to be homogeneous, even if classified as rock, since rock ground motion can exhibit high variability. Overall, it is good to have two or more sensors per NI. A true free-field, more distant sensor could also help as a reference station, as could a downhole station (the latter also avoiding noise).

The notion of a high-frequency "site" effect on the recorded data is complex and multi-faceted and it can include crustal amplification, site-specific amplification from shallow impedance contrasts, including weathered rock, effects of inclined layering and lateral discontinuities (2D/3D), surface topography at various scales, the resonance of the sensor itself or its installation system/housing, and SSI with nearby buildings. Placement and installation should consider such factors. Metadata should be assembled and conditions that are important to the high-frequency range should be flagged.

3.3. Data processing

Raw data should always be kept and not overwritten by down sampled, filtered or processed data. This is because new methods can eventually render previously rejected data exploitable, thus increasing the sometimes severely restricted nuclear installation datasets available. The data processing should seek to preserve high-frequency content as much as possible.

The new noise-modelling technique of Pikoulis et al. (2020) presented at the workshop can address low signal levels due to low magnitudes or high site noise due to nuclear installation operation (machinery hum, electricity spikes, etc.). Because the method also suggests that all existing κ values may carry some underestimation due to noise, tests on new datasets are encouraged.

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Appendix A. List of participants

A total of 175 participants registered from 80 different affiliations, including academia (universities and research centres), the nuclear sector (power corporations, regulating bodies), and consultancies. Participants came from 20 countries, namely Austria, Belgium, Canada, Czechia, Finland, France, Germany, Greece, Hungary, India, Italy, Japan, Korea, Mexico, Poland, Russia, Spain, Switzerland, Türkiye and the United States.

Below is the list of all participants registered to the event, in alphabetical order.

No.	First name	Last name	Organisation	Country/Region
1	Norman	Abrahamson	University of California Berkeley	United States
2	John	Adams	Natural Resources Canada	Canada
3	Kofi	Addo	BC Hydro	Canada
4	Byeongseok	Ahn	Pukyong National University	Korea
5	Yolande	Akl	Canadian Nuclear Safety Commission	Canada
6	Ragi	Aly	Canadian Nuclear Laboratories	Canada
7	Nasser	Aly	Ontario Power Generation	Canada
8	Cedric	Androuet	Canadian Nuclear Safety Commission	Canada
9	Jamal	Assaf	Western university	Canada
10	Gail	Atkinson	Western university	Canada
11	Tarek	Aziz	TSAziz Consulting Inc.	Canada
12	Pierre-Yves	Bard	Isterre	France
13	Francisco	Beltran	Belgar Engineering Consultants	Spain
14	Allison	Bent	Natural Resources Canada	Canada
15	Mounia	Berdaï	Canadian Nuclear Safety Commission	Canada
16	Paolo	Bergamo	Swiss Seismological Service - ETH	Switzerland
17	Yesim	Biro	Gebze Technical University	Switzerland
18	Andrei	Blahoianu	Nuclear Engineering Consultancy	Canada
19	Yousef	Bozorgnia	UCLA	United States
20	Julie	Brown	Canadian Nuclear Safety Commission	Canada
21	Anupama	Bulkan	Canadian Nuclear Safety Commission	Canada
22	Giovanni	Castellanos	Canadian Nuclear Laboratories	Canada
23	Seku	Catacoli	BC Hydro	Canada
24	Shreyasvi	Chandrasekhar	GEM foundation	India
25	Jason	Chen	Canadian Nuclear Laboratories	Canada
26	Inkil	Choi	Korea Atomic Energy Research Institute	Korea
27	Hoseon	Choi	Korea Institute of Nuclear Safety	Korea
28	A. Egon	Cholakian	Harvard University / NIH	United States

29	Robert	Choromokos	EPRI	United States
30	Leonardo	Colavitti	INGV	Italy
31	Patrick	Collins	Canadian Nuclear Safety Commission	Canada
32	Josh	Corbett	USACE	United States
33	Maria J	Crespo	PRINCIPIA	Spain
34	Luis	Dalguer	3Q-Lab GmbH	Switzerland
35	Guillaume	Daniel	EDF	France
36	Robert	Darragh	Pacific Engineering & Analysis	United States
37	Nan	Deng	Bechtel Corporation	United States
38	Ali	Djaoudi	Tractebel	Belgium
39	Arthur	Eberhardt	Sargent & Lundy	United States
40	James	Eduful	Canadian Nuclear Safety Commission	Canada
41	Amr	Elaghoury	Canadian Nuclear Laboratories	Canada
42	Peter	Elder	Canadian Nuclear Safety Commission	Canada
43	Medhat	Elgohary	Kinectrics Inc.	Canada
44	Diego	Escrig	NEA	France
45	Reza	Esfahani	University of Potsdam	Germany
46	Mike	Fairhurst	BC Hydro	Canada
47	Cyril	Feau	CEA	France
48	Chiara	Felicetta	INGV	Italy
49	Laetitia	Foundotos	International Center for Theoretical Physics	Italy
50	Ioannis	Fountoulakis	National Observatory Athens	Greece
51	Yoshimitsu	Fukushima	IAEA	Austria
52	Dušan	Gabriel	Institute of Thermomechanics	Czechia
53	Celine	Gelis	IRSN	France
54	Hadi	Ghofrani	Western University	Canada
55	Georgia	Giannaraki	University of Patras	Greece
56	Josee	Giguere	Canadian Nuclear Safety Commission	Canada
57	Faidra	Gkika	National Observatory Athens	Greece
58	Konstantin	Goldschmidt	Technische Universität Kaiserslautern	Germany
59	Vladimir	Graizer	US Nuclear Regulatory Commission	United States
60	Ioannis	Grendas	Aristotle University of Thessaloniki	Greece
61	Zeynep	Gulerce	MIDDLE EAST TECHNICAL UNIVERSITY	Turkey
62	Vladimir	Gupalo	Nuclear Safety Institute of the Russia Academy of Sciences	Russia
63	Sam	Gyepi-Garbrah	Canadian Nuclear Safety Commission	Canada
64	Jeong-Gon	Ha	Korea Atomic Energy Research Institute	Korea
65	Annabel	Haendel	GFZ	Germany
66	Miroslav	Hallo	Swiss Seismological Service - ETH	Switzerland
67	Behzad	Hassani	BC Hydro	Canada
68	Fabrice	Hollender	CEA	France
69	Attila	Hugyecz	Ministry for Paks II. nuclear new-build project,	Hungary
70	Sudhir	Ingole	Nuclear Power Corp. of India Ltd.	India
71	Paulina	Janusz	Swiss Seismological Service - ETH	Switzerland

72	Youngjun	Jeon	Korea University	Korea
73	Boris	Jeremic	University of California Davis	United States
74	Ali	Khalili	BC HYdro	Canada
75	Minkyu	Kim	Korea Atomic Energy Research Institute	Korea
76	Minook	Kim	Korea Institute of Nuclear Safety	Korea
77	Ken	Kirkhope	Canadian Nuclear Safety Commission	Canada
78	Nathan	Kline	Canadian Nuclear Safety Commission	Canada
79	Michal	Kolaj	Natural Resources Canada	Canada
80	Mustafa	Korkut	EUAS	Turkey
81	Pola	Kościukiewicz	National Atomic Energy Agency	Poland
82	Sreeram Reddy	Kotha	Isterre	France
83	Olga-Joan	Ktenidou	National Observatory Athens	Greece
84	Pierre	Labbé	LABBE Consultant	France
85	Giovanni	Lanzano	INGV	Italy
86	Aurore	Laurendeau	IRSN	France
87	Namho	Lee	Candu Energy Inc	Canada
88	Miguel	Leonardo-Suarez	UNAM	Mexico
89	Jiayue	Lin	POLIMI	Italy
90	Karina	Loviknes	GFZ	Germany
91	Alexandr	Manevich	Geophysical Center RAS	Russia
92	James	Marrone	Bechtel Corporation	United States
93	Martin	Mazanec	Charles University	Czechia
94	Hazem	Mazhar	Canadian Nuclear Safety Commission	Canada
95	Kihun	Min	Korea Institute of Nuclear Safety	Korea
96	Varun Kumar	Mishra	Nuclear Power Corp. of India Ltd.	India
97	Mark	Moland	New Brunswick Power Corp.	Canada
98	Paola	Morasca	INGV	Italy
99	Shin	Morita	NEA	France
100	Derek	Mullin	New Brunswick Power Corp.	Canada
101	Debra	Murphy	Slate Geotechnical Consultants	United States
102	Shunhao (Sean)	Ni	Candu Energy Inc	United States
103	Anguel	Nikolov	Canadian Nuclear Laboratories	Canada
104	Thambiayah	Nitheanandan	Canadian Nuclear Safety Commission	Canada
105	Olli	Okko	Radiation and Nuclear Safety Authority	Finland
106	Fatih Mehmet	Önder	EUAS	Turkey
107	Nebojsa	Orbovic	Canadian Nuclear Safety Commission	Canada
108	Farhang	Ostadan	Bechtel Corporation	United States
109	Francesca	Pacor	INGV	Italy
110	Samantha	Palmer	Western University	Canada
111	Francesco	Panzera	Swiss Seismological Service - ETH	Switzerland
112	Seonjeong	Park	Korea Institute of Nuclear Safety	Korea
113	Yongcheol	Park	Korea Polar Research Institute	Korea
114	Hayoung	Park	Korea University	Korea
115	Donghe	Park	Structural and seismic design research group	Korea

116	Félix	Pascual	Iberdrola Generación Nuclear	Spain
117	Osmar	Penner	BC Hydro	Canada
118	Claire	Perry	Natural Resources Canada	Canada
119	Erion-Vasilis	Pikoulis	University of Patras	Greece
120	Marco	Pilz	GFZ	Germany
121	Vishnu	Pooviah	Canadian Nuclear Safety Commission	Canada
122	Hoby	Razafindrakoto	GFZ	Germany
123	Philippe	Renault	swissnuclear	Switzerland
124	John	Richards	EPRI	United States
125	Lauri	Rinne	AFRY	Finland
126	Jovica	Riznic	Canadian Nuclear Safety Commission	Canada
127	AD	Roshan	Atomic Energy Regulatory Board	India
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129	Véronique	Rouyer	NEA	France
130	Roxanne	Rusch	IRSN	France
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132	Genadijs	Sagals	Canadian Nuclear Safety Commission	Canada
133	Hugo	Sanchez Reyes	IRSN	France
134	Abdullah	Sandıkkaya	Hacettepe University	Turkey
135	Ayman	Saudy	Kinectrics Inc.	Canada
136	Oona	Scotti	IRSN	France
137	Dogan	Seber	US Nuclear Regulatory Commission	United States
138	Andrew	Seifried	Lettis Consultants International	United States
139	Sara	Sgobba	INGV	Italy
140	Shikha	Sharma	IIT Gandhinagar	India
141	Megan	Sheffer	BC Hydro	Canada
142	Upendra	Singh	Nuclear Power Corp. of India Ltd.	India
143	Madhumita	Sircar	US Nuclear Regulatory Commission	United States
144	Pierre	Sollogoub	PSC	France
145	Safak	Soylemez	Bogazici University	Turkey
146	Daniele	Spallarossa	Unige	Italy
147	Vojtech	Spanihel	CEZ Group	Czechia
148	George	Stoyanov	Canadian Nuclear Safety Commission	Canada
149	Grant	Su	Canadian Nuclear Safety Commission	Canada
150	Tsuyoshi	Takada	Japan Atomic Energy Agency	Japan
151	Viktor	Tatarinov	Geophysical Center RAS	Russia
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153	Gernot	Thuma	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH	Germany
154	Luben	Todorovski	GE Hitachi	United States
155	Gabriel	Toro	Lettis Consultants International	United States
156	Paola	Traversa	EDF	France
157	Robert	Truszkowski	National Atomic Energy Agency	Poland
158	Elif	Türker	GFZ	Germany
159	Aman	Usmani	Kinectrics Inc.	Canada
160	Jan	Valenta	Charles University	Czechia

161	Joseph	Van Meter	Canadian Nuclear Laboratories	Canada
162	Anis M	Vengasseri	Atomic Energy Regulatory Board	India
163	Emmanuel	Viallet	EDF	France
164	Jennie	Watson-Lamprey	Slate Geotechnical Consultants	United States
165	Kathryn	Wooddell	Slate Geotechnical Consultants	United States
166	Tatsuhiro	Yamazaki	IAEA	Austria
167	Li	Yan	BC Hydro	Canada
168	Ming-Hsuan	Yen	GFZ	Germany
169	Emrah	Yenier	Nanometrics Inc.	Canada
170	KwanHee	Yun	KEPCO-ENC	Korea
171	Arash	Zandieh	Lettis Consultants International	United States
172	Jiri	Zdarek	UJV Rez a.s.	Czechia
173	Irmela	Zentner	EDF	France
174	Yezi	Zhang	Canadian Nuclear Laboratories	Canada
175	Chuanbin	Zhu	GFZ	Germany

Appendix B. Agenda of the workshop

25 May 2021

10:00-10:15 am (ET)

- Opening remarks
  - Veronique Rouyer, NEA Head of Division Nuclear Safety, Technology and Regulation
  - Peter Elder, the CNSC Vice-President and the Chief Scientific Officer

- Context of the Workshop and Goals, Neb Orbovic (CNSC, Chair and the Moderator of the Workshop)

10:15 – 11:45 am

- Fabrice Hollender (CEA, Cadarache, France), Paola Traversa (EDF, Aix-en-Provence, France), Emeline Maufroy (Université Grenoble Alpes), and Zafeiria Roumelioti (University of Patras, Greece), **What are the local features that influence the high frequency content of ground motion records? Lessons learned from the French accelerometric network and other sites**
- Fabrice Hollender (CEA, Cadarache, France), Paola Traversa (EDF, Aix-en-Provence, France), Hussein Shible (CEA, Cadarache, France), and Pierre-Yves Bard (Université Grenoble Alpes**), Tackling the 'reference motion' issue: alternative approaches to Vs-Kappa corrections**

11:45– 12:00 am BREAK

12:00 – 1:30

- Norman Abrahamson (UC Berkeley, United States): **New method for Kappa scaling factors**
- Vasilis-Erion Pikoulis (University of Patras, Greece) and Olga-Joan Ktenidou (National Observatory of Athens, Greece): **Kappa estimation in challenging conditions: how to reach higher-than-before frequencies**

26 May 2021

10:00 – 11:30 am

- Samantha Palmer and Gail Atkinson (University of Western Ontario, London, Ontario, Canada): **Kappa at rock sites in eastern Canada** (CNSC/Western Research Project)
- Olga-Joan Ktenidou (National Observatory of Athens, Athens, Greece), Robert B. Darragh (Pacific Engineering & Analysis, El Cerrito, CA, United States), Paola Traversa (EDF, France), Yousef Bozorgnia (UCLA, Los Angeles, California, United States), and Walter J. Silva (Pacific Engineering & Analysis, El Cerrito, CA, United States): **Kappa estimation at hard-rock sites**

11:30- 11:45 am BREAK

11:45 – 1:15 pm

- Giovanni Lanzano, Chiara Felicetta, Francesca Pacor, Sara Sgobba, Leonardo Colavitti, Paola Morasca (INGV, Milano, Italy) and Daniele Spallarossa (INGV, Milano, Italy and University of Genoa, Italy): **High-frequency attenuation parameter κ in Italy: estimation methods and regional features**
- Paola Traversa (EDF, Aix-en-Provence, France), Fabrice Hollender (CEA, Cadarache, France), Celine Gélis (IRSN, Fontenay aux Roses, France), Aurore Laurendeau (IRSN, Fontenay aux Roses, France) and Jessie Mayor (EDF, Saclay, France): **Ground motion at reference sites in weak to moderate seismicity areas: case study of France**

27 May 2021

10:00 – 11:30

- Fabrice Cotton, Annabel Haendel, Marco Pilz and Chuanbin Zhu (GFZ German Research Centre for Geosciences, Potsdam, Germany): **Variability of high-frequency site responses at surface and depth**
- Annabel Haendel (GFZ), John Anderson (University of Reno, Reno, Nevada, United States) Marco Pilz, and Fabrice Cotton (GFZ German Research Centre for Geosciences, Potsdam, Germany): **A frequency-dependent model for the shape of the Fourier amplitude spectrum at high frequencies**

11:30 -11:45 BREAK

11:45-1:15 pm

- Lauri Rinne (AFRY, Espoo, Finland), **Seismic wave attenuation and spectral decay parameter, kappa, in crystalline bedrock at Olkiluoto, SW Finland**
- Yoshio Fukushima (IAEA, Vienna, Austria), **Necessary consideration of theoretical backgrounds for high frequency decay on the site effect**

28 May 2021

10:00-11:30 am

- Discussion - Proposal for Conclusions and Recommendations – ALL

Appendix C. Abstracts of invited presentations

Day 1: Tuesday 25 May 2021

1.1. Fabrice Hollender (CEA, Cadarache, France - ISTerre, Grenoble, France), Paola Traversa (EDF, Aix-en-Provence, France), Emeline Maufroy (ISTerre, Grenoble, France), Zafeiria Roumelioti (University of Patras, Greece)

What are the local features that influence the high frequency content of ground motion records? Lessons learnt from the French accelerometric network and other sites.

Site-specific seismic hazard assessment addresses a wide range of issues, whether on the “target side” (site where the hazard is investigated) or on the “host side” (accelerometric networks producing the data needed to derive ground motion prediction models). Most efforts have long focused on the characterisation of “target” sites, whether in terms of instrumentation deployment, three-dimensional geological modelling, geophysical measurements, or even rheological property measurements to consider nonlinearity. At the same time, the characterisation effort has remained quite low for ‘host’ sites, i.e. the sites that host stations of the strong motion networks that produce the signals necessary to establish ground motion prediction equations (GMPEs). In this presentation, this paper highlights that the methods of setting up permanent seismological stations (i.e. installation of sensors on small concrete slabs) as well as installation at very shallow depths (e.g. seismic vaults) can also have significant impact on the high frequency content of the recordings. Small structures hosting permanent strong-motion stations (often anchored on small concrete slabs) generate soil-structure interaction effects that can amplify the high-frequency recordings. Installation depth of a station, even if very shallow (i.e. a few metres), can also change the recorded response, mainly by deamplifying the signal in high frequencies. Such effects imply that there are actual differences between recorded and true free-field signals. In addition, the ARGONET network database has revealed strong seasonal variation in V_S values in the first few metres, which are correlated to soil moisture content in the unsaturated zone. All these local features strongly impact the high-frequency content of recording, making the measurement of the “kappa” parameter measurement very difficult, if not impossible in most cases. It is, thus, becoming clear that such effects should be considered in studies involving high-frequency seismic motion. To do so, scientists need a detailed description of the conditions of installation and housing of seismological and accelerometric stations.

1.2. Fabrice Hollender (CEA, Cadarache and ISTerre, Grenoble, France), Paola Traversa (EDF, Aix-en-Provence, France), Hussein Shible (CEA, Cadarache, France), Pierre-Yves Bard (ISTerre, Grenoble, France)

Tackling the "reference motion" issue: alternative approaches to Vs-Kappa corrections

In the framework of site-specific seismic hazard assessment, the definition of reference motion is a crucial step. Reference motion is generally associated with hard-rock conditions, characterised by S-wave velocity exceeding 1 500 m/s. However, ground motion recorded at sites with such conditions is poorly represented in existing strong-motion databases. Thus, the validity domains of most empirical ground motion prediction equations are not representative of reference rock conditions. The method that has long been followed to define reference motions at hard rock is the so-called V_{S30}/kappa adjustment method. However, this approach is based on physical assumptions that are not widely accepted and the parameter kappa (as the slope of the high frequency Fourier spectrum) is very difficult, if not impossible, to measure correctly in many cases. To overcome this limitation and assess ground motion at reference conditions, the so-called "deconvolution approach" proposed by Laurendeau et al, 2018) consists in removing theoretical 1DSH site response from surface recordings. With the same purpose, it is possible to apply the deconvolution approach using empirical site response estimates as an alternative to theoretical ones. Using the KiK-net data, this work estimates empirical site responses at KiK-net stations using generalised inversion techniques (GIT) in addition to those from 1DSH numerical simulations, presented in the companion paper. Finally, a reference ground motion model is determined based on empirically-deconvolved ground motions. The advantage of using empirical rather than 1DSH site responses in the deconvolution approach is that in the former case the reference ground-motion model (RGMM) can be built based on records from an extensive set of sites, while the latter case is restricted to well-characterised sites with dominant 1D behaviour. This makes the proposed approach easily exportable to different regions of the world, where the precise site characterisations are not systematically available, and the knowledge of site behaviour is limited. The results obtained diverge widely from the classical V_{S30}/kappa approach, particularly at high frequencies.

1.3. Norman A. Abrahamson (University of California at Berkeley, United States)

New method for kappa scaling factors

The κ is defined as the high-frequency slope of the logarithm of the Fourier Amplitude spectrum. The shape of the source spectrum, anelastic attenuation (Q), high-frequency site amplification, and damping at the site all affect κ. After removing the source, path and site, the remaining κ, called κ_0, has been interpreted to represent damping at the site. With this interpretation, a low κ_0 value for hard-rock sites implies low damping which must increase the high-frequency ground motion. For a typical hard-rock κ_0 of 0.006 s and soft-rock κ_0 of 0.035 s, the increase in the high-frequency response spectral values is about a factor of 3. This large increase in the amplitude of high-frequency ground motion at hard-rock sites compared to soft-rock site is not seen in empirical data from the NGA-East Project and from British Columbia (Ktenidou and Abrahamson, 2016).

The estimated κ_0 includes the effects of errors in the source spectrum model, Q model and site amplification model. It is not just due to damping at the site. The amplitudes of the high-frequency hard-rock ground motions from NGA-East and BC are consistent with κ_{damp} in the range of 0.015 to 0.030 s, even though the average κ_0 for these hard-rock sites is about 0.006 s. This indicates that the errors in the models assumed for the source, path and site effects result in a net average κ of -0.009 to -0.024 s.

The assumption that $\kappa_0 = \kappa_{damp}$ is rejected by the hard-rock data evaluated by Ktenidou and Abrahamson (2016). The current standard approach of applying κ corrections to GMMs for soft-rock site conditions based on the assumption that κ_0 is only due to damping has been the standard approach used in ground motion characterisation for the last 25 years, but it leads to a large overestimation of the high-frequency ground motion and should be discontinued.

If κ corrections are used, a method to estimate the κ_{damp} is needed. In this paper, an initial methodology for estimating κ_{damp} is developed based on relation between the shortest period at which the response spectrum reaches 1.5 times the PGA (called $T_{AMP1.5}$) and the κ_{damp} that is consistent with the observed 20 Hz amplification. An example using the NGA-West data set shows that for a hard-rock site with V_{S30}=2000 m/s and a κ_0 of 0.006 s, the κ_{damp} is 0.028 s. This leads to an increase of a factor of 1.3 in the 20 Hz response spectral values compared to the factor of 3 that results if κ_0 is assumed to be equal to κ_{damp}. This factor of 1.3 is consistent with recent evaluations of the SR/HR (soft-rock-to-hard-rock) site factors for the NGA-East data set and with the empirical scale factors developed by Ktenidou and Abrahamson (2016).

1.4. Erion-Vasilis Pikoulis (University of Patras, Greece) and Olga-Joan Ktenidou (National Observatory of Athens, Greece)

Kappa estimation in challenging conditions: how to reach higher-than-before frequencies

Kappa estimation and interpretation suffers from its trade-offs with many other parameters, such as stress drop, path attenuation, near-surface amplification, sensor issues and more. In addition, its calculation per se often suffers from limited usable bandwidth, either due to low sampling rates or noisy recording environments, making it even more challenging to resolve the various trade-offs.

In industrial facilities such as NIs, seismic recordings are often of poor quality, with low signal-to-noise ratios (SNRs) owing to the elevated background noise, and this can severely limit their usability at high frequencies. Considering that such recordings are often few, and that – especially in stable continental regions – one cannot wait for more or stronger events to be recorded, a technique to address the problem of noise and increase the usable frequency band of seismic data collected at/near NIs could make the difference.

The new method presented in this talk (based on Pikoulis et al., 2020) addresses this issue and offers for the first time a way to make use of data that were up to now considered unusable at high frequencies due to noise. It is recommended that from now on one should model rather than avoid the noise. By stochastically simulating the noise within the seismic record in the frequency domain and correcting the signal spectrum for it rather than using it within the frequency bands traditionally defined by SNR thresholds, it is proposed that a more robust estimation of high-frequency parameters can be made. This is demonstrated on κ.

Using both simulated and recorded data, it is shown that noise modelling can increase SNR and extend usable bandwidth upwards. Examples include previously unusable, low-quality signals (with SNR close to 1) yielding κ values close to the 'true' ones. It is also demonstrated that unconventional noise models such as spectral peaks and spikes can be successfully addressed, hence no longer posing obstacles to high-frequency spectral analysis. Finally, it is demonstrated that certain cases of apparent bilinear κ trends that may be considered as due to frequency dependence (i.e. Q(f)) may be due to noise.

In the examples shown, traditional threshold-based methods slightly but systematically underestimate κ, even for typically acceptable quality signals. This is more prominent near the noise floor. This issue should be addressed in future on a larger scale, to detect potential systematic tendencies in global literature κ values.

The proposed method does not depend on a specific theoretical model or assumption (e.g. a hypothesis on the source spectrum), and so it is applicable to any model derived from spectral domain analysis and can even be extended to other parameters, aside from κ where more bandwidth is deemed beneficial.

Day 2: Wednesday 26 May 2021

2.1. Samantha Palmer, Gail Atkinson and Hadi Ghofrani (University of Western Ontario, London, Canada)

Kappa on rock sites in Eastern Canada

High-frequency ground motions on rock sites are controlled by the combination of amplification and de-amplification effects. Amplification of seismic waves on rock sites is typically assumed to be negligible; inspection of high-frequency ground motions shows that this appears to be a poor assumption. To understand how rock sites in Eastern Canada affect the high frequency content of ground motions, this work examines earthquakes recorded at 25 broadband seismic stations of the Canadian National Seismograph Network (CNSN). The moment magnitude (M) of the selected records ranges from 1.5 to 5 and the maximum station-to-earthquake distance is 150 km. Two different methods were utilised to measure kappa, the slope of the Fourier spectral amplitude decay. The first method, a modified version of Anderson and Hough's acceleration spectrum method, is applicable for events of M≥3.5 and is thus applicable to only 20 earthquakes in this dataset. This method suggests values of kappa of ≈7 ms and 0 ms for horizontal and vertical components, respectively (Palmer and Atkinson, 2020). The second method, broadband inversion, is appropriate over a broader magnitude range. It is applied to 3 318 earthquakes with M ranging from 1.5 to 3.5. A preliminary inversion of the broadband dataset is completed assuming that the effective Fourier amplitude spectrum of acceleration (FACCN) can be modelled assuming a bilinear geometric spreading of amplitudes (b_1, b_2) with transition at R_t:

$$\ln\left(FACCN_{ij}\right) = E_i + S_j - \gamma R_{ij} - b_1 \ln\left[\min\left(R_{ij},\ R_t\right)\right] - b_2 \ln\left[\max\left(\frac{R_{ij}}{R_t},\ 1\right)\right]$$

This is solved to find the best b_1, b_2, R_t, E_i (event term) for every event i, S_j (station term) for every station j at a hypo central distance R_{ij}. The anelastic attenuation is assumed to be given by $\gamma = 0.0017f^{0.5}$. From this preliminary inversion the source terms were well behaved and followed the simple Brune model shape. The geometrical spreading was steep with $b_1 = 1.5$, $b_2 = 0.8$, and $R_t = 60$ km.

To interpret the site terms, an average rock amplification function is assumed, as given by Boore and Campbell's (2017) theoretical amplification functions for a representative rock profile with a time-averaged shear-wave velocity to 30 m (V_{S30}) of 1 500 m/s. After removing the assumed crustal amplification function, an average kappa of 2 ms (horizontal component) is inferred based on inspection of the high-frequency slope, for events of M≈3 to 3.5. A higher kappa of ≈15 ms was inferred based on the Fourier displacement slope for the lower magnitude (M1.5-2.5) events, at lower frequencies. The higher kappa value could be plausible if strong rock amplifications at high frequencies (greater than that in the Boore and Campbell model) occurs. This study shows that rock amplifications are as important in controlling the high-frequency amplitudes of the Fourier spectrum as kappa. Rock amplification and kappa effects are also highly variable from one rock site to another and do not correlate well with V_{S30}.

2.2. Olga-Joan Ktenidou (National Observatory of Athens, Greece), Robert B. Darragh (Pacific Engineering & Analysis, United States), Paola Traversa (EDF, Aix-en-Provence, France), Yousef Bozorgnia (UCLA, United States), and Walter J. Silva (Pacific Engineering & Analysis, United States)

Kappa estimation at rock and hard-rock sites in Quebec, Canada and France

This work summarises the results of a collaborative project dedicated to the estimation of kappa (the high-frequency site attenuation factor), which has just been completed. Several rock and hard-rock sites were selected, namely seven in Quebec and eight in mainland France.

One of the keys aims of the project was to focus on well-characterised stations (with measured Vs profile and sufficient broadband seismic data), as some of the authors' earlier attempts (Ktenidou and Abrahamson, 2016; Ktenidou et al., 2016), which followed upon EPRI (1995), showed that site amplification may likely bias kappa estimation, even at rock sites where amplification has been considered minimal. Previous work on kappa has considered generic linear-elastic crustal amplification (based on, for example NEHRP site classes), but not site-specific transfer functions derived from in situ Vs measurements. The latter is done for the first time in this project at a significant number of hard-rock sites in Eastern Canada and France, many of which were characterised ad hoc for the purposes of the EPRI/PEER/SIGMA/UCLA project. A suite of methods was applied to estimate kappa and its uncertainty, including broadband inversions that solve for source, path and site parameters, as well as band-limited approaches targeted at the site, all using recorded data at the sites (e.g. Fourier amplitude or 5% damped response spectra, as well as HVSR, i.e. horizontal-to-vertical spectral ratio).

The results show that the ability to correct for the site amplification due to measured shallow (of the order of a few tens of metres at most) velocity contrasts and gradients improved the robustness of site attenuation estimates. However, the variability in the results also showcased another aspect: κ_0 most likely also includes components from the deeper geological structure, which are not accounted for through typical (geophysical) shallow site characterisation. The scatter in κ_0 from different hard-rock stations in Quebec increased when considering both provinces together, namely Grenville (i.e. Canadian Shield) and Appalachian (i.e. elongated belts of folded and thrust faulted marine sedimentary and volcanic rocks). This indicates that if one combined profile that are dissimilar at depth, some of the apparent aleatory uncertainty found in κ_0 may be epistemic.

The effect of deeper regional structure is in line with existing conceptual models proposed in the past by the group (Ktenidou et al., 2015), but is more challenging to quantify. These results help explain and refine uncertainty found in κ_0 estimates when combining sites with similar near-surface but significantly different deeper characteristics.

The detailed results of this work are described in the Electric Power Research Institute (EPRI) Report No. 3002020750, publicly available at www.epri.com/research/programs/061177/results/3002020750 (EPRI, 2021).

2.3. Giovanni Lanzano (INGV, Milano, Italy), Chiara Felicetta (INGV, Milano, Italy), Francesca Pacor (INGV, Milano, Italy), Sara Sgobba (INGV, Milano, Italy), Leonardo Colavitti, Paola Morasca (INGV, Milano, Italy) and Daniele Spallarossa (INGV, Milano, Italy and University of Genoa, Italy)

High-frequency attenuation parameter κ_0 in Italy: estimation methods and regional features

In this work, an estimation of the high-frequency attenuation parameter κ_0 for several Italian recording stations has been provided, exploiting the huge number of records following the 2016-2017 Central Italy seismic sequence, by using two methods (Ktenidou et al. 2014): a) the path-corrected value ($\kappa_{0,AS}$) derived from the high-frequency linear decay of the station records (S-waves) in FAS, κ_r (Anderson and Hough, 1984); b) the high-frequency attenuation of the amplification functions ($\kappa_{0,TF}$) computed from Generalised Inversion Technique, GIT (Drouet et al., 2010).

Focus has been devoted to reference sites, i.e. rock or stiff-soil sites with flat and unamplified response with frequency, showing a strong variability at high frequencies. These estimates were also used to calibrate an adjustment factor to scale the prediction of a ground motion model from a generic ($V_{S,30}$=800 m/s) to a reference rock.

The six reference rock sites with the lowest κ_0 ($\kappa_{0,AS}<0.015$ s) were then employed as reference sites for the GIT analysis. The GIT analysis and a non-ergodic regional GMM, consistent with that proposed by Sgobba et al, 2021) for predicting spectral accelerations in Central Italy, are both calibrated using as a reference the median observations of the selected six sites: the ground motion models produce similar results in terms of GIT amplification function and the non-ergodic site-term residuals ($\delta S2S_{ref}$), computed w.r.t the median observation of the six reference sites. The $\kappa_{0,TF}$ estimates from GIT amplification functions are compared to those manually inferred by FAS ($\kappa_{0,AS}$), obtaining similar values.

Both estimations of κ_0 are also compared with high frequency $\delta S2S_{ref}$ amplitudes. The statistical coefficient between $\delta S2S_{ref}$ and κ_0 shows a significant level of anti-correlation in the 5-25 Hz frequency range (i.e. as κ_0 increases, we observe an overall reduction in $\delta S2S_{ref}$), particularly for $\kappa_{0,TF}$. Furthermore, the relation between κ_0 and other site-effect proxies, such as the average shear-wave velocity $V_{S,30}$ was investigated. These parameters are weakly correlated, confirming that they can be considered as independent parameters for site effects characterisation. The dependency of κ_0 on the lithological characteristics of the recording sites was also studied: lower values of the attenuation parameters correspond to rigid formations composed of limestone, while higher values are mainly located on flyschoid units, widely represented in Italy.

As a further ongoing activity, a semi-automatic procedure to compute the values of $\kappa_{0,AS}$ is in development. Preliminary results show that automatic and manual estimations of $\kappa_{0,AS}$ are consistent. These outcomes will be the basis for developing a continuous map of spatially correlated κ_0 of reference sites for some regions in Italy.

2.4. Paola Traversa (EDF, Aix-en-Provence, France), Fabrice Hollender (CEA, Cadarache, France), Celine Gélis (IRSN, Fontenay aux Roses, France), Aurore Laurendeau (IRSN, Fontenay aux Roses, France) and Jessie Mayor (EDF, Saclay, France)

Ground motion at reference sites in weak to moderate seismicity areas: case study of France

When performing site-specific hazard assessment, it is necessary to determine the reference ground motion at bedrock, which is used as input for numerical or empirical site response analyses. In current studies, and particularly in low-to-moderate seismicity regions, ground motion adjustments are often performed, to ensure that the ground motion assessed at bedrock is representative of the attenuation properties and velocity structure of the crust in the target region. Such adjustments are based on two parameters (Vs profile and κ, empirically measured as the slope of the high frequency spectral decay of recorded ground motion). Therefore, to ensure unbiased site-specific ground motion at the ground surface, the ground motion assessed at bedrock should be exempt of any amplification related to lithological, topographical or other effects. However, recent works highlighted that ground motion recorded at sites with $V_{S,30}$ exceeding a given threshold (commonly 800 m/s in Europe) are not necessarily exempt from amplification effects, particularly in the high frequency range. The objective of the present work is to identify reference rock sites and to characterise reference rock ground motion in mainland France, focusing on the high frequency content and κ estimate. To fulfil the objective, a database of ground motions is used that was recorded over the 1996-2019 period in mainland France. The analysis reveals that few rock sites in France can be considered reference rock sites, in many cases the recorded ground motion is affected by amplifications at high frequency. Therefore, to perform realistic κ measures in France, only recordings either, from reference sites, or corrected from site-specific response should be used.

Preliminary κ estimates performed on selected reference rock sites in Southern France using different approaches show that the epistemic uncertainty on κ is high. Correlation between $V_{S,30}$ and κ parameters is not significant when considering reference rock sites in France, which argues for κ to correlate with regional geological context rather than $V_{S,30}$. This supports the regional asymptotic κ conceptual model proposed by other authors. κ values in France are compared to values estimated in other regions of the world (Greece, Switzerland and two regions in Canada: the Greenville and the Appalachian regions), showing that the stabilisation of κ seems to occur at relatively low $V_{S,30}$ values in France and that asymptotic κ is larger than in Canadian provinces and close to values assessed in Greece.

The analysis also reveals that the impact of the sensor installation conditions, and housing can be significant on the content of recorded ground motion and must be properly characterised and considered.

Day 3: Thursday 27 May 2021

3.1. Fabrice Cotton (GFZ, Potsdam, Germany), Annabel Haendel (GFZ, Potsdam, Germany), Chuanbin Zhu (GFZ, Potsdam, Germany), Sreeram Reddy (ISTerre, Grenoble, France), Marco Pilz (GFZ, Potsdam, Germany), Reza Dolatabadi (GFZ, Potsdam, Germany)

Variability of high-frequency ground motions at surface and depth

The variability of ground motions (Fourier Spectra) is analysed and the factors which are controlling this variability at high frequencies are evaluated. The overall variability of ground motions at high frequencies is high. This high variability is not driven by the within-event (single-station) variability which only slightly increases at high frequencies but rather by the between-station variability. Such high variability of ground motions at high frequencies reflects the high variability of attenuation both close to the surface (site) but also along all paths from the fault to the surface. It is shown that such variability is not reproduced by classical 1D amplifications modelling and relationships between Vs and quality factors.

The variability of ground motions and kappa at depth is further analysed, selecting 175 KiK-net (Japan) sites where the bottom sensor is deployed at rock or hard-rock conditions resulting in a database with many recordings at Vs ≥1 500 m/s. The variability of kappa at depth remains high and there is a high correlation between the kappa measured at the surface and depth. The findings suggest that kappa at depth is still a deep site parameter rather than a characteristic value of the regional upper crust.

3.2. Annabel Haendel (GFZ, Potsdam, Germany), John Anderson (University of Reno, Nevada, United States) Marco Pilz (GFZ, Potsdam, Germany), and Fabrice Cotton (GFZ, Potsdam, Germany)

A frequency-dependent model for the shape of the Fourier amplitude spectrum at high frequencies

One of the main assumptions of the kappa model as introduced by Anderson and Hough (1984) is that the decay of the Fourier acceleration spectrum at high frequencies can be explained by attenuation, characterised by a frequency-independent quality factor Q. Yet, many seismological studies have found that Q is, in general, a function of frequency, i.e. Q(f). This is confirmed by some recent observations in which the high-frequency slope of the acceleration spectrum is not exactly linear in log-linear space but curved, resulting in estimated values of kappa that strongly depend on the chosen frequency band of analysis.

This work explores the possibility of substituting a frequency-dependent Q model into the kappa model to explain the dependence of kappa on the frequency band. The spectral slope in log-linear space is then described by two parameters instead of the single parameter kappa. This new approach is referred to as the “zeta model” for the high frequency spectral shape. Equivalent to the kappa model, one of the model parameters can be split into a path-dependent and a path-independent part to account for different effects between source and site. The zeta model is applied to vertical array data of the Euroseistest site in Greece and test its applicability on some synthetic examples using the stochastic method.

One of the main conclusions is that a large enough bandwidth is needed to apply the zeta model to data. This is only ensured if there are recordings with high sampling rates and no anti-alias filters at frequencies below 50 Hz. Furthermore, noise inclusion instead of avoidance techniques as presented by E.-V. Pikoulis and O.-J. Ktenidou could help to broaden the bandwidth if the signal-to-noise ratio of recordings is bad.

These findings confirm the results of other studies that kappa is not a simple attenuation parameter. Instead, it is influenced by many factors as e.g. site amplification, source effects or frequency-dependent attenuation.

3.3. Lauri Rinne (AFRY Finland Oy)

Seismic wave attenuation and spectral decay parameter κ, kappa, in crystalline bedrock at Olkiluoto, SW Finland

The value for the site-specific kappa parameter (κ_0) was calculated first time in the crystalline bedrock of Finland at the underground disposal facility for spent nuclear fuel at Olkiluoto, Southwestern Finland. The κ_0 calculated with the original Anderson and Hough (1984) method was between 0.002 and 0.004 s. These results are in line with kappa values from geologically similar regions around the world, e.g. Eastern North America, where the calculated κ was 0.006 s (Douglas et al., 2010).

The seismicity of the Olkiluoto site has been monitored with a seismic network since 2002 to record the background seismicity before the construction of the final disposal facility, which started in 2004. The observed seismicity on the island of Olkiluoto is at a low level and has been linked to the excavation of the final disposal facility, i.e. seismicity is induced by excavation blasting or injections with largest microearthquake of $M = -0.5$ in local magnitude scale.

Data for κ_0 calculations was gathered with the seismic monitoring network of Posiva Oy, the company tasked with handling the final disposal of the spent nuclear fuel generated by its owners. The network consists of 32 underground and surface sensors, both geophones and accelerometers. Recordings of seven stations and a total of 297 registrations were used in the calculations. As each registration was divided to three different components, one vertical and two horizontal, a total of 473 κ-values were calculated using microearthquakes. All the events had a station-to-event distances varying from tens to few hundred metres. As a result, all the calculated κ values are effectively site-specific kappa or κ_0-values.

Events for κ calculations were selected based on the previous study of local microearthquakes at Olkiluoto by Kaisko and Malm (2019). From this study, the 51 events with moment tensor solutions occurring in 2016-2018 were selected. The event data was imported to IRIS SAC programme, corrected for orientation and instrument response, and visually inspected. After the inspection, the spectra were computed and least-square best-fit line was set between the 1.5 x corner frequency and signal-to-noise ratio of three. From the slope of this line value of κ was calculated. Displacement kappa by Biasi and Smith (2001) was not calculated due to the high noise level and low signal strength at low frequencies.

Five single blasts were also selected for κ-calculations. The process for calculating κ from blasts was like the process of calculating κ from microearthquakes. Each of the five events was divided to three components and a total of 15 κ-values were calculated. Anderson and Hough kappa was calculated from blasts and results presented κ-values from 0.001 to 0.002 s.

3.4. Yoshimitsu Fukushima (IAEA, Vienna, Austria)

Necessary consideration of theoretical backgrounds for high frequency decay on the site effect

The IAEA published the TecDoc on “Seismic Hazard Assessment in Site Evaluation for Nuclear Installations: Ground Motion Prediction Equations and Site Response” in 2016 (IAEA, 2016) and various site response evaluations were introduced for the member states. The kappa was introduced to represent the amplitude decay of observed ground motions at high frequency. It consists of source, path and station dependences. However, the TecDoc introduced not only kappa, but also many other methodologies for evaluation of the site effect. Segregation among each dependence on kappa is challenging. Therefore, application of all available techniques for the nuclear installation sites is encouraged including kappa. All available site effect evaluations complement each other. Particularly, collection of whatever information will be respected to verify and validate the evaluations. The Vs_{30}-kappa correction is not appropriate for safety of nuclear installations only with the profile down to 30 m depth and more information need to be acquired such as ground motion observations since the uncertainty of the V_{s30}-kappa correction is extremely large. Some potential explanations were introduced in the presentation for source, path and site effects respectively. The empirical approach of the kappa might be interpreted with innovated physic-based approaches. Oversimplification of the ground motion model cannot capture individual heterogeneities of source, path and site effects. Moreover, the state-of-art simulation technique with the higher performance super machines FUGAKU was introduced as an example of the potential to interpret the whole elements of the strong motion estimation. Potential influences of the kappa were:

- fmax (fc and is close each other with Q influence)
- Simplification of plain wave propagation from complete wave field
- Scattering in the wave path like coda characteristics
- Incident angle of the wave and inhomogeneity of the medium
- Topographical effect
- Oversimplification of horizontal layer modelling
- Half space of rock is quite rare and usually weathered
- Scatter with thin layers, cracks, irregular boundary of the layers
- Nonlinear effect up to liquefaction
- 3-D underground structure
- SSI with objects above surface (Tall conifers, Highrise buildings, Nuclear Installations, etc.)
- Usual sampling of 100 Hz cannot capture harmonic signal amplitude above 25 Hz

Finally, calibration of the kappa scheme with actual site effects in high seismicity area was encouraged using enough strong motion records, that can evaluate residuals between observed response spectral acceleration and the predicted ones by the GMPEs directly.

Respecting observation, interpretation of the amplitude decay in high frequency based on seismological background need to be considered before blindly apply the empirical correction due to large uncertainty. Our goal is seismic safety of nuclear installations whatever the scheme is.