A streamlined approach for the seismic hazard assessment of a new nuclear power plant in the UK

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This article presents a streamlined approach to seismic hazard assessment aimed at providing regulatory assurance, whilst acknowledging commercial and program constraints associated with the development of safety-critical facilities. The approach was developed based on international best practice and followed the spirit of the Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 requirements, while incorporating the key features of the SSHAC Level 3 process aimed at achieving regulatory assurance, but with a more flexible implementation. It has also benefited from experience gained by others regarding the implementation of the SSHAC process in projects in the USA, Switzerland and South Africa. The approach has been successfully applied as part of the Safety Case for the new-build nuclear power plant at Hinkley Point, UK. The proposed approach can be considered as a cost-effective solution for the seismic hazard evaluation of safety-significant facilities where a high level of regulatory assurance is required.

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1. Introduction

The UK government energy policy currently considers the development of eight new nuclear power plants (NPPs). Hinkley Point C is expected to be the first of this new fleet of

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power plants to be built, and it will be the first nuclear plant to be built in the UK since 1995 when Sizewell B became operational.

Table 1 List of abbreviations

Abbreviation	**Meaning**	**Abbreviation**	**Meaning**
CBR	Centre, body and range	PRT	Peer review team
CEUS	Central and eastern United States	SAP	Safety assessment principles
CH2M	CH2M Hill	SE	Subject Expert
EDF	Électricité de France	SSC	Seismic source characterization
GEM	Global Earthquake Model	SSM	Seismic source model
GMM	Ground-motion model	SHWP	Seismic Hazard Working Party
HID	Hazard input document	SRID	Site response input document
IAEA	International Atomic Energy Agency	SSHAC	Senior Seismic Hazard Analysis Committee
NNB GenCo	Nuclear New Build Generation Company (subsidiary of EDF Energy)	TAG	Technical assessment guides
NPP	Nuclear power plant	TDI	Technically defensible interpretations
ONR	Office for Nuclear Regulation	TDT	Technical Delivery Team
PSHA	Probabilistic seismic hazard analysis	TI	Technical Integrator
PMT	Project management team	USNRC	US Nuclear Regulatory Commission
PPRP	Participatory peer review panel		

As part of the UK regulatory requirements for new NPPs, utility operators are required to undertake a robust assessment of external hazards, including earthquake-related hazards, as a critical part of the NPP safety case. Such an assessment must be carried out following relevant good practice and to the satisfaction of the Office for Nuclear Regulation (ONR).

The UK government operates a non-prescriptive, goal-setting approach to nuclear safety regulation. This means that the ONR sets out its regulatory expectations and requires duty-holders to determine how best to achieve them and justify their chosen approach. The ONR inspectors use Safety Assessment Principles (SAPs) (ONR 2014), together with Technical Assessment Guides (TAGs), to guide the regulatory decision-making process. However, owing to the ONR's non-prescriptive approach, these documents do not provide detailed guidance, although they have been developed to be consistent with the International Atomic Energy Agency's (IAEA) safety standards, to which they make reference.

In addition to the IAEA safety standards, the ONR guidance also recognizes the validity of "relevant good practice" from other industries, as long as it is demonstrated to be appropriate to the specific nuclear application. Furthermore, regulatory guidelines acknowledge that *"reactors built in the UK should be at least as safe as modern reactors anywhere else in the world"* whilst preventing *"gold-plating of reactor designs for use in the UK"* (HSE 2009).

Given the hiatus between the last construction of NPPs in the UK (mid 1990s) and the current new build, the reorganization of the regulator (from Nuclear Installations Inspectorate to Office for Nuclear Regulation), and the ONR's non-prescriptive approach to seismic safety cases, there was uncertainty as to what standards in new PSHA studies would be considered acceptable by ONR.

It was in this context that CH2M (now Jacobs) and collaborators developed an innovative approach to PSHA aimed at providing regulatory assurance, whilst acknowledging the commercial and program constraints faced by utility operators in the UK. This paper presents the background to the development of the approach and discusses the main differences/adaptations from the SSHAC process for Level 2 and Level 3 studies (Budnitz et al. 1997; USNRC 2012). The approach to PSHA presented in this paper has successfully been implemented for the seismic hazard evaluation underpinning the Safety Case for the Hinkley Point C site, which is described in detail in Tromans et al. (2018).

It should be noted that TAG-13 on external hazards is currently being updated (ONR 2017a), including its Annex 1 on seismic hazards (ONR 2017b), to provide more detail on regulatory expectations for its evaluation (ONR Expert Panel on Natural Hazards 2017). A draft version of the updated TAG-13 was circulated by the ONR for comments from industry in late 2017 and the final version is expected to be published in autumn 2018. The approach presented in this study is expected to be in agreement with the updated TAG-13 guidelines.

2. PSHA approach development background

The UK has a strong tradition of using PSHA for the evaluation of the seismic hazard for NPPs, dating back to the 1980s when the Seismic Hazard Working Party (SHWP) carried out seismic hazard assessments for a number of UK NPP sites (Musson 2014). The SHWP was a group of specialist consultants led by David Mallard of the Central Electricity Generating Board, including staff from Principia Mechanica Ltd. and Soil Mechanics Ltd. The SHWP developed a set of working practices for the evaluation of the seismic hazard, which were published as a two-volume methodology report: Volume 3M (SHWP 1988) and its supplement (SHWP 1991). Although the SHWP methodology, which included treatment of uncertainties through a logic-tree framework and consideration of multiple expert judgement, was state-of-the-art at the time, it no longer represents best practice when compared against modern standards and was therefore assessed as unlikely to be acceptable by the ONR to support the Safety Case of a new-build NPP. Nevertheless, it sets a ‘regulatory precedent’, which has to be considered alongside methodological developments in the intervening years.

A few years after the work by the SHWP was completed, in the mid-1990s the Senior Seismic Hazard Analysis Committee (SSHAC) published in the USA what is commonly known as the SSHAC guidelines (Budnitz et al. 1997). These guidelines, which have been endorsed by the United States Nuclear Regulatory Commission (USNRC) as the recommended approach for the development of new models to be used in PSHA (e.g., Regulatory Guide 1.208, USNRC 2007), focused on methodological aspects of the PSHA, aiming in particular to provide a structured framework for multiple-expert hazard assessments. The underlying motivation was to reconcile the findings of two multi-expert PSHA studies for NPP sites in the Central and Eastern United States (Bernreuter et al. 1989; EPRI 1989), discrepancies between which were found to stem primarily from procedural differences. The SSHAC guidelines define four levels of PSHA study, reflecting increasing levels of technical complexity and resources allocated to the study, as described in Table 4.2 of NUREG-2117 (USNRC 2012). A notable feature of this classification scheme is the large increment in both complexity and regulatory assurance between the lower (1 and 2) and higher (3 and 4) levels of study. The higher levels of study are generally associated with a greater level of regulatory assurance owing to the greater level of effort expended to capture the centre, body and range (CBR) of technically defensible interpretations (TDI), which is the common goal of all four levels. For this reason, the USNRC requires Level 3 or 4 studies for nuclear facilities.

Since its publication, the SSHAC process has been used for numerous natural hazard studies not only in the USA but also worldwide, in particular those developed for safety-critical facilities such as NPPs. Examples of this are the PEGASOS project (Abrahamson et al. 2002) and PEGASOS Refinement Project (Renault 2013) in Switzerland, and the Thyspunt project in South Africa (Bommer et al. 2015). As a result, the original SSHAC guidelines have recently been supplemented by NUREG-2117 (USNRC 2012) in order to incorporate practical insights gained during recent PSHA projects implementing the higher levels of the SSHAC process.

Efforts have also been made to suggest solutions to improve the cost-effectiveness of SSHAC studies. In particular, Coppersmith and Bommer (2012) proposed that for multiple sites, a regional SSHAC Level 3 or 4 study followed by site-specific Level 2 refinement studies represented the most efficient solution in terms of cost and duration. This approach has been implemented in the development of regional seismic source (CEUS-SSC project; Salomone 2015) and ground-motion models for the Central and Eastern United States (EPRI 2013). Bommer (2010) recommended a similar approach be adopted for the UK. However, to date, SSHAC guidelines have not been applied in the UK.

At present, guidance for the organization of SSHAC studies is well-developed for Levels 3 and 4 but is limited for Levels 1 and 2. This will be addressed in a forthcoming update to NUREG-2117 (Juckett et al. 2016, USNRC 2018), which for obvious reasons was not available for the development of the PSHA approach described in the present paper. A wide variety of approaches can technically be considered “Level 2”, even when the engagement of outside experts is minimal. When utility operators are on a tight schedule, as is the case for UK new build NPP, the long duration of level 3 and 4 studies, which would normally be more than two-and-a-half years for a SSHAC Level 3 study (Coppersmith et al. 2013; Bommer and Coppersmith 2013), is a source of difficulty.

Fortunately, the UK sites currently under consideration for new-build NPPs are all located in the immediate vicinity of operational or decommissioned NPPs, and as a result there is an extensive body of pre-existing site-specific information available for modern PSHA studies. However, given the safety-critical nature of NPP sites, the level of regulatory assurance required remains high. Therefore, there was a need for a more compact study, closer to a SSHAC Level 2 study in terms of duration and cost, but with a similar level of regulatory assurance to a SSHAC Level 3 study. A Level 2/3 approach is not sanctioned by the SSHAC guidelines (Bommer and Coppersmith 2013); anything that falls between the specification for Level 2 and Level 3 is de facto Level 2. However, as long as the hybrid approach, which could be classified as an “enhanced Level 2”, meets the approval of both the operator (for cost and timescale) and the regulator (for regulatory assurance), it is a practical solution. It is worth noting that the forthcoming update to NUREG-2117 is expected to specifically sanction Level 2 studies with augmented options. In this sense, the procedure developed and applied for the Hinkley PSHA could be considered as an illustrative example and practical application of the general concept of an enhanced Level 2 study.

Our approach to PSHA, discussed in this paper, is in line with international best practice and follows the principles of the SSHAC Level 2 requirements, but incorporates key features of the SSHAC Level 3 process, particularly those aimed at achieving regulatory assurance. The structure of the project and roles of the various participants is more flexible than in the SSHAC approach, allowing for adjustments to the approach as the project develops based on knowledge acquired during the execution of the project and making more efficient use of the already limited pool of available experts in the field.

3. Project structure and implementation

As previously discussed, the proposed methodology does not formally follow the framework of a SSHAC Level 3 study. It was developed so as to satisfy all the requirements of a SSHAC Level 2 study, but with a particular emphasis on incorporating those elements of a SSHAC Level 3 process that contribute to regulatory assurance. Regulatory assurance is defined in NUREG-2117 (USNRC 2012) as *"confidence that views of the larger technical community have been properly considered and that the center, body, and range of technically defensible interpretations has been represented and documented"*. Elements that have been identified as particularly important to achieve regulatory assurance include:

- Number of participants, with a larger project team, of similar size as normally required for a SSHAC Level 3 study, and several international (UK, US and continental Europe) Subject Experts (eleven in total);
- Participatory nature of peer-review, allowing for participation at all stages, not only at workshops, the incorporation of feedback and correction of issues as soon as they arise, rather than at a late stage in the process;
- Transparency of interactions, with thorough documentation of the decision process (see Section 4.4), and the participation of client's and nuclear regulator's representatives at the various workshops run throughout the project in an observer role;
- Clear recognition of cognitive biases, in particular the distinction between resource and proponent views; and

- The iterative nature of the collective process of reducing epistemic uncertainties within the seismic hazard community, with each new project benefiting from the insights gained and lessons learnt in previously completed projects.

Consistent with this perspective, the proposed approach aimed to develop further the methodology implemented to date, by others, in other similar projects and to incorporate insights gained from personal involvement of individual project team members in recently completed SSHAC Level 3 and 4 projects. These are predominantly based on experiences of the SSHAC Level 3 PSHA for the Thyspunt new-build NPP site in South Africa (Bommer et al. 2015), and the refinement phase of the PEGASOS project for the revision of the design bases at four NPP sites in Switzerland (Renault 2015). Methodological aspects of other recently completed SSHAC Level 3 studies were also considered.

4. Project delivery team structure

The project delivery team structure is shown in Figure 1. As illustrated, the project delivery structure is similar to that of a SSHAC Level 3 study, with the main difference being the amalgamation of Resource Experts and Proponent Experts, as per SSHAC terminology, into the single role of Subject Experts and the consideration of two independent Hazard Calculation teams, which significantly contributed towards the QA process and increased regulatory assurance. Other aspects of the SSHAC Level 3 structure, including an independent Peer Review Team overseeing the project from inception (fundamental for the objective of achieving regulatory assurance), and a larger Technical Delivery Team (Technical Integrator Team as per SSHAC terminology) were kept.

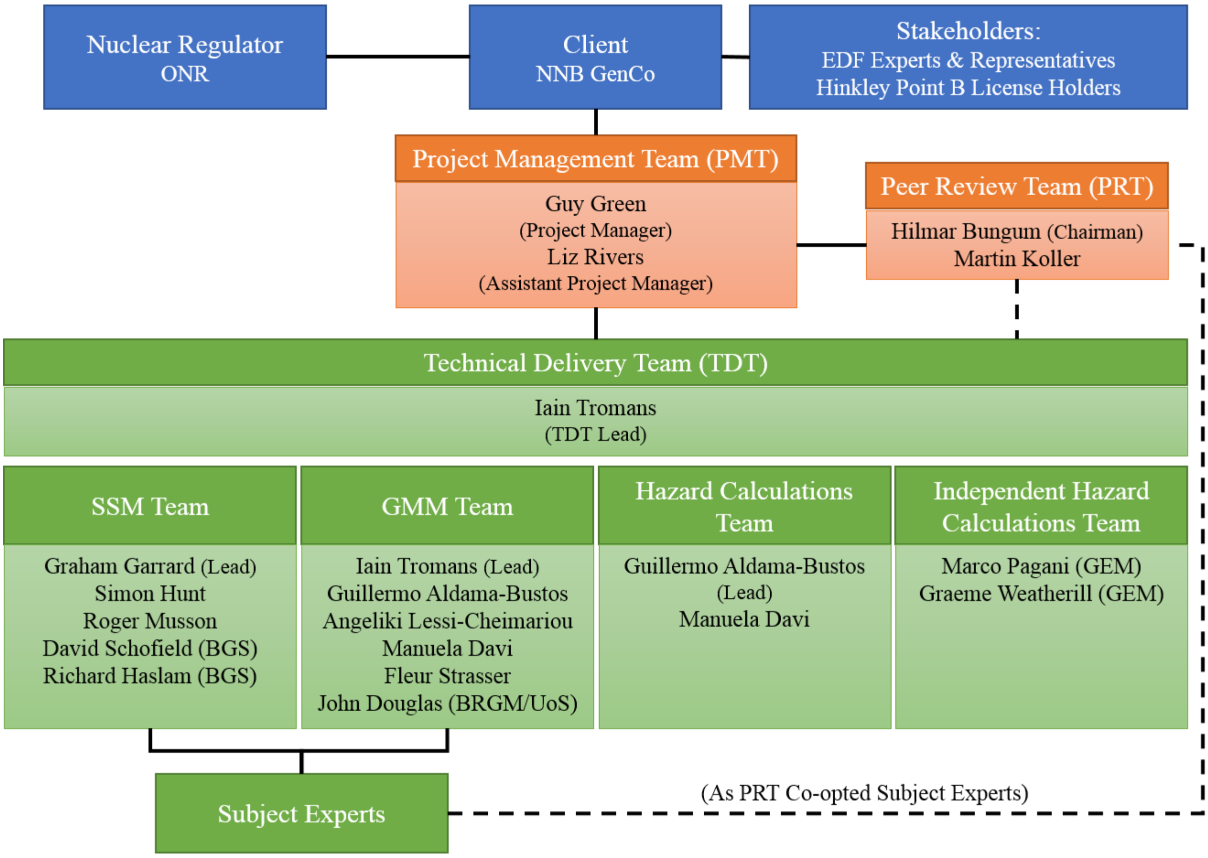

Fig. 1 Hinkley PSHA project delivery team and team structure

Solid lines in Figure 1 represent direct formal interactions between the various groups of the project. Dashed lines represent a close interaction between the PRT and the TDT, while the PMT remain as the "formal" channel of communication, and the possibility for the PRT to co-opt SEs to their team to assist with their PRT role when considered necessary (see also discussion in Section 4.3).

Note that since the approach deviates from the guidelines for a SSHAC Level 3 study, the terminology adopted deliberately avoids the use of SSHAC terminology, to prevent confusion between original and adapted concepts.

The Technical Delivery Team (TDT) was an amalgamation of CH2M's internal specialists, combined with key experts in the form of retained consultants and sub-consultants from the University of Edinburgh (formerly at the British Geological Survey) and the University of Strathclyde (formerly at the Bureau de Recherches Géologiques et Minières). The Peer Review Team (PRT) was composed of experts external to CH2M, which was considered essential to maintain their independence. PRT members were selected based not only on their experience and technical knowledge of the PSHA process, but also their knowledge of the SSHAC process through participation in previous SSHAC Level 3 and Level 4 studies.

4.1. Project plan

Overall, the Project Plan followed the structure of a SSHAC Level 3 as described in NUREG-2117 with a phased approach punctuated by working meetings and workshops representing the key milestones in the development of the project. Figure 2 presents the project plan for the Hinkley PSHA, which consists of three phases:

Phase 1 – *Study Definition Stage* concentrated on defining the scope of works necessary for a detailed and robust PSHA. It also included a high-level review of existing data and studies, identification of hazard sensitive issues, identification of further data requirements and the setup of a databank for relevant information.

Phase 2 – *Implementation Stage* constituted the main part of the project, including Subject Expert and PRT interactions, development of the models, and calculations.

Phase 3 – *Support Stage* consisted of any ad hoc support to the client, NNB GenCo, on the Safety Case submission, as required.

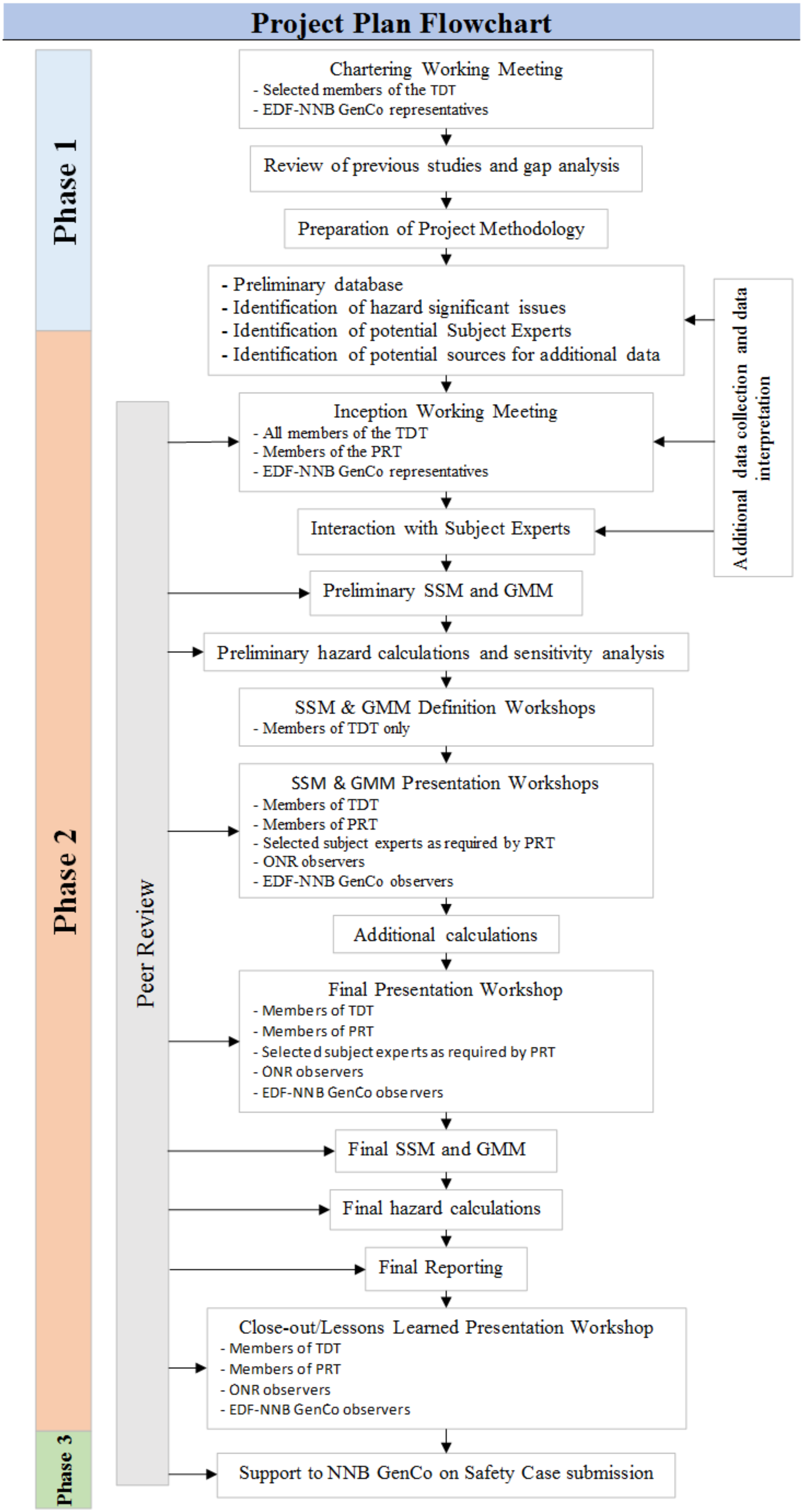

Fig. 2 Hinkley PSHA project plan

Within the context of the project plan, the term “workshop” was taken in the conceptual sense, and denoted any form of interaction (physical or virtual) within the TDT (‘internal’ Definition Workshops), or between the TDT and the PRT (Presentation Workshops), to which the client’s representatives, and the ONR’s representatives and retained experts were invited in the role of Observer to satisfy themselves that these interactions were in line with the project objectives. The study methodology also provided the PRT with the discretion to invite a number of Subject Experts to attend the Presentation Workshops, as co-opted members of the PRT.

The Definition Workshops had the objective of discussing within the TDT and agreeing on the interim seismic source model (SSM) and ground-motion model (GMM) components of the PSHA based on the review and interpretation of the available data, the expert engagement process, and the findings from the preliminary hazard calculations. Following the Definition Workshops, the TDT presented the technical justification for the interim models to the PRT, in two formal Presentation Workshops, covering the SSM and GMM components of the study. A Final Presentation Workshop was also run to help finalize outstanding issues before the final hazard calculations. This process gave the TDT the opportunity to obtain feedback from experts outside the TDT before finalization of the relevant models.

Although the large majority of the TDT members were based in two fairly nearby offices in the UK (London and Swindon), due to the logistical constraints imposed by the compressed project duration, video- and tele-conference facilities were used during working meetings and workshops when required. Such facilities were also used for interactions between the TDT and SEs, mainly for those based in the US or continental Europe, and with the PRT, which were based in Switzerland and Norway. Such “virtual” workshops can also be used in projects with a more generous schedule as a cost-effective tool. Presentation Workshops were scheduled to allow for attendance in-person of all members of the PRT, including PRT co-opted Subject Experts, and key relevant members of the TDT.

An important element of the Project Plan was the definition of formal communication and reporting protocols that would allow the efficient and controlled exchange of information between the various parties, with particular attention to how elicitation of expert judgement would be undertaken and recorded, and how the independence of the PRT would be demonstrated; both of these elements being crucial for the goal of achieving regulatory assurance. The protocols adopted for the Hinkley PSHA are summarized in Figure 3.

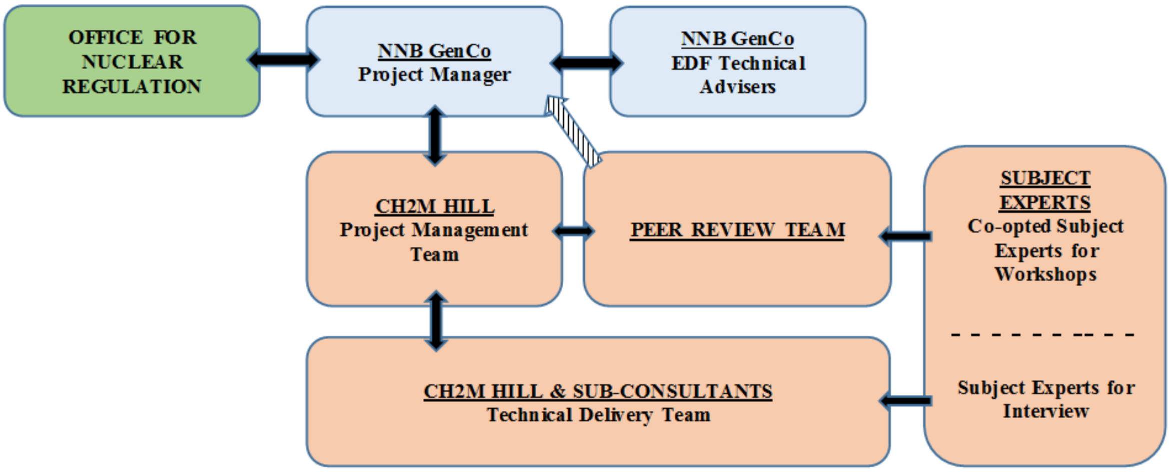

Fig. 3 Hinkley PSHA communications chart

4.2. Subject Expert roles

In practice, it is often inevitable that multiple expert roles within the same project are taken on by the same individual (e.g. an evaluator expert may also be the proponent of a model, or a resource expert on specific data). The SSHAC guidelines allow for such situations, provided the change in expert role is explicitly acknowledged and made clear to all other evaluators, and that, when returning to their role as an evaluator, the expert carries out their assessment in an impartial and objective way. The process of challenges from other evaluators within the team and the general oversight by the participatory peer review panel (PPRP, as per SSHAC terminology) ensure that the guidelines are met. Also, practical implementation has revealed the difficulty in finding a consistent terminology for individuals assisting the delivery process without being part of the (core) Technical Integrator (TI, as per SSHAC terminology) team in terms of ownership of the models. Such individuals have been variously described as "database developers" or "technical support staff", while performing tasks that were often similar in nature to the contributions of resource experts.

For the approach presented herein, the concept of "Subject Expert" (SE) was therefore developed. This was defined as any individual who contributes on one or more technical aspect(s) (data, model, interpretation) of the technical delivery process, without, however, having an ownership stake in the model developed. Although a number of members of the TDT are expected to fulfil the role of SEs for some technical aspects of the PSHA, for simplicity of the approach and terminology, the term of SE was applied only to specialists co-opted from outside the TDT.

Although the combined expertise of the TDT was broad, it has to be acknowledged that in a small-to-medium sized team, it is unlikely that interactions within the TDT alone are sufficient to capture the full breadth of technically defensible interpretations. Therefore, the TDT had to identify and enter into discussions with SEs within the wider technical community to ensure that the project captured, documented, and understood the significance and relevance of the available data, and any valid alternative interpretations. Identification of the subject areas requiring expert engagement, and the subsequent selection of suitable Subject Experts, was an iterative process considering technical factors such as specialisms and level of expertise, but also heeding logistical project constraints, such as availability within the project timeframe. This selection process was carried out in conjunction with the PRT.

Engagement of SEs was based on face-to-face meetings, or teleconferences, between each individual expert and relevant members of the TDT. Depending on whether resolution of the topics discussed during the meeting was achieved or not, additional meetings were scheduled. In advance of each meeting, SEs were provided with relevant project-specific information on the topic to be discussed, which may include data, preliminary interpretations of the data or models, or preliminary results of a particular analysis, *inter alia*. Following each of the interviews, agreed summaries of the discussions were formally captured and documented as part of the project records, and approved by the SE. The summaries of the SE interviews were made available to the PRT for their consideration and feedback.

One of the main differences with the expert interaction approach required for a SSHAC Level 3 study was that no formal direct interaction between individual SEs took place, as it would in the second workshop of a SSHAC Level 3 study. In most cases, more than one expert was interviewed on a particular topic, interviews with different SEs occurred relatively closely in time to each other, and more than one interview with the same SE was often required (particularly on the most controversial issues). Therefore, SEs were often made aware of other SEs' view on the same topic. This could be argued to represent an informal type of interaction between SEs. Additionally, for methodological uncertainties that are not region- or site-specific, the "slipstream effect" generated by the publication of detailed documentation of expert elicitation and interaction on specific topics in other recent projects should be acknowledged, since the availability of such documentation greatly facilitates the capture of the CBR of the TDI.

The approach adopted for the engagement of experts was not as comprehensive as that required for a formal SSHAC Level 3 study. However, it allowed for greater flexibility, and was considered proportionate for the project, providing appropriate representation of the range of valid expert judgements within the technical community, and it was considered to be consistent with the ONR's Safety Assessment Principles. Also, despite the differences in the approach for a formal SSHAC Level 3 study, the objectives of the SE interactions were in line with the "multiple-expert assessment" approach defined in NUREG-2117, rather than the traditional "expert elicitation" approach.

Although the TDT were seeking the SEs' specialist judgements and comments, the synthesis and incorporation of any technical interpretations into the Hinkley PSHA, as well as the assessment of their defensibility, were fully the TDT's responsibility, using the same "ownership" criterion as in NUREG-2117. Generally, the SEs provided similar judgements and hence the use of their inputs by the TDT was relatively straightforward. When differing judgements were encountered, the TDT carefully studied the various SE viewpoints and, if required, asked them for clarification before developing their final models in an objective, transparent and well-documented manner that sought to avoid "sponsor bias". The final PSHA model includes some logic-tree branches that reflect alternative viewpoints provided through discussions with the SEs.

4.3. Participatory Peer-Review

Participatory peer review is an integral, and critical, part of state-of-the-art PSHAs for high-value infrastructure projects, and a key element of the SSHAC guidelines. It is strongly recommended by the USNRC for SSHAC Level 3 and Level 4 studies, and a requirement in the forthcoming update to NUREG-2117. Participatory peer review in this context means that the review is continuous throughout the project to ensure that advice and comments can be conveyed while there is still time to address them.

The participatory peer review process implemented in the Hinkley PSHA broadly followed the requirements for a SSHAC Level 3 study, with a smaller number of members than could be expected for a SSHAC Level 3 study but greater flexibility and more frequent interactions with the TDT. As in the SSHAC guidelines, the role of the PRT for this project was focused in two main areas: process and technical review. The process review ensures that the PSHA approach conforms to the requirements of a high-level study, while the technical review is concerned with assessing that the full range of data, models and methods have been duly considered, and that all technical decisions have been adequately justified and documented. Collectively, these two aspects of the peer-review process led to assurance that the work was performed appropriately.

The main differentiators from the SSHAC methodology were: a closer interaction between the TDT and the PRT than normally done in SSHAC Level 3 projects, and the option for the PRT to co-opt SEs as part of the team when considered appropriate to cover specific technical areas. When PRT co-opted SEs also acted as SEs for the TDT, they were made aware of their change of role and asked to remain impartial on their assessment of the data interpretation and/or models developed by the TDT. Other factors contributing towards the objective assessment of the PRT co-opted SEs were: the participation of PRT co-opted SEs being limited to their attendance of workshops, where entire models (e.g., SSM or GMM) or hazard calculations results were presented and discussed rather than individual technical topics on which the PRT co-opted SEs may have engaged with the TDT under their role of SE. Also, PRT co-opted SEs' comments and feedback from the workshops were provided directly to the PRT for the PRT's evaluation and integration into a single consolidated PRT report.

For the Hinkley PSHA some of the SEs were allowed to play both roles as co-opted members of the PRT and technical advisors to the TDT. This dual role was justified on the basis of a limited pool of experts and a constrained schedule, and potential bias on their assessments as co-opted members of the PRT was avoided by implementing the measures discussed above. However, the authors acknowledge that, if the schedule, budget and available pool of expertise allow it, it is preferable to have different SE in for these two roles.

The interactions between the TDT and PRT were not limited to the review of deliverables, and face-to-face exchanges at the various Presentation Workshops held at various stages of the project, but also included the use of ad hoc teleconferences to discuss contentious issues as they arose. Where advised, the TDT produced "white papers" to help explain to the PRT a particular method or model in order to obtain "approval in principle" in advance of the development of the models and/or calculations, and submission of the deliverables. The use of teleconferences and white papers were invaluable tools to make the peer-review process as efficient as possible by reducing the likelihood of abortive work or major modifications following the PRT's review of the final deliverables.

The PRT for the Hinkley PSHA comprised two members: Dr Hilmar Bungum and Dr Martin Koller, both highly respected international seismic hazard experts, with extensive experience of SSHAC Level 3 and Level 4 studies, and whose combined expertise covers a broad range of areas including seismic source modelling, ground-motion prediction, site characterization, and procedures to manage and incorporate expert judgement.

A total of three SEs were co-opted by the PRT to provide advice on the fields of ground-motion modelling, geological and tectonic interpretation, and site characterization and site-response analysis. PRT co-opted SEs were invited to attend the Presentation Workshop corresponding to their area of expertise.

4.4. Documentation

One of the key differences between the lower (1 and 2) and higher (3 and 4) SSHAC levels of study is the emphasis placed on documentation of the evaluation and integration process; although in all cases a complete documentation of the PSHA is required. In a Level 2 study, this is effectively left at the discretion of the TI team, with the result that it is difficult to assess the generic level of transparency and regulatory assurance that can be expected from this level of study.

The approach implemented by the project delivery team for the Hinkley PSHA followed the documentation principles for higher-level SSHAC studies by incorporating thorough and detailed documentation of all "formal" interactions within the TDT, between the TDT and Subject Experts, and between the TDT and the PRT. This also included a comprehensive justification and reporting of all decisions taken in the development of the hazard model.

While some of the formalism of SSHAC, in particular regarding team and expert interactions, was relaxed to meet the schedule of the project, as discussed above, the documentation process was instead rendered more formal than described in the SSHAC guidelines for a Level 3 study, with much the same aim. A hierarchical structure was adopted for the reporting of the various technical elements of the PSHA (e.g., historical seismicity, earthquake catalogue, ground-motion model), which is schematically represented in Figure 4.

In general, Level 4 reports cover the data collation, review and assessment, and verification and validation of hazard calculations. Level 3 reports generally integrate the outputs of Level 4 reports to define input models to the PSHA and site response. The Level 2 report is a summary of the whole PSHA process, while the Level 1 report is an executive summary of the project. Level 1 and Level 2 reports should be self-contained and sufficient to obtain an informed overview of the study, without the need to consult lower level reports. A total of 19 technical reports were produced as part of the Hinkley PSHA, which together form the Safety Case justification for vibratory ground-motion hazard submitted to the ONR.

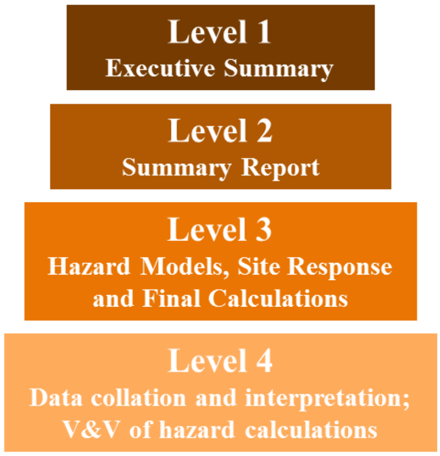

Fig. 4 Hinkley PSHA reporting structure

This hierarchical reporting structure facilitated a phased delivery and review of PSHA inputs and results, which contributed towards a smooth and timely delivery of the project, and helped to build peer-review and regulatory assurance progressively throughout the various stages of the project.

In line with established practice for high-level PSHA studies, hazard input documents (HIDs) and site response input documents (SRID) were produced. The objective of the HIDs and SRIDs was to present in a clear and unambiguous manner to the seismic hazard and site response analysts, all the necessary information / data needed to perform the calculations undertaken at various stages of the project (e.g., preliminary hazard calculations, cross-checking calculations and final hazard calculations).

The development of high-quality HIDs and SRIDs was found to be a crucial element of the quality assurance system. Clear and unambiguous definition of the seismic hazard calculation requirements resulted in a quick convergence of the cross-checking calculations. These calculations were implemented by two independent teams using different software [i.e., CH2M using CRISIS2015 (Ordaz et al. 2015) and GEM using the OpenQuake-engine code (Pagani et al. 2014)], following a similar approach to that outlined in Bommer et al. (2013). The achieved differences in the results between the two sets of analyses, which are intrinsic to the use of different codes (e.g., Thomas et al. 2010), were smaller (typically below

1% on the calculated AFoEs, and in no case larger than 5%) than those observed in similar projects.

5. Concluding remarks

The implementation of the approach to PSHA described in this paper allowed the successful completion of the Hinkley PSHA, which achieved its two main objectives:

- To achieve regulatory approval within the non-prescriptive UK nuclear regulatory environment for a new-build NPP at the Hinkley Point site; and
- To complete the study within a relatively short period of time (21 months) and at considerably lower cost than a SSHAC Level 3 study.

Nevertheless, it has to be acknowledged that the availability of previous (at their time state-of-the-art) seismic hazard studies for the site as well as the collective knowledge of the seismicity of the UK, in addition to ground-investigations carried out in advance of the commencement of the PSHA study, were important contributors to the short duration of the project.

Although the approach to PSHA presented in this paper, which can be considered as an enhanced SSHAC Level 2, was developed to achieve regulatory approval within the UK nuclear regulatory context, it could be adapted to any other type of high-value and/or safety-significant infrastructure, and regulatory environment, as a cost-effective approach with a high reliability assurance.

A summary of the key features of the approach developed for this study, and its comparison against requirements for SSHAC Level 2 and Level 3 studies is presented in Table 2. The upcoming update to NUREG-2117 (USNRC 2018) will provide further guidance on the requirements for Level 2 studies, which has not been included in Table 2 as it is expected to represent the status of the SSHAC guidelines at the time the PSHA approach for this study was developed. USNRC (2018) will also provide guidance to Level 2 studies with augmented options, which resembles the approach described in this paper.

Table 2 Attributes of the approach developed for this study in comparison with Level 2 and Level 3 studies (after Table 4.2 of USNRC 2012)

SSHAC Level / SSHAC Component	Level 2	This Study (Enhanced Level 2)	Level 3
Number of	• Project Manager	• Project Manager.	• Project Manager.

SSHAC Level / SSHAC Component	Level 2	This Study (Enhanced Level 2)	Level 3
participants	• Small TI (Technical Integrator) team. • Peer reviewers. • Hazard calculation team. • Resource experts • Proponent experts.	• Project TDT. • Larger TDT team. • Peer reviewers. • Resource experts and proponent experts (jointly referred to as Subject Experts). • Hazard calculation team.	• Project TI. • Larger TI team. • Peer reviewers. • Resource experts. • Proponent experts. • Data team. • Hazard calculation team.
Interaction	• Proponent and resource experts contacted individually.	• Subject Experts contacted individually. • Individual members of the TDT then take on the role of proponent/resource experts at workshops, with the TDT as a whole acting as evaluator/integrator. • All interactions with Subject Experts are thoroughly documented and subjected to the scrutiny of the PRT.	• Proponent and resource experts interact with TI Team in facilitated workshops.
Peer review	• Late stage.	• Participatory. • PRT may include co-opted subject experts where appropriate to cover specific technical areas.	• Participatory.
Ownership	• TI Team.	• Technical Delivery Team (TDT).	• TI Team.
Transparency	• Dependent on documentation.	• Client and regulator can view interactions at workshops. • Participatory peer reviewers observe workshops and participate at all stages of the process where appropriate. • All interactions with Subject Experts as well as the evaluation and integration process are thoroughly documented.	• Interested parties can view interactions at workshops. • Participatory peer reviewers observe workshops, participate in Workshop #3. • Dependent on documentation.
Regulatory Assurance	• Individual interaction with proponent and resource experts increases confidence over	• Individual interaction with subject experts is thoroughly documented and subjected to the scrutiny of the PRT, hence increased confidence over	• Interaction among proponent, resource, and evaluator experts in facilitated workshops greatly

SSHAC Level / SSHAC Component	Level 2	This Study (Enhanced Level 2)	Level 3
	Level 1. • Depends on TI team; degree to which data, models, and methods are readily available; and success in obtaining additional information and understanding from individual interactions.	Level 2. • Thorough documentation of all decisions and underlying rationale is a key component of the approach. • Hierarchical reporting structure ensures phased delivery to regulator as well as client.	increases confidence over Level 2. • Documentation of evaluation and integration process by TI Team key to high levels of confidence.
Cost	• Slightly greater than Level 1 because of time required for interaction with proponent and resource experts.	• Greater than Level 2 due to greater number of participants and inclusion of workshops, but smaller than Level 3 by holding separate meetings with Subject Experts and Subject Experts' judgements/views being integrated by the TDT at internal workshops. • Physical dispersion of team is limited, systems to remotely access data and information already in place as part of CH2M's standard operations. • Use of telephone and video conferencing for interactions with subject experts wherever feasible. • TDT working meetings coincide with workshops, resulting in a reduced cost compared to Level 3 where workshops and working meetings are typically kept separate.	• Significantly greater than Level 2 because of greater number of participants and use of facilitated workshops. • Greater likelihood that TI team members are physically dispersed, requiring costs for systems to remotely access data and information. • Costs associated with TI Team working meetings.
Duration	• Slightly greater than Level 1 because of time required for interaction with proponent and resource experts.	• Greater than Level 2 due to enhanced documentation and scrutiny of individual interactions with Subject Experts, and inclusion of workshops, hence need to	• Significantly greater than Level 2 because of constraints in organizing workshops around proponent and

SSHAC Level / SSHAC Component	Level 2	This Study (Enhanced Level 2)	Level 3
	• Typically, 6-12 months.	consider personal schedules. • Shorter than Level 3 as constraints in organizing workshops are reduced by replacing direct intervention of external Subject Experts at workshops by a summary of individual interactions with these experts. • Between 18 and 24 months.	resource expert, TI team member, and PPRP member personal schedules. • Typically, ≥30 months.
Management Challenge	• Slightly greater than Level 1 because of need to interact individually with proponent and resource experts whose schedules cannot be controlled.	• Intermediate between Level 2 and Level 3. • Subcontracts are typically required for subject experts. • Longer engagement of subject experts.	• Significantly greater than Level 2 because of increased number of participants (a number of whom may require subcontracts) and the logistics of organizing workshops.

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