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## **AN APPLICATION OF THE SSHAC LEVEL 3 PROCESS TO THE PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE THYSPUNT NUCLEAR SITE IN SOUTH AFRICA**

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### **ABSTRACT**

A probabilistic seismic hazard analysis (PSHA) has been conducted for the seismic characterization in terms of vibratory ground motions for the coastal Thyspunt site in the Eastern Cape Province, one of sites under consideration for the construction of new nuclear power plants in South Africa. In order to conform to international best practice, the state-owned energy utility Eskom contracted the Council for Geoscience (CGS) to undertake the site-specific PSHA according to Regulatory Guide 1.208 and following a SSHAC Level 3 process, in accordance with the most recent guidelines issued by the US Nuclear Regulatory Commission in NUREG-2117. The project was executed by an international team contracted to CGS, and was completed on schedule, with a duration of just over two years from the launch of the PSHA project to delivery of the draft final report for review. The project is the first application of the SSHAC Level 3 process to a PSHA for a new-build nuclear site and also the first application of the SSHAC framework in the developing world. The Thyspunt PSHA provides an opportunity to learn new lessons regarding the implementation of the SSHAC Level 3 process (addressed in the companion paper by Bommer and Coppersmith, 2013). The successful completion of this project on schedule and on budget, despite the logistical challenges, is an important demonstration that SSHAC Level 3 hazard studies can now be planned, scheduled and budgeted with a high degree of confidence, executed without deviation from the project plan, and completed with products that have direct use in design and regulatory licensing.

### **INTRODUCTION**

The population of South Africa is now close to 50 million and in order to meet the growing energy demands in this emerging economy, the state-owned energy utility, Eskom, is increasing electricity generation. A large proportion of electricity in South Africa is obtained from coal-fired power stations, with a single two-unit nuclear power plant at Koeberg, north of Cape Town, which began operation in 1984. The South African government is committed to the construction of several new nuclear power plants, with the coastal site at Thyspunt (Figure 1), west of Port Elizabeth in the Eastern Cape Province, being considered as one of the sites for characterization.

Although South Africa is not a region of elevated seismicity, destructive earthquakes have occurred: during the twentieth century, notable events include earthquakes of February 1920 ( $M_w$  6.2) and July 1976 ( $M_w$  5.8) at Koffiefontein in the Free State province, and the Ceres-Tulbagh earthquake ( $M_w$  6.2) of September 1969 in the Western Cape province (Green and McGarr, 1972). Eskom is committed to satisfy the stringent licensing requirements of the National Nuclear Regulator (NNR), and sought to make a reliable assessment of the earthquake hazard at the Thyspunt site in face of inevitably large uncertainty in this region of infrequent earthquakes with a sparse network of seismographs. In order to address these objectives, Eskom commissioned a site-specific probabilistic seismic hazard analysis (PSHA) to be conducted following the most stringent international standards, namely following the requirements of

Regulatory Guide 1.208 (USNRC, 2007) and carried out within the framework of a SSHAC Level 3 procedure (Budnitz et al., 1997). Specifically, the hazard study was to be conducted following the guidelines and requirements specified in NUREG-2117 (USNRC, 2012).

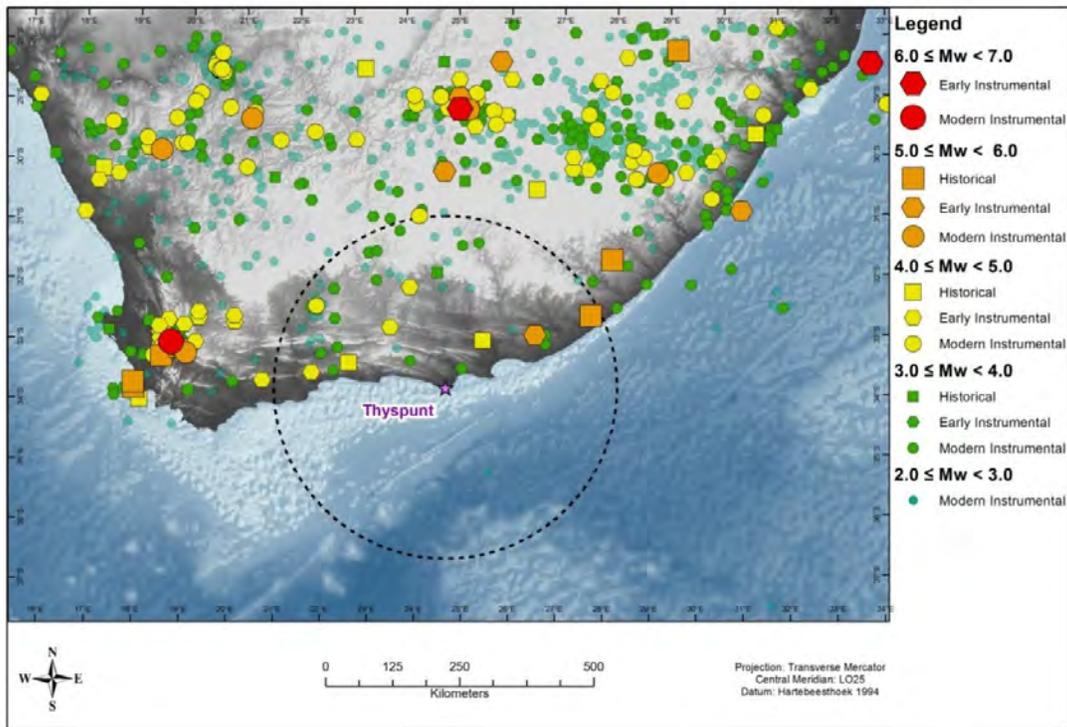


Figure 1. Location of the Thyspunt site in South Africa, together with seismicity south of the 28°S parallel for events with  $M_w \geq 2$ . The dashed circle indicates the 320km regulatory radius around the site specified as the minimum for geological and seismological investigations in RG 1.208.

## PROJECT ORGANIZATION

In order to conduct the SSHAC Level 3 PSHA for the Thyspunt site, Eskom contracted the South African Council for Geoscience (CGS), which had already provided support to Eskom's nuclear site characterization work for several years. As the organization responsible for the geological mapping of South Africa and for operating the South Africa National Seismograph Network (Saunders et al., 2008), CGS houses unparalleled local knowledge and databases that would provide essential input to the study. However, to execute the PSHA following a SSHAC Level 3 procedure, it was necessary for CGS to contract international consultants with experience both of high-level SSHAC projects and of conducting hazard assessments for low-seismicity regions and regulated environments. Initial contact was made with the lead author of this paper during review of earlier work on site characterization for Eskom, and he was then appointed as Project Technical Integrator (PTI). Working with the second author of this paper, selected to lead the Seismic Source Characterization (SSC) activity while the first author led the Ground Motion Characterization (GMC) component of the project, a team was established to populate the roles required for a SSHAC Level 3 study, applying the selection criteria for each role specified in NUREG-2117. The organizational structure of the project is illustrated in Figure 2. CGS assumed all of the responsibilities of project management, including contracting, organization of field work and workshops, and Quality and Safety Assurance; the third author of this paper served as Project Manager, supported by a number of colleagues at CGS.

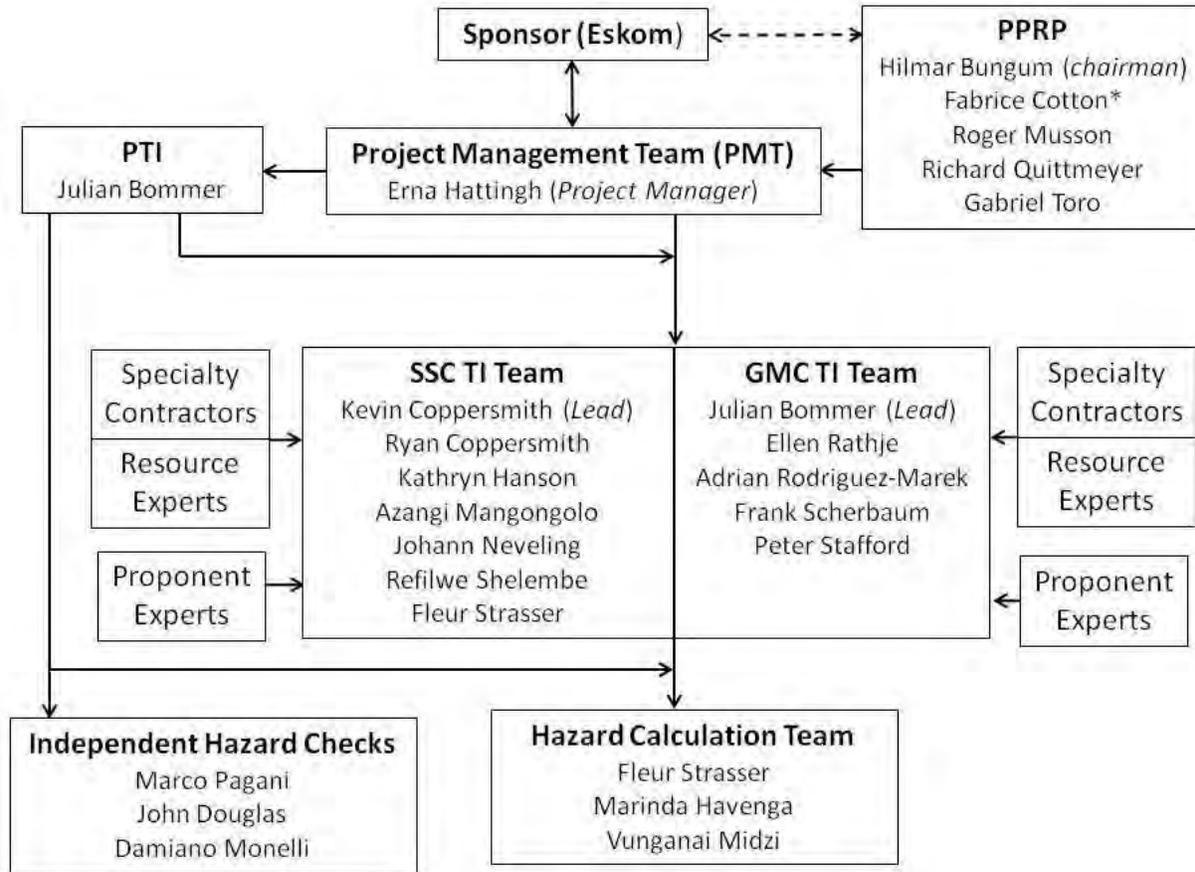


Figure 2. Organizational structure for the SSHAC Level 3 PSHA for the Thyspunt site (\*Prof. Cotton was appointed to the PPRP mid-way through the project because of the resignation, for health and personal reasons respectively, of two other Panel members, Drs Leon Reiter and Annie Kammerer)

The SSC Technical Integration (TI) Team included two seismologists and two geologists from CGS, bringing extensive local knowledge to the evaluation of available data and models, and also to the integration phase in which the SSC logic-tree was developed. Since there are no strong-motion data at all in South Africa, local knowledge within the GMC TI Team was considered less important than experience in the development of ground-motion predictions models, particularly for regions of low seismicity. As explained later in this paper, both TI Teams received considerable support and input from Specialty Contractors and others who assisted with the development of the project databases.

A key element of a SSHAC Level 3 study is the Participatory Peer Review Panel (PPRP), which conducts continuous process and technical review throughout the project. The PPRP members are collectively required to possess technical expertise in both SSC- and GMC-related disciplines, extensive knowledge of PSHA, and direct experience of the SSHAC process. The five members of the PPRP have a collective experience in this field exceeding 130 years, and each of them is a highly-regarded expert in their field.

The composition of the core project teams, with members from five countries on three continents (with up to 10 hours of time difference), posed a logistic challenge in terms of coordination and meetings. If the Resource and Proponent Experts who participated in the project Workshops are also considered, then the project participants came from a total of eight countries on four continents. Despite the geographical dispersion of the team members (a feature that would be difficult to avoid for such a project in most developing countries), the project was carried out strictly within schedule and also within budget.

## PROJECT SCHEDULE

In accordance with the requirements for a SSHAC Level 3 study specified in NURGE-2117, the Thyspunt PSHA was built around three major workshops, as indicated in Figure 3. The project was formally launched on February 1<sup>st</sup>, 2011, at a meeting held at CGS in Pretoria. Work began several weeks earlier, in October 2010, when the TI Leads were engaged to develop a Project Execution Plan (PEP), which included recruitment of the TI Team members, and the Specialty Contractors. The PPRP was assembled in parallel by the Project Management Team working in close liaison with the sponsor, Eskom. The schedule for the project, including the dates of the three formal Workshops, were fixed in the PEP; the only deviation from the schedule in the original PEP was to bring forward by two weeks the delivery date for the final draft report to the PPRP to allow greater time for the review (with no change in the final delivery date). Insights gained regarding optimal timing of the Workshops for SSHAC Level 3 studies, and other lessons learnt with regard to schedule and the organization of the project Workshops, are recorded in Bommer and Coppersmith (2013).

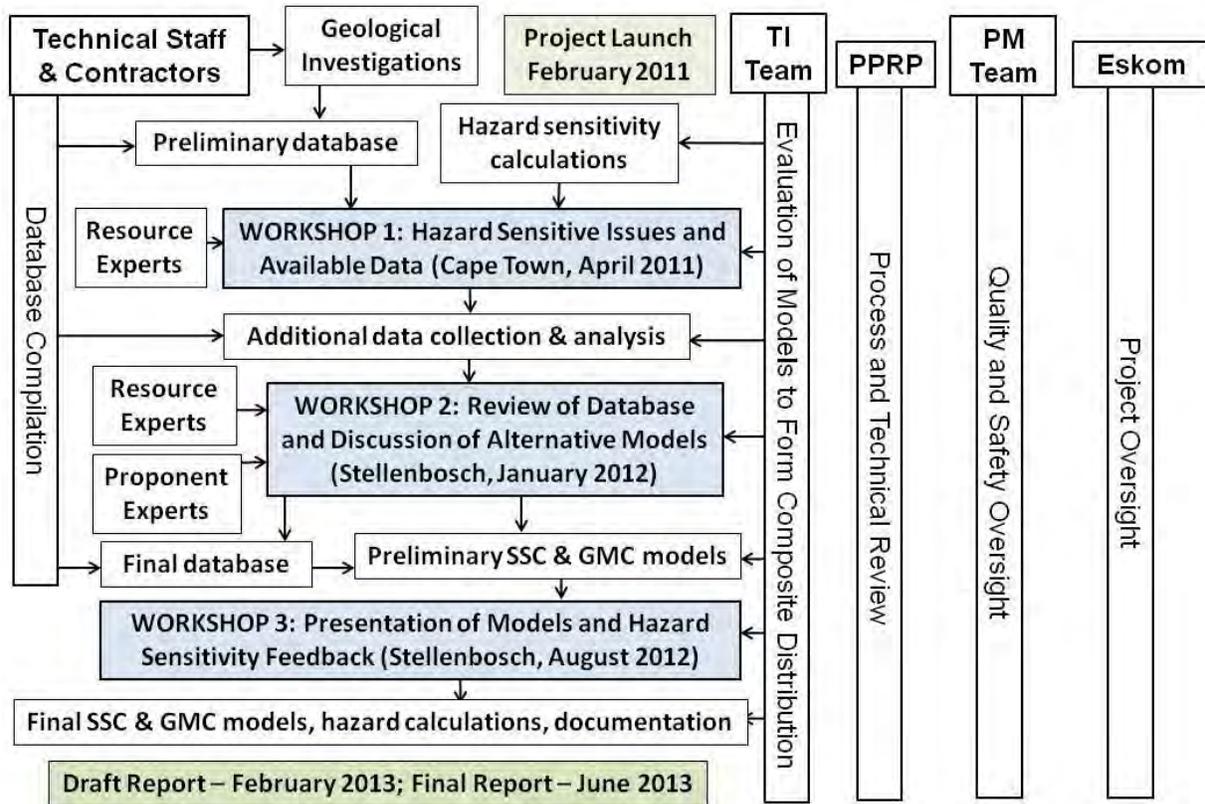


Figure 3. Sequence of tasks and engagement of different project participants; time runs downwards from the top of the diagram but the diagram is schematic and placement is not proportional to timing.

In parallel with the drafting of the PEP and assembling of the project teams, geological investigations began prior to the formal project launch to avoid delays related to processing of samples by geo-chronology laboratories. These investigations required assessment of the key geological structures that could influence the hazard at the site, for which useful insights were obtained from a SSHAC Level 1 PSHA conducted for Eskom two years earlier.

As mentioned earlier, central to the SSHAC Level 3 process are three Workshops. These workshops were all of at least one week's duration, and all were held in South Africa. A large number of

Resource and Proponent Experts were invited to participate in the workshops to present datasets or models of potential relevance to the seismic characterization; the Proponent Experts are listed in Table 1.

Table 1: Proponent Experts participating in Workshop #2.

| <b>Name and Affiliation</b>  | <b>Topic of Presentation at Workshop #2</b>  |
|--|--|
| Marco Andreoli<br>Necsa, South Africa  | Implications of neotectonic evidence in the Eastern Cape Region (SSC)  |
| Paul Bierman<br>University of Vermont, USA   | Cosmogenic geochronology investigations for uplift rates and ages of surfaces: Implications for the tectonic stability and geomorphic evolution of Southern Africa (SSC) |
| Hayley Cawthra<br>GCS, Bellville, South Africa   | Depositional and erosional processes occurring on the continental shelf and slope: Implications to causative mechanisms and origins of seafloor features (SSC)           |
| Coenie de Beer<br>GCS, Bellville, South Africa   | Tectonic interpretation of the Ceres earthquake area and implications to the locations of future seismicity (SSC)  |
| Ray Durrheim<br>Wits University, Johannesburg / CSIR   | Regional crustal studies and implications for seismotectonic models (SSC)  |
| Marc Goedhart<br>Kainos South Africa, South Africa   | Palaeoseismic characteristics of the Kango fault and associated uncertainties, Coega fault style and potential CFB SSZs (SSC)  |
| Chris Hartnady<br>Umvoto, South Africa   | Seismotectonic model for southern Africa and implications of tectonic features to seismic hazard (SSC)   |
| Andrzej Kijko<br>Aon Benfield Natural Hazard Centre,<br>University of Pretoria, South Africa | $M_{max}$ and its estimation (SSC)   |
|  | Ground-motion prediction equations for South Africa (GMC)  |
| Bob Youngs<br>AMEC, Oakland, USA   | Bayesian approach to assessing $M_{max}$ for PSHA (SSC)  |
|  | Recurrence model options and incorporation of catalogue-related uncertainties (SSC)  |
| Martin Brandt*<br>CGS, Pretoria, South Africa  | Constraints on the processes giving rise to the African Superswell (SSC)   |
| Linda Al Atik<br>Independent consultant, CA, USA   | Evaluation of $V_s$ -kappa scaling using IRVT and empirical ground-motion data (SSC)   |
| Kenneth W. Campbell<br>EQECAT, Inc., Beaverton, Oregon, USA                                  | The hybrid-empirical method for developing ground-motion prediction equations (GMC)  |
| Oona Scotti<br>IRSN Institut de Radioprotection de<br>Surete Nucleaire, France               | Inferring geometrical spreading from the attenuation of macroseismic Intensity with distance (GMC)   |
| Trevor Allen<br>Geoscience Australia, Canberra, Australia                                    | Similarities and differences in SCR ground motions inferred from instrumental recordings (GMC)   |

\*Presenting an overview of several Proponent Experts' positions

In accordance with SSHAC guidelines, the full PPRP was present in all Workshop sessions, and in keeping with the guidance in NUREG-2117, the Panel members suspended their observer status at Workshop #3 and directly posed questions to the TI Teams regarding the technical bases for the preliminary SSC and GMC models. Representatives from the NNR were present at all the Workshops as well, which allowed the regulator to observe the process and the development of the PSHA models.

In order to share the experience of this implementation of the SSHAC Level 3 process, representatives from regulatory bodies and nuclear utilities from around the world were invited to attend Workshop #2 as observers. In response to these invitations, delegates from Brazil, Finland, Sudan and the UK attended as observers and subsequently provided Eskom with feedback on their impressions.

## PROJECT DATABASES AND MODEL BUILDING

The core activity of a SSHAC Level 3 study is to assemble all available data and models for a region and a site, which the TI Teams then evaluate in terms of their quality, completeness and relevance. On the basis of this evaluation, the TI Teams then proceed to the integration phase, in which logic-trees are constructed that represent the best estimates for each element of the input to the PSHA calculations, together with the inferred distribution of epistemic uncertainty. This objective, as expressed in NUREG-2117, is to capture the center, the body, and the range of technically-defensible interpretations (or the CBR of the TDI).

### *Database Compilation and Analyses*

Epistemic uncertainty reflects lack of knowledge regarding earthquake processes and seismic ground motions, both in general and in the specific setting that the hazard assessment is being made. A degree of epistemic uncertainty in seismic hazard studies is unavoidable, since there will always be several defensible interpretations of the available data, and the PSHA calculations will need to consider scenarios that are not represented in the data at all. Both of these statements are particularly true for a region of relatively infrequent earthquake activity like South Africa. For this reason, and in order both to develop the best models possible and to constrain the associated epistemic uncertainty, it is considered imperative to begin by compiling databases including as much of the available information as possible.

For the SSC TI Team, a major database was compiled of papers and reports related to the tectonics, geology and seismology of Southern Africa, the site region, and analogous regions worldwide. These publications were studied by the TI Team members, who then produced Data Summary Tables so that the entire Team could make easy reference to the available information.

Another key SSC-related activity was to compile an earthquake catalog, using all available information from instrumental sources (primarily the SANSN but also regional and global agencies) and published reports on historical events. The development of the catalog required extensive analyses to merge the data from these diverse sources, homogenize the magnitudes (in terms of moment magnitude,  $M_w$ ), remove foreshocks and aftershocks (and also to remove events of anthropogenic origin, especially mining-related seismicity), and assess the completeness periods of the record for different magnitudes. The seismologists in the SSC TI Team were assisted in these tasks by Specialty Contractor Dr Céline Beauval from the Université Joseph Fourier in Grenoble, France. Focal mechanisms for South African earthquakes were also compiled as part of this effort, and waveform modeling was used to calculate focal depths (which are generally fixed in routine CGS locations).

A database of intensity observations, including published isoseismal maps, macroseismic questionnaires distributed by CGS and its predecessor organization (the Geological Survey of South Africa), and newspaper reports. The latter two data sources were re-interpreted to assign intensities to many locations affected by earthquakes for which instrumentally-determined source parameters were available. These newly-assigned values, combined with those taken from published maps, created a set of more than 1,000 intensity data points (IDPs). These IDPs were used by the SSC TI Team to calibrate empirical relationships to assign locations and magnitudes to pre-instrument earthquakes, and by the GMC TI Team to explore the range of amplitudes covered by the ground-motion predictions.

Another component of the GMC database was derived from 50,000 waveforms from the SANSN, which were analyzed by Specialty Contractors Prof. Andreas Rietbrock of the University of Liverpool and Dr Stéphane Drouet from GEOTER in France. These analysts independently carried out stochastic inversions of the weak-motion data, which provided information regarding stress drops and attenuation characteristics of ground motions in South Africa. Recordings from particular stations were also analyzed to estimate the near-surface attenuation parameter, kappa ( $\kappa$ ).

As valuable and informative as these various databases were, it was clear from an early stage of the project that considerable additional constraint on the both the SSC and GMC models could be obtained from carefully targeted activities to collect new data. Although new data collection is not

necessarily required as part of the SSHAC process, it is strongly encouraged in NUREG-2117 when it is likely to lead to appreciable reductions in uncertainty.

### ***New Data Collection***

A major data collection exercise for the Thyspunt PSHA were geological investigations designed to estimate regional uplift and deformation rates, on the one hand, and to assess the earthquake potential of a number of mapped geological faults on the other. The key activities were marine terrace studies and fault corridor studies, the latter involving trenching, and both activities leading to the recovery of numerous rock samples that were dated using a variety of techniques. These studies provided conclusive evidence that allowed five faults (Baviaanskloof, eastern Coega, western Coega, Kouga and Cape St. Francis) to be definitively classified as non-seismogenic. The findings also led to the assignment of low seismic probabilities to four other faults (Gamtoos, Plettenberg, Worcester and Agulhas) while the Kango fault in the western Cape, the only recognized Quaternary fault in South Africa, was confirmed as a clearly active structure.

Although the first seismograph was installed in South Africa in 1899, instrumental recording of earthquakes has developed relatively slowly: in 1970, the national network consisted of just 7 stations. In order to extend the earthquake catalog back in time, Dr Paola Albini of INGV in Milan, Italy, was engaged as a Specialty Contractor retrieve historical accounts of earthquakes in South Africa and in particular in the Eastern Cape Region. Using information obtained from newspaper and other archives in South Africa and Europe, Dr Albini and her co-workers compiled more than 300 macroseismic observations at 225 locations for 27 earthquakes that occurred between 1850 and 1936. These included eight new earthquakes that were previously unknown, and also helped to identify two earthquakes listed in some catalogs as fakes. In addition to the information on these earthquakes, the historical study established completeness and detection thresholds for different locations and periods, which provided a basis for confirming that the apparently low seismicity of the Eastern Cape Province as being genuine rather than due to events having gone undetected or having not been reported.

For the GMC database, the key new data collection activity was characterization of the shear-wave velocity ( $V_s$ ) profiles at the Thyspunt site. Active and passive MASW measurements were made at the site, but with the energy sources that were permissible under environmental and archaeological restrictions, these did not provide adequate resolution for the Goudini bedrock at the site because of the thick overlying layers of sand. Excellent data were obtained from PS logging in 26 boreholes on the site, some of which reached depths of 100m. The  $V_s$  measurements were viewed as being indispensable since there were no data available regarding the dynamic characteristics of the site, and this would have been a major source of uncertainty in the ground-motion model in the absence of quantitative data.

### ***Developing the SSC and GMC Logic-trees***

With the full databases compiled, and informed by the presentations made by Resource and Proponent Experts at Workshops #1 and #2, the TI Teams were able to carry out their evaluations and then develop the logic-trees to represent the CBR of the TDI. Although the Workshops are a vital part of the SSHAC process, and provide the opportunity for the process to be observed by the full PPRP, the sponsor and the regulator, the main effort of the TI Teams is made outside of the meetings through concerted and sustained work on the development and analysis of the databases. Much of that work is performed by the TI Team members working individually or in small groups, but since collective ownership of the final models by the full Team is an essential requirement of the SSHAC process, key features of the process are focused Working Meetings where all the individual contributions are presented and discussed. The technical challenge and defense that naturally occurs among the TI Team members in these meetings as a consensus logic-tree is constructed is an invaluable part of the SSHAC Level 3 process. Each TI Team held four Working Meetings (in addition to large numbers of conference calls and informal meetings between individual team members) throughout the duration of the project. As a result

of the geographical distributions, different locations were selected for these meetings: the SSC TI Team held two meetings in Pretoria and two in San Francisco; the GMC TI Team held one meeting in San Francisco, another in Potsdam, and two in London. One member of the PPRP, a representative from Eskom and the Project Manager were present as observers at all of the Working Meetings.

The preliminary SSC and GMC models were developed through two Working Meetings in between Workshops #2 and #3. Extensive hazard sensitivity calculations were then performed, showing how different branches of the logic-trees impacted the hazard estimates and to identify the elements of uncertainty contributing most strongly to the overall results. These results were presented at Workshop #3 with the purpose of allowing the TI Teams to identify those elements of the models most warranting further consideration and refinement. In accordance with NUREG-2117, Workshop #3 also provided the PPRP with the opportunity to question the Teams regarding their preliminary models. On the basis of all the feedback received at Workshop #3, the TI Teams then engaged in additional analyses prior to their fourth and final Working Meetings to develop the final SSC and GMC models, and to plan the documentation of these models and their technical bases.

## HAZARD CALCULATIONS AND PRESENTATION OF THE RESULTS

Although the target elevation for the design ground motions is on rock (at the top of the Goudini formation underlying the Thyspunt site, with  $V_{s30} \sim 1,700$  m/s), it was decided that in order to capture and accurately model the influence of any near-surface impedance contrasts, the hazard would first be calculated at a deeper horizon within the bedrock (with  $V_s \sim 3$  km/s), and then transferred to the surface through site response analyses. This also has the advantage of allowing the basic GMC model to be applied at other sites. In order to accurately preserve the annual frequencies of exceedance calculated at the bedrock level, it was decided to use the fully probabilistic convolution of bedrock hazard and site response, generally referred to as Approach 3 (McGuire et al., 2001). This approach also allowed sufficient randomization of the dynamics properties defining the site response profile to allow the GMC model to invoke the concept of single-station sigma (Rodriguez-Marek et al., 2012).

The final SSC and GMC logic-trees were distilled into HIDs (Hazard Input Documents) which convey the essential information to completely define the models without any explanation of their technical bases. The HID was passed to the Hazard Calculation Team at CGS, who performed the PSHA calculations using the FRISK88 software from Risk Engineering Inc. This software was selected because it has been qualified for nuclear applications in the United States. In order to check the implementation of the logic-trees, several exercises were conducted, including some independent hazard calculations performed using the *OpenQuake* software developed in the GEM (Global Earthquake Model) project. In the first stage, the GMC model was implemented in both FRISK88 and *OpenQuake*, as well as in a third independent implementation at BRGM in France. Spectral accelerations were calculated for 6,500 scenarios (magnitude-distance-oscillator period-style of faulting-GMC branch combinations), and the 3-way checks iterated until exact convergence was achieved. The SSC model was then implemented in FRISK88 and *OpenQuake*, and hazard curves calculated for 15 subsets of the total logic-tree, each sampling all the branches associated with an individual source and a single GMC branch; six of the test cases were based on the critical host source zone in which the site is located. Exact agreement was not expected due to differences in the way each program performs the hazard integration (Thomas et al., 2010), but very good agreement was obtained for all 15 cases, with only minor differences between the outputs from the two programs (with neither being consistently higher than the other).

Once these tests were completed, the full set of hazard runs for bedrock were executed, yielding mean and fractile hazard curves in the bedrock for a series of oscillator periods agreed with Eskom (Figure 4). The spread of the hazard fractiles, and the separation of the mean and median curves, reflect the degree of epistemic uncertainty that was captured in the SSC and GMC logic-trees. The mean hazard at selected periods was then disaggregated following the guidelines of RG 1.208 to define the input to the site response analyses, which yielded site amplification factors that were then convolved with the rock hazard to obtain seismic hazard curves at the surface elevation. Uniform hazard spectra and the design

basis GMRS were then determined from these hazard curves, and the vertical response spectra obtained by application of suitable V/H ratios. Disaggregations of the hazard were developed at all the target oscillator periods and for annual exceedance frequencies of  $10^{-4}$ ,  $10^{-5}$  and  $10^{-6}$ .

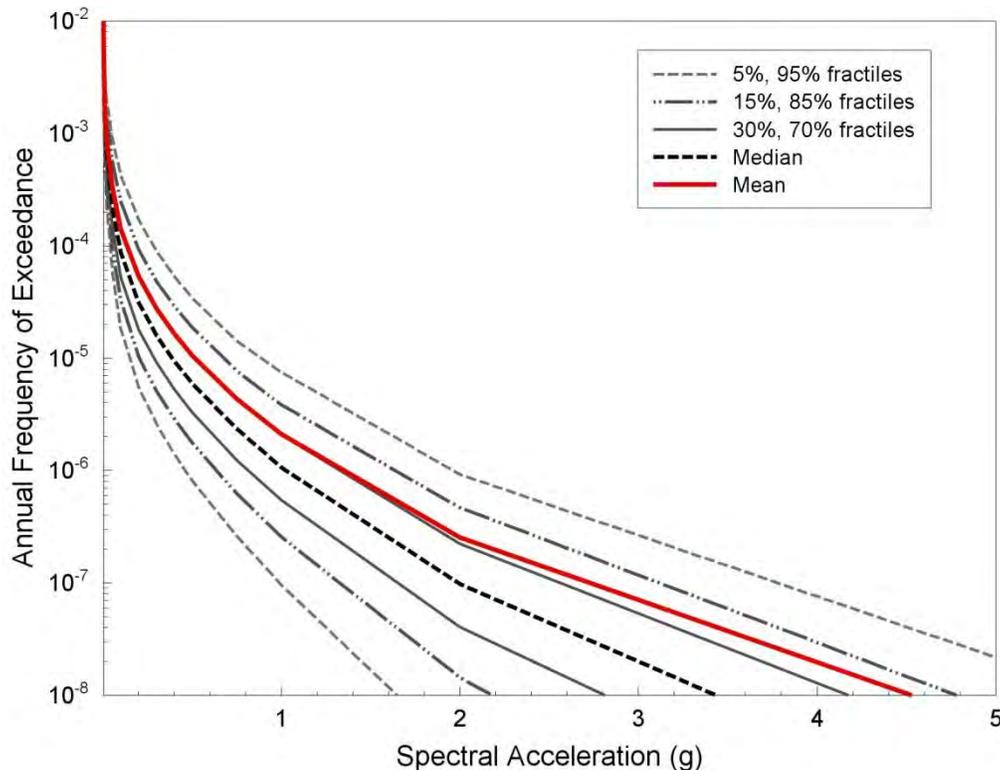


Figure 4. Seismic hazard curves in the deep bedrock horizon for spectral accelerations at a response period of 0.1s. The design motions at the surface elevation are obtained through convolution of these hazard curves with site amplification factors.

The final report on the PSHA project documented the project structure and organization, the process followed, the databases compiled and evaluated, the development of the SSC and GMC models, and the hazard results. In addition to the full report, an appendix of electronic supplements was prepared containing all of the supporting and background information that led to the development of the final PSHA input models, including reports on the geological investigations, the historical earthquake investigations, the earthquake catalog, the intensity database, and the stochastic inversions of the weak-motion data, as well as all the SSC Data Summary and Evaluation Tables, and the full reports from the Workshops, including the agendas, all presentations, the PPRP comments and the responses to these comments from the TI Leads. The supplements also included the hazard results in digital format, and detailed reports of the V&V (verification and validation) exercises.

The final draft report was submitted to the PPRP for review, and then revised together with comprehensive responses to these comments; the revised report and the responses were then submitted to the PPRP for final approval. At this stage, the PPRP issued its final closure letter, which is included as an appendix to the final report (as are the HID and the CVs of project participants).

In order to convey and explain the models and the hazard results, the PTI presented the study to the NNR at meetings in South Africa in January and June 2013. Additionally, a meeting has been arranged between the PPRP and the NNR for October 2013, to provide an opportunity for the regulator to discuss the project and its findings with the independent reviewers. This meeting will take advantage of a meeting in Pretoria, sponsored by Eskom and hosted by CGS, in which the TI Teams, PPRP and other

invited participants will gather to review the project and record lessons learned, particularly with a view to the planned hazard assessments for characterizing other sites in South Africa.

An overview of the technical aspects of the project, including greater details regarding the databases and the developments of the SSC and GMC models, is presented in Bommer et al. (2013).

## ACKNOWLEDGMENTS

The success of the Thyspunt PSHA project was made possible through the contributions and collaborations of many organizations and individuals. Some of these people are named in this paper (including those in Figure 2 and Table 1), but there are many others who made equally valuable contributions to the overall success of the project, including staff at CGS, Eskom, SRK Consulting (South Africa) Ltd., the GEM Foundation and BRGM (for the independent hazard checks), the Institute of Mining Seismology (for the passive MASW measurements), Park Seismic (for interpretation of the MASW), and Robertson Geologging for the PS logging at the site, among many others. The full list of acknowledgments in the final project report runs over several pages (and would almost fill the full length this paper). The purpose of this section, therefore, is not to attempt the impossible task of offering suitable expressions of thanks to everyone who contributed to the project, but to clarify that the absence of suitable individual acknowledgments is due only to the lack of space and not any lack of gratitude and appreciation.

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