

UPDATING THE SEISMIC DESIGN GUIDANCE FOR HMNB CLYDE

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Abstract: *The seismic design hazard at His Majesty's Naval Base (HMNB) Clyde is quantified as a design response spectrum (DRS) applicable at the top of bedrock. For many years, the PML hard site spectrum was used as the DRS. In 2017, a probabilistic seismic hazard assessment was completed for the site, producing a site-specific uniform hazard response spectrum (UHRS). Further studies were carried out to convert the UHRS into a new site-specific DRS with matching ground motion histories (GMHs). The seismic design guidance document (DGD) for HMNB Clyde was also updated to take account of developments in modern standards and regulatory expectations. This paper describes some of the key issues that were addressed in the development of the new DRS, the GMHs and the DGD. The paper provides an overview of the new seismic design hazard, which – perhaps for the first time in UK context – distinguishes between different definitions of horizontal response spectra. A shortfall in GMHs is identified, and two remedies are proposed. The paper outlines the role of operating, design and beyond design basis earthquakes in the context of the nuclear safety case for the site. The paper touches on the topic of topographic amplification. Finally, the paper offers some reflections on the whole process and gives recommendations for future work.*

Introduction

The fundamental definition of the seismic design hazard at His Majesty's Naval Base (HMNB) Clyde² is a design response spectrum (DRS). The DRS shows the peak response of an ensemble of independent single degree-of-freedom systems situated on the top of outcropping bedrock when excited by earthquake excitation. The DRS does not represent the motions of a single earthquake; rather, it should be viewed as an envelope of possible motions from earthquakes associated with a certain probability of exceedance within a defined timeframe. Various other representations of the design hazard are derived from the fundamental definition, including ground motion histories (GMHs) and in-structure response spectra (ISRS), the latter being used for seismic qualification of plant and equipment within the nuclear safety implicated (NSI) facilities on site.

Historically, the Principia Mechanics Ltd (PML) hard site spectrum (PML, 1981) anchored to 0.20g or 0.25g peak ground acceleration (PGA) was used as the fundamental DRS. Occasionally, the PML medium and soft site spectra were also used, depending on the local ground conditions. The PML spectra formed the basis of the seismic substantiation of the Northern Area facilities in Faslane and the Trident facilities in Coulport when the facilities were designed and built in the 1980s and 1990s.

The PML spectra continued to underpin the seismic substantiation for another two decades. However, as the discipline of engineering seismology developed, the absence of a site-specific seismic hazard study was noted. Some of the methods used to perform the first seismic assessments of the NSI facilities on site also began to show their age. As a result, in 2012 a process was instigated with an aim to update the seismic safety substantiation for the NSI facilities in line with modern standards and relevant good practice.

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² HMNB Clyde comprises two sites: Faslane and Coulport. However, this paper mostly refers to HMNB Clyde as single site.

As a first step in this process, a site-specific probabilistic seismic hazard assessment (PSHA) covering HMNB Clyde was undertaken. Further studies were then carried out to develop a new DRS with due cognisance of guidance issued by the Office for Nuclear Regulation (ONR). Five sets of DRS-compatible GMHs were also developed. The new design motions were published in an update to Appendix A of Design Guidance Document (DGD) 505 (HMNB Clyde, 2020).

The main aim of this paper is to present an overview of the key issues that were encountered in the development of the new seismic design hazard. The paper focusses on the DRS, the GMHs and the contents of DGD 505 Appendix A. The paper also touches on the transition from the old PML spectrum to the new DRS and some of the issues that arose during the transition – including the concept of so-called interim ISRS, which is explained below. Finally, the paper offers some reflections on the whole process and gives recommendations for future work.

Probabilistic seismic hazard assessment

Between 2012 and 2017, a comprehensive site-specific PSHA (ABS Consulting, 2017) was undertaken to reassess the seismic hazard at HMNB Clyde. The work was performed in accordance with modern techniques and standards prevalent at the time, including International Atomic Energy Agency (IAEA) Specific Safety Guide SSG-9 (2010). The PSHA was intended to address recent Periodic Review of Safety findings related to the absence of a site-specific study underpinning the PML hard site spectrum, which until then had been used as the fundamental DRS for HMNB Clyde. Key aspects in PSHA were the use of modern data and seismic hazard models, expert elicitation, logical treatment of uncertainties, sensitivity studies, and peer review and oversight.

The PSHA produced a series of 5% damped uniform hazard response spectra (UHRS) at different annual exceedance probabilities and different confidence levels. Figure 1 shows an example of the UHRS for Faslane and Coulport. The PSHA also produced a series of seismic hazard curves for the spectral accelerations at 1 Hz and 25 Hz, and the PGA. A sample of the hazard curves is shown in Figure 2.

Crucially, the PSHA results indicated a significant shift of the peak spectral acceleration to higher frequencies. In the PML hard site spectrum, the peak region is between 5 and 12 Hz; in the new UHRS, the peak region is centred around a frequency of 25 Hz. The new high frequency spectrum reflects the influence of local ground conditions on the seismic motions. HMNB Clyde is underlain by a geological unit known as the Beinn Bheula Schist formation, which is a hard rock characterised by a high shear wave velocity (a best estimate of 2,100 m/s in the upper 30m). These conditions produced the greatest spectral accelerations in the frequency region around 25 Hz.

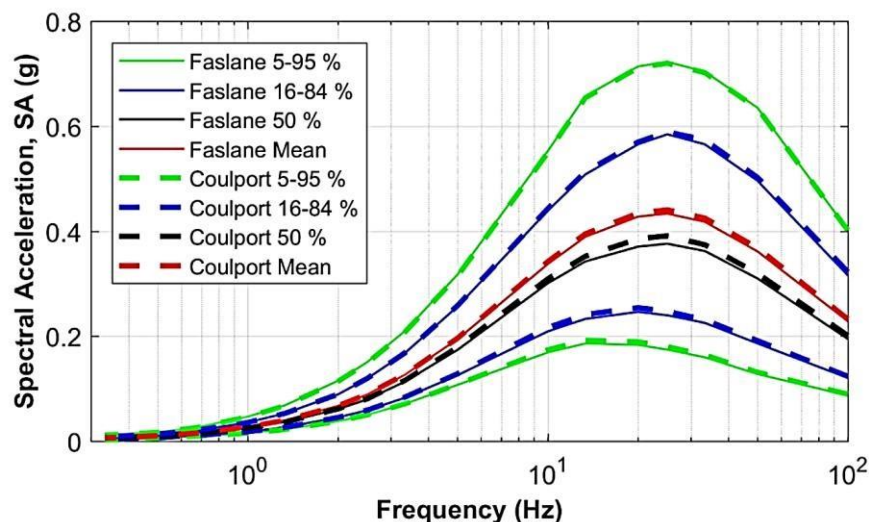


Figure 1. Horizontal UHRS for HMNB Clyde, 10^{-4} annual probability of exceedance (ABS Consulting, 2017)

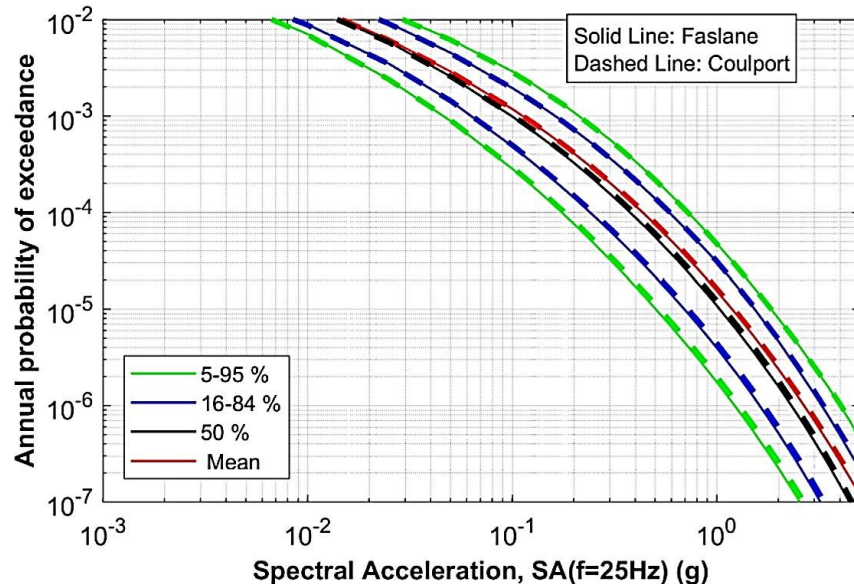


Figure 2. Hazard curves for horizontal spectral acceleration at 25 Hz (ABS Consulting, 2017)

Development of a new design response spectrum

After the publication of the PSHA report in 2017, work was instigated to review the PSHA results and produce recommendations for a new site-specific DRS and GMHs. This work was largely complete in 2020. The following subsections provide an overview of the work.

Horizontal DRS at 5% damping

ABS Consulting (2019) developed the new DRS with due cognisance of ONR guidance (ONR, 2018). As shown in Figures 1 and 2, the PSHA results indicated little difference between Faslane and Coulport in terms of the seismic hazard at the two sites, so a decision was made to envelope the UHRS for the two sites. The horizontal DRS at 5% damping and 10^{-4} annual probability of exceedance was computed as an envelope of four spectra:

- the enveloped UHRS at 90% confidence level;
- the PML hard site spectrum anchored to 0.10g PGA;
- a recently published response spectrum for very hard rock (Dalguer & Renault, 2017), also anchored to 0.10g PGA; this spectrum is referred to as “EUR hard site spectrum”;
- and a DRS computed in accordance with ASCE 43-05.

The UHRS at 90% confidence level was adopted to provide a suitable level of conservatism in the definition of seismic design motions in line with the expectations of the ONR (2018).

There is a regulatory expectation that NSI facilities should be able to resist a minimum level of strong ground motion irrespective of the results derived from a PSHA. The IAEA and the Western European Nuclear Regulators Association (WENRA) identify this minimum as a “horizontal freefield standardized response spectrum anchored to a PGA value of 0.1g” (ONR, 2018). The PML hard site and the EUR hard site spectra were included in the enveloping process to ensure that the new DRS would not fall below this minimum level.

Finally, another regulatory expectation is to demonstrate that there is no abrupt change in the seismic hazard curve below the 10^{-4} annual probability of exceedance. Inspection of the hazard curves in the PSHA report (ABS Consulting, 2017) did not indicate any rapid change in spectral acceleration below the 10^{-4} mark (cf. Figure 2). Nevertheless, recognising that the ASCE 43-05 DRS accounts for the slope of the hazard curve, it was decided to include this DRS in the enveloping process.

Figure 3 shows the variation of spectral velocity for this new composite DRS between 0.1 and 10 Hz. Using colours, the figure shows the frequency bands where each of the constituent response spectra is enveloping. Above 10 Hz, the UHRS is always enveloping.

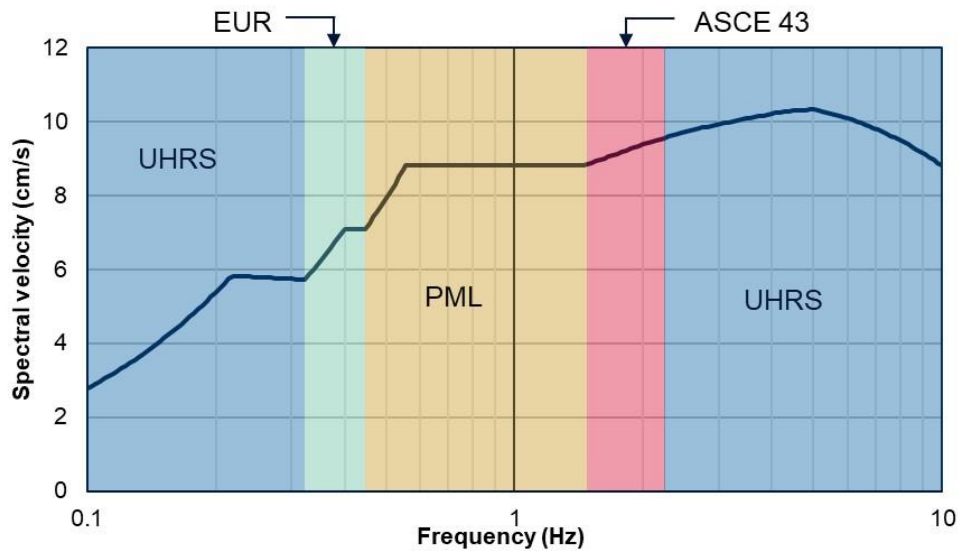


Figure 3. Composition of the new DRS at 5% damping

The new DRS is compared to the PML hard site spectrum in Figure 4. This figure clearly shows the shift to higher frequencies of the peak spectral acceleration. As the legend indicates, the definition of the DRS in this figure is maximum component (MC). What this means will be explained next.

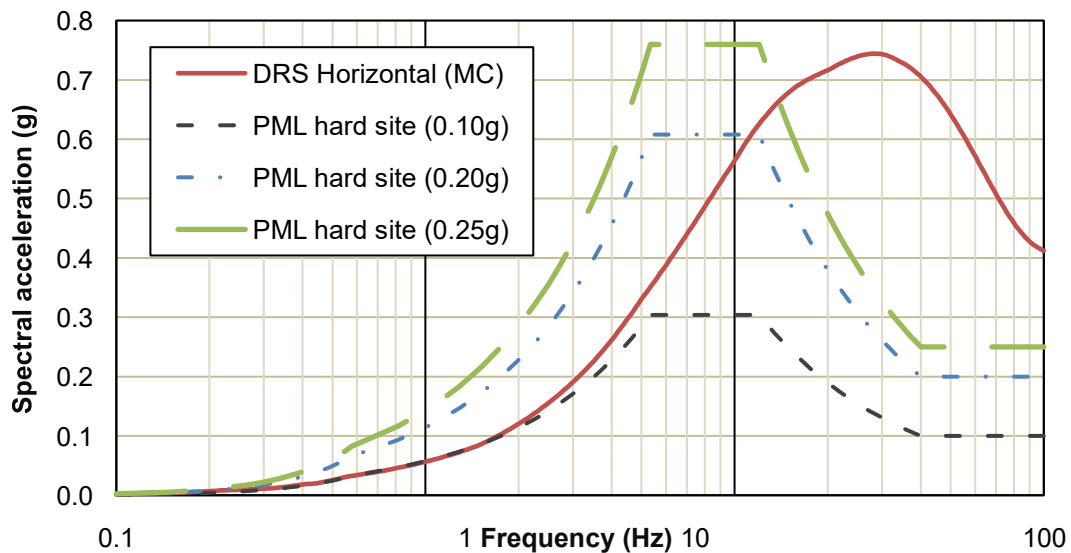


Figure 4. Comparison of new DRS with PML hard site spectra (5% damping)

Definition of the horizontal component

One of the key changes introduced in the new DRS definition is a distinction between the geometric mean (GM) and the MC, which are two different, but equally valid, definitions of the horizontal spectral acceleration. Formally, an accelerometer located at any point will measure three perpendicular motions during an earthquake: two horizontal and one vertical. The two horizontal motions (measured along the X- and Y-axis, respectively) can be converted to two response spectra S_x and S_y . The GM spectrum is then computed as the square root of the product of S_x and S_y . The MC spectrum is the maximum of S_x and S_y . In this manner two orthogonal motions can be condensed in a single response spectrum although some information is lost in the process.

The UHRS were developed as GM spectra. However, it is not necessarily conservative to use a GM spectrum for design purposes. Moreover, the PML spectra, which had been used for many decades at HMNB Clyde, were defined as MC spectra. A GM spectrum is not directly comparable to an MC spectrum. A decision was therefore made to derive a formula that would convert a GM spectrum to an MC spectrum and, through inversion, an MC spectrum to a GM spectrum. This formula is (ABS Consulting, 2019):

$$S_{MC}(f) = \Omega(f) S_{GM}(f) \tag{1a}$$

$$\Omega(f) = \Omega_0 + \sum_{i=1}^n \frac{\Omega_i}{f_i} \frac{1}{f} \frac{1}{f_i} (i+1) \log(\log(f/f_i)) \tag{1b}$$

where f is frequency, $S_{MC}(f)$ is spectral acceleration defined as MC, $S_{GM}(f)$ is spectral acceleration defined as GM, $\Omega(f)$ is the conversion factor, and f_i and Ω_i are constants given in Table 1.

i	f_i (Hz)	Ω_i
1	0.10	1.270
2	0.36	1.195
3	2.22	1.182
4	12.5	1.135
5	100	1.149

Table 1. Constants used in the GM-to-MC conversion formula (Equation (1b))

It should be noted that Equation (1) was developed specifically for HMNB Clyde; it not necessarily applicable to other sites.

DRS at other damping levels

The fundamental DRS was derived for 5% damping. The DRS at other damping levels ranging from 0.5% to 10% were developed by ABS Consulting (2020a). The DRS at those other damping levels were computed by applying a frequency-dependent damping scaling factor (DSF) to the DRS at 5% damping. The DSF was largely based on the work by Rezaeian *et al* (2012) with some adjustments to cater for the relatively high frequency of the spectral peak in the DRS. The DSF computed in this manner was validated by comparison to results from time history analyses.

Vertical DRS

The vertical DRS was derived by applying the vertical-to-horizontal (V/H) ratios from the PSHA report to the horizontal DRS at all damping levels.

Development of ground motion histories

Five sets of DRS-compatible GMHs were also developed (ABS Consulting, 2020b). The GMHs were based on a suite of real strong motion accelerograms which had been obtained from the PEER Ground Motion Database and selected as suitable candidates. The accelerograms had been recorded on sites in the western USA and Italy. The accelerograms were modified and, in this process, matched to the target response spectra (the horizontal GM DRS and the vertical DRS), thus creating a suite of GMHs. The software used for this purpose was RspMatch09 (Al Atik & Abrahamson, 2010). Finally, the GMHs were checked against the acceptance criteria described in Section 2.4 of ASCE 43-05 and found to be generally compliant.

The modified GMHs were defined with 0.005 second time step, giving a Nyquist frequency of 100 Hz. They were characterised by total durations between 28.3 and 40 seconds, which, at least in this author’s experience, is relatively long compared to other GMHs typically used in the UK nuclear industry. However, the strong motion durations as measured by the 5-75% Arias intensity were relatively short, with values between 1.2 and 4.9 seconds. A typical GMH is shown in Figure 5. This GMH has a strong motion duration of 3.9 seconds, and it is characterised by two spikes of relatively high acceleration.

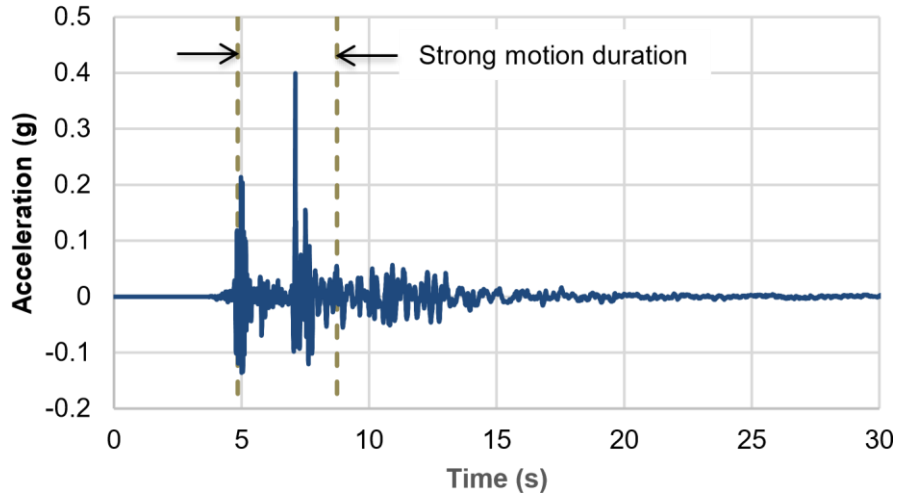


Figure 5. Typical GMH (ABS Consulting, 2020b)

The mean GM and MC response spectra computed from the suite of horizontal GMHs are plotted together with the target response spectra (the GM DRS and the MC DRS) in Figure 6. The mean GM response spectrum matches the GM target quite well and satisfies the acceptance criteria in ASCE 43-05 over the range of frequencies of engineering interest. However, the mean MC response spectrum falls short of the MC target. This shortfall, which was discovered only after the GMHs had been finalised, is discussed further below.

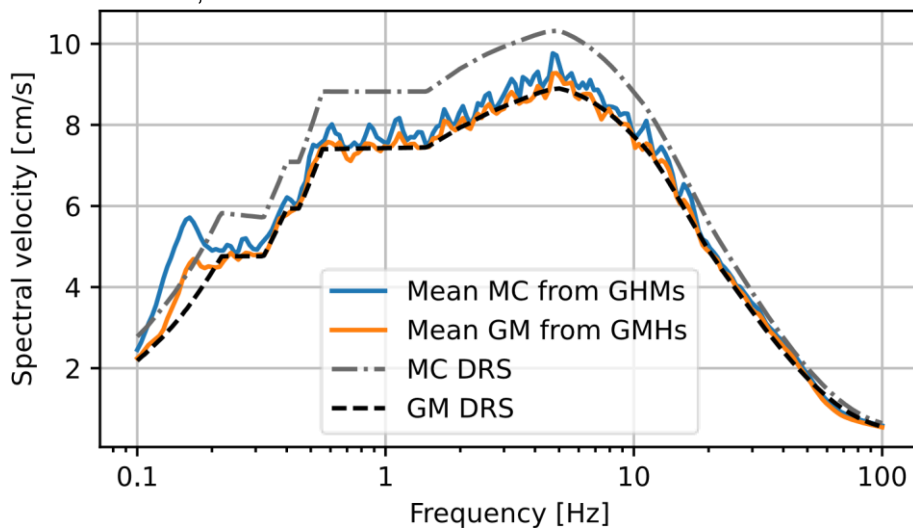


Figure 6. Comparison of horizontal DRS with mean response spectra from original GMHs.

As noted above, the horizontal GMHs were matched to the GM DRS, which was chosen as target. They were in fact matched too "tightly" to the target. Ideally, the GMHs should have been selected and modified such that the mean MC response spectrum is matched to the MC DRS and such that the mean GM response spectrum is matched to the GM DRS. Unfortunately, the mean MC response spectrum falls below the mean MC DRS consistently over all frequencies. Two remedies are proposed to address this shortfall, as described next.

The first remedy is theoretically the more satisfying. We have five sets of GMHs. For each set, we take the two horizontal components (A_x, A_y), transform each component into frequency domain using a discrete Fourier transform FT and obtain the complex Fourier coefficients (C_x, C_y):

$$(C_x, C_y) = FT A A(x, y) \quad (2)$$

We then modify the Fourier coefficients, creating two sets of data:

$$(D_x, D_y) = (C_x, -1C_y) \quad (3)$$

$$(E_x, E_y) = (-1C_x, C_y)$$

where $\square = \square(f)$ from Equation (1b). It should be noted that Equation (1b) was developed for conversion of response spectra, not Fourier spectra. However, the formula seems to work equally well on Fourier spectra. We then transform the data back into time domain using an inverse Fourier transform *IFT*:

$$(A_{X \gamma, A}) = IFT \square(D_{X \gamma, D}) \square \tag{4}$$

$$(B_{X \gamma, B}) = IFT \square(E_{X \gamma, E}) \square$$

It is only necessary to modify the horizontal components in this manner; the vertical component is not modified. For each original set of GMHs, we now have two modified sets: in the first set, the X component has been factored up and the Y component has been factored down, whereas in the second set, the X component has been factored down and the Y component has been factored up. Performing this operation on each original set generates a new suite of ten modified sets. The mean GM and MC spectra from the modified suite are plotted in Figure 7, which shows that we have preserved the match to the GM target and improved the match to the MC target.

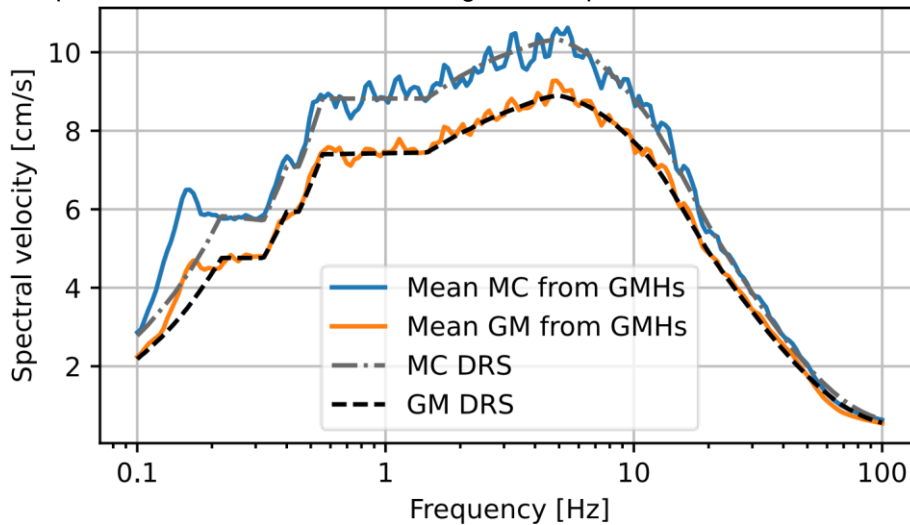


Figure 7. Comparison of horizontal DRS with mean response spectra from modified GMHs (first remedy)

The second remedy is simpler. Here we simply factor all horizontal GMHs by a time- and frequency-independent factor of 1.15. This does not increase the number of sets as the first remedy did. Figure 8 shows that the match of the mean MC spectra is good; however, the match of the GM spectra is now poor as expected.

The first remedy would be suitable for both linear and non-linear analysis. However, implementing the first remedy would double the number of analysis runs that in most cases would have to be completed. The second remedy is simpler and demonstrably conservative in the context of linear analysis, but it might not be suitable for non-linear analysis.

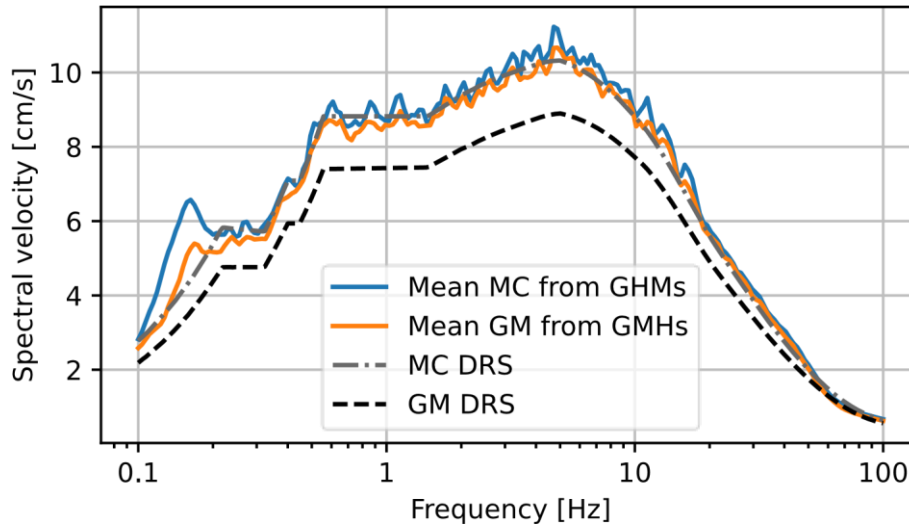


Figure 8. Comparison of horizontal DRS with mean response spectra from modified GMHs (second remedy)

The new Appendix A of DGD 505

The new DRS and the GMHs are formally presented in Appendix A of HMNB Clyde's guidance document for environmental and accidental hazards, DGD 505 (HMNB Clyde, 2020). The main purpose of Appendix A is to define the seismic design hazard. The document also provides some guidance on seismic design and assessment of structures, systems and components (SSCs) within the context of nuclear safety. This section summarises a few salient aspects of the document.

Consideration of different intensity levels for seismic performance

In a nuclear safety case, the safety functional requirements (SFRs) form a fundamental link between high-level safety claims placed on SSCs and their detailed technical substantiation. The SFRs should be detailed enough that the seismic performance requirements can be derived. Generally, the SFRs may require consideration of multiple levels of seismic intensity. These different levels are:

- Design basis earthquake (DBE)
- Operating basis earthquake (OBE)
- Beyond design basis earthquake (BDBE)

The DBE is an event with a nominal 10^{-4} annual probability of exceedance. The DRS and the GMHs are considered to equal or bound the DBE motions on outcropping bedrock with a high degree of confidence. Therefore, the DRS and the GMHs may be used as DBE motions. Consideration of the DBE is typically required for SSCs whose failure could give rise to an unacceptable radiological consequence. The safety functions of such SSCs must be assured during and after a DBE.

Under some circumstances, events with a higher probability of exceedance, and therefore lower values of spectral accelerations, can be used to define DBE motions provided proper safety justification is made. These circumstances include the justification of SSCs with limited remaining life, or SSCs with a low radiological inventory. However, the latest revision of Appendix A offers no direct route to deriving the motions for events with probabilities of exceedance between 10^{-4} and 10^{-2} per annum. This might be rectified in future revision if the need arises.

The OBE represents an event with a nominal 10^{-2} annual probability of exceedance. As such, the OBE is an event deemed likely to occur at least once in the life of the base. The OBE for HMNB Clyde is defined as 20% of the DBE. This reduction applies to the DRS and the GMHs. Theoretically, for OBE, the shape of the UHRS on which the DRS is based could change as different events of different magnitudes and different source-to-site distances become more dominant. However, this would complicate direct scaling of motions. Defining the OBE as a percentage of the DBE avoids such issues and is considered appropriate since the OBE is rarely critical in the technical substantiation of SSCs.

Consideration of the OBE may be required for certain SSCs depending on their seismic performance requirements and their sensitivity to seismic excitation. Typical considerations

include continued functionality of safety-related SSCs under repeated occurrences of ground motions at OBE level, and plant shutdown (e.g. by means of seismic trigger systems).

The BDBE is not defined as an event with a specified probability. Rather, the BDBE is defined as a rare, but possible, earthquake exceeding the DBE. The BDBE accounts for the contribution of events greater than the DBE to the overall risk of failure. Consideration of BDBE is also motivated by the uncertainty inherent in engineering modelling and the requirement to confirm the absence of cliff-edge effects just beyond the design basis (ONR, 2014 & 2018). DGD 505 Appendix A provides further guidance on the beyond design basis assessment.

Topographic amplification

The DRS and the GMHs represent ground motions that are applicable at the top of a flat uniform site (they are so-called free-field motions). However, it is well known that topographic irregularities such as hills, ridges and valleys can have a significant effect on the ground motions. Therefore, a desk-based study of the ridge formed by the Rosneath Peninsula, where Coulpport is situated, was undertaken (Atkins, 2020). The top of the ridge is about 180m above Ordnance Datum, and the average slope angles are approximately 6° on the western flank and 12° on the eastern flank. The slopes are, the study noted, relatively shallow compared to the slopes normally considered significant in the context of topographic amplification. The study acknowledged the general absence of guidance on the subject in design standards (a notable exception being Part 5 of Eurocode 8). The study also surveyed several academic papers on the subject and found that none were sufficiently mature or general in scope to be used for design purposes. The study concluded that it would be appropriate and consistent with the current design codes to neglect topographic amplification for Coulpport. By implication, the same conclusion applies to Faslane.

Horizontal component of ground motion

Engineers should ensure that an appropriate definition of the horizontal ground motion is used. The appropriate definition depends on the analysis approach and the dynamic properties of the SSC under consideration. The MC DRS preserves the historic precedent set by the PML spectrum (which was an MC spectrum) and is considered a suitably conservative basis for assessment of all SSCs. The GM DRS may be used in some limited cases, including for assessment of structural members that resist seismic action in one horizontal direction only. This latter permission to use the GM DRS in some cases is based on consideration of probability. If a structural member is oriented along a specific axis, then it is unlikely that the member will experience the MC of horizontal motion. The GM provides a better estimate of the most likely magnitude of motion in that direction. Despite this permission, it is expected that engineers will use the MC DRS for most assessments.

The current issue of DGD 505 Appendix A was written before the shortfall in the definition of the GMHs was fully realized. Therefore, Appendix A states that, for time domain analysis, the GMHs may be used directly (no conversions are required). This will be rectified in a future revision.

Interim in-structure response spectra

Throughout the work required to update the seismic hazard for HMNB Clyde, the base remained dependent on the older ISRS that had been computed in the past for seismic qualification of plant and equipment within the NSI facilities on site. The concept of interim ISRS was introduced to address this dependency on obsolescent data. Work was instigated to derive a methodology for the computation of interim ISRS and produce the required data. The interim ISRS were based on extant ISRS, but modified in an approximate manner to account for the anticipated effects of changing the free-field motions from the PML spectrum to new site-specific DRS. The methodology underpinning the interim ISRS is explained in an internal report (HMNB Clyde, 2023). At the time of writing, the interim ISRS constitutes the best estimate of the seismic hazard within the various NSI facilities on site. However, the interim ISRS are just that – interim – and work is now underway to update the ISRS based on modern analysis methods and relevant good practice.

Closing comments and recommendations

New seismic design motions have been developed for HMNB Clyde, and the seismic DGD has been updated. For the first time in a UK context (at least as far as the author is aware), the design guidance distinguishes between different definitions of horizontal motion (GM and MC). This distinction gave rise to several challenges along the way, from the initial seismic hazard studies to the ongoing seismic assessments. For other sites in the UK looking to embark on similar work, it is recommended that a robust strategy is developed at the outset. Ideally, as pointed out by

Beyer & Bommer (2006), the aleatory variability associated with conversions between different definitions of horizontal component should be considered already at PSHA stage. The selection and scaling of real accelerograms for bi-directional loading requires careful consideration. Finally, the complexity of seismic hazard needs to be simplified into practical and reasonably (but not overly) conservative guidance that can be understood and used by practising engineers. Hopefully, this paper provides some useful pointers for future work.

Acknowledgements

The present paper attempts to summarise a large body of work by many people. It would be impossible to list all those involved. However, due recognition should be given to the team at Arup who undertook the PSHA (subcontracted through ABS Consulting); to Malcolm Goodwin (formerly ABS Consulting, now retired) who was responsible for developing the DRS; and to John (“Jack”) Gerrard (formerly Babcock International Group, now retired) who acted as the intelligent customer on behalf of the MOD and wrote the first draft of the new DGD 505 Appendix A.

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