QUANTITATIVE ASSESSMENT OF SEISMIC VELOCITY PROFILES AT A HARD ROCK SITE

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ABSTRACT

This paper summarises the quantitative assessment of data from a range of geophysical techniques, to develop shear and compression wave velocity profiles at Wylfa Newydd, a hard rock site in North Wales, UK. Horizon Nuclear Power is developing the site for a proposed new advanced boiling water reactor nuclear power plant capable of providing at least 5,400 MW of low carbon electricity. The seismic velocity profiles in the bedrock are key data for a comprehensive probabilistic seismic hazard assessment, site response studies, seismic soil-structure interaction analysis, and the assessment of rock mass deformation under loading.

The site geology consists of a relatively thin surficial layer of glacial deposits overlying bedrock comprising psammite and phyllite. Comprehensive ground investigations were designed and executed in stages in accordance with IAEA (2004). A significant number of velocity measurements were acquired using a range of geophysical tests. This enabled a robust statistical assessment of the data. Comparison of the resulting velocity profiles from different geophysical tests identified significant discrepancies. Close collaboration between the data-users and the client has enabled these discrepancies to be confidently attributed to differences in the testing techniques. These differences, in combination with discontinuity spacing and in situ stress can influence techniques abilities to reliably measure rock mass velocity.

By resolving the discrepancies, representative velocity profiles were produced from each geophysical technique. These profiles were combined to provide lower characteristic, best estimate and upper characteristic seismic velocity profiles, consistent with the deterministic requirements for ground stiffness in ASCE 4-16 (2017).

Keywords: Seismic velocity; rock; geophysical testing.

1. INTRODUCTION

This paper presents the results of a ground investigation at the proposed Wylfa Newydd nuclear power station development. This was led by the project developer Horizon Nuclear Power supported by Atkins who developed the ground investigation scope, supervised the ground investigation and conducted full interpretation of the findings. The interpretation was supplemented, as appropriate for a nuclear development, by extensive collaboration and peer review with other parties, see Section 7.

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1.1 Wylfa Newydd Proposed Nuclear Power Station

Wylfa Newydd is a proposed nuclear power station site located adjacent to the, now being defueled, Magnox Sites Wylfa Nuclear Power, Station in Anglesey, North Wales. The proposed development comprises two advanced boiling water reactors, which together will have a generating capacity of at least 5400 MW, sufficient to supply around 10 million UK households. As part of the nuclear safety case for the development structures, systems and components must be qualified for environmental hazards, including seismic loading, proportionate with the radiological and environmental risk. Typically for Seismic Category 1, this is a conservatively assessed earthquake with an annual probability of exceedance of 1 x 10⁻⁴. The main structures will be predominantly founded on rock, with the main reactor buildings embedded up to 25 m below the proposed site platform level of 18 mOD. Current rock head level at the site is about 10 to 20 mOD. Current ground levels vary from about 10 mOD where the superficial glacial deposits are thin to 40 mOD where drumlins are present.

1.2 Geology

The site is in a geologically complex area. Predominantly glacial origin superficial deposits, overlie metamorphic bedrock of late Pre-Cambrian and Cambrian age with some minor igneous intrusions of Palaeozoic and Tertiary age (British Geological Survey, 2014a).

All the main structures will be founded on the New Harbour Group which originated as marine mudstones, siltstones, sandstones and conglomerates which underwent low grade metamorphism to become phyllite, psammite and metaconglomerates respectively. Deformation has produced a complex structure and fabric, including folding and a foliated almost schistose fabric. The original sedimentary depositional environment caused the composition of the rock to vary both laterally and with depth. The subsequent metamorphism and deformation has produced further variability, such that correlation of lithological units between even relatively closely spaced boreholes was not possible. This has also resulted in discontinuities in the rock mass, consisting of faults, joints (including foliation fractures) and fragmented zones.

The New Harbour Group generally comprises a fresh to slightly weathered, medium strong to strong interbedded phyllite and psammite. The average intact rock strength (UCS) was around 60 MPa and the average density was 2.76 Mg/m³. There is generally limited weathering, occurring at isolated and varied depths, commonly near faults. Discontinuities in the bedrock are generally closely to medium spaced. Several joint and fault sets have been identified. Discontinuities are distributed unequally over the site; limited localised areas with dimensions typically 10 to 30 m were found to have significantly higher discontinuity frequency.

1.3 Ground Investigations

The project has adopted IAEA (2004) stages for ground investigation. Selection stage and characterisation (verification) stage investigations were carried out from 2008 to 2011. The characterisation (confirmation) stage investigation was undertaken from 2014 to 2015. Over 300 boreholes, with a total length more than 20 km, provided a comprehensive evaluation of the ground conditions and geotechnical parameter values suitable for the design of the facility.

1.4 Seismic Wave Velocity – Project Requirements

Reliable seismic wave velocity information was required as input to the project specific probabilistic seismic hazard assessment (PSHA) and future site response and seismic soil-structure interaction (SSI) analyses. Specifically, these require profiles of shear (s) wave and compression (p) wave velocity (v_s and v_p) with elevation through the bedrock.

A key requirement of the project was to minimise epistemic variability, associated with the limitations of the different geophysical techniques, in the seismic velocity datasets. The variability of the finalised
datasets was required to be predominantly aleatory and therefore representative of the natural variation of the in situ seismic velocity of the rock mass. The final datasets were used to establish mean and ± one standard deviation velocity profiles for the site. This was not only for the PSHA but also for assessment of lower bound, best estimate and upper bound rock stiffness profiles for seismic SSI analyses in accordance with ASCE (2000) and the deterministic elements of ASCE (2017).

2. ROCK VELOCITY BEHAVIOUR FRAMEWORK

To understand the limitations of the different geophysical techniques, factors which affect rock mass velocity were identified. Previous studies provide a sound framework for expected variation of velocity or stiffness based on several factors.

2.1 In Situ Stress and Discontinuities

For seismic waves, where wavelengths are normally long relative to discontinuity spacing, seismic wave propagation through a fractured rock mass can be modelled as wave propagation through an equivalent elastic medium, defined in terms of equivalent Young’s modulus ($E_x$; $E$ in direction x) and shear stiffness ($G_{xy}$; $G$ in plane xy) (Jaeger et al., 2007), where (Equations 1 and 2):

$$\frac{1}{E_x} = \frac{1}{E_t} + \frac{1}{S_t\kappa_{nx}}$$  \hspace{1cm} (1)

$$\frac{1}{G_{xy}} = \frac{1}{G_t} + \frac{1}{S_t\kappa_{sx}} + \frac{1}{S_y\kappa_{sy}}$$  \hspace{1cm} (2)

Where, $E_t$ and $G_t$ are intact rock stiffness, $S$ is discontinuity spacing and $\kappa$ is normal (n) or shear (s) stiffness of the discontinuities.

Furthermore, both the intact rock stiffness and discontinuity stiffness are known to vary with in situ stress. David et al (2013) and Paillet & Cheng (1991) presented laboratory tests on intact core samples, showing a trend of both $v_s$ and $v_p$ increasing with confining stress. Discontinuity normal stiffness has been shown by Bandis (1990) and Goodman (1976) to increase with normal stress. Barton (2002) presents empirical correlation between his rock mass quality value $Q$ and $v_p$. Barton’s correlation indicates that $v_p$ increases with $Q$ value.

In simple terms, these studies indicate the equivalent stiffness and therefore velocity of the in situ rock mass increases with intact rock stiffness, in situ stress and discontinuity spacing and stiffness.

3. GEOPHYSICAL TECHNIQUES

In the characterisation (confirmation) stage ground investigation, four borehole geophysical techniques were employed: (i) downhole seismic - 21 boreholes, (ii) crosshole seismic - in borehole arrays at two different locations (referred to as the 725 and 741 arrays), (iii) suspension logging - 6 boreholes and (iv) sonic logging - 300 boreholes. Each of these techniques has potential epistemic variability depending on the rock conditions. Therefore, using a combination of techniques is desirable to obtain a robust interpretation of seismic velocity profiles in a range of rock conditions. Sonic and suspension testing was conducted in stable unlined boreholes. Downhole and crosshole seismic testing was conducted in boreholes with plastic liners secured by a cementitious grout. Cement-bond logs were recorded and reviewed in all the lined boreholes to confirm the integrity of the ground–grout–liner bond.

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3.1 Downhole Seismic

Downhole seismic testing was carried out to ASTM (2008). Ground-level seismic sources were used to generate p-wave and s-wave signals. Wave arrivals were detected using two sets of multi-axis receivers separated by two metres, clamped within the borehole liner.

The direct and interval methods of interpretation were used to produce $V_{svh}$ and $V_{pv}$ velocity profiles with depth. The direct method plots the arrival times versus ray-path distance (or corrected arrival times versus depth) for each receiver individually at every test depth. The interval method evaluates seismic wave velocity using the difference in arrival times between the two receivers and the fixed distance between them.

3.2 Crosshole Seismic

One crosshole seismic test array was positioned at each of the two proposed reactor locations. The boreholes at each crosshole seismic test location were arranged in an L-shape array. Each arm of the array had three boreholes spaced at 10 m. The spacing was larger than recommended in ASTM (2014). This was necessary to minimise the effect of ‘pick’ errors (the tolerance in measuring arrival times). The arms were aligned parallel and perpendicular to the dip direction of the foliation of the rock to assess whether the foliation produced a significant anisotropy resulting in stiffness being a function of azimuth.

Velocities were calculated from both source-to-receiver and receiver-to-receiver travel times. Normally, receiver-to-receiver travel times are preferred as they eliminate trigger errors. In the high velocity rock at Wylfa Newydd, the compound effects of pick errors in the receiver-to-receiver travel times resulted in greater velocity variability. Receiver spacing was determined from borehole verticality surveys. To confirm the repeatability of the tests, in each arm of the arrays the source and outer receiver were swapped and the tests repeated.

Testing was carried out using two different downhole seismic sources, a shear hammer and a sparker. The shear hammer allows calculation of $V_{svh}$ and $V_{ph}$. The sparker allows calculation of $V_{shh}$ and $V_{ph}$. Measurement of s-wave velocities with horizontal and vertical polarisation allows assessment of stiffness anisotropy between the horizontal and vertical plane.

3.3 Sonic Logging

The sonic logging was carried out using a monopole source tool raised through the borehole at a constant rate. The source generates a p-wave in the borehole fluid which interacts with the rock mass, generating surface waves in the borehole wall and body waves in the rock mass. As each of these refracted waves propagates through the rock mass they generate compression or ‘head’ waves in the borehole fluid. Each of these head wave arrivals is recorded at the tool’s receivers (Figure 1). Given the arrangement of the test, the calculated velocities are considered to be $V_{svh}$ and $V_{pv}$. 

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6 The first letter refers to the wave type (s or p), the second to the assumed direction of propagation (h – horizontal or v – vertical) and the third to the wave polarisation (h – horizontal or v – vertical). There is no polarisation of p-waves.
Semblance analysis, which uses cross-correlation and coherency techniques to compare receiver signal arrivals (Haldorson, 2006; Close et. al., 2009), was used to determine shear wave velocities. P-wave velocities were determined from first arrivals and comparison to semblance analysis.

Interpretation of sonic results needs care to avoid significant epistemic variability. In ‘slow’ formations, in which the rock’s s-wave velocity is close to or less than the p-wave velocity of the borehole fluid (~1500 m/s for fresh water), critically refracted body waves are not generated and overlapping wave arrivals may occur. Therefore, body wave arrivals cannot be clearly identified (Haldorsen et al, 2006). Sonic logging signal quality and results may also be affected by fracturing (Paillet & Cheng, 1991), and hence in situ velocities may be misrepresented (Crow, 2012).

3.4 Suspension Logging

Suspension logging is similar in principle to sonic logging but was typically carried out at discrete depths. A source and receiver specifically designed for shear wave velocity determination and a larger receiver separation was used. This should allow better quantification of the effect of discontinuities on velocity. Advanced suspension logging tools are available for slow formations but these were not used at Wylfa Newydd.

4. COMPARISON AND INTEGRATION OF DATASETS

4.1 Data Processing

All the velocity data was subject to the testing contractors’ project quality assurance procedures. Review and checking was also undertaken by Atkins to confirm datasets were acceptable for inclusion in the study.

Data was processed to calculate the average and ± one standard deviation $v_{sv} \text{vsh}$ and $v_{p-v}$ velocity profiles, shown on Figure 2 and 5. Downhole interval datasets were not included for reasons explained below. The crosshole velocity $v_{sv}$ and $v_{p-h}$ results are plotted as individual data points from each test, noting that in isotropic conditions $v_{sv} = v_{vsh}$ and $v_{p-h} = v_{p-v}$.

All the data in this paper is consider as a function of elevation – this is to provide robust datasets for future engineering development which may significantly modify existing ground levels.
assessments of the data based on depth below ground and depth below rockhead in individual boreholes have been made. These demonstrated similar trends.

4.2 Basic Trends

Figure 2 shows a general trend of velocities increasing with depth to about -20 mOD but with different velocities produced by the different techniques. Below this, velocities from different techniques converge and are relatively constant with increasing depth. This trend is consistent with the rock velocity behaviour framework identified at the outset.

4.3 Validation of the Rock Velocity Behaviour Framework

The validity of the rock velocity behaviour framework is assessed by more detailed inspection of the rock fracturing and s-wave velocities at the 741 and 725 crosshole arrays, see Figure 3. The two arrays show significantly different fracture spacing and velocity profiles which are towards the extremes of the ranges seen across the site. In shallow rock the trends in 741 array, site wide average and 725 array fracture spacing are similar to the corresponding trends in s-wave velocity. The convergence of the 741 array and site wide average fracture spacing at -10 mOD is replicated exactly in the corresponding velocity profiles. At greater depth whilst significant differences remain between the fracture spacings at the two arrays, the velocity profiles are broadly consistent. It is considered that at greater depths the in-situ stresses are sufficiently high to diminish the influence of fractures, as predicted by Barton (2002). This supports the discontinuity and stress dependent velocity behaviour framework presented in Section 2.

![Figure 2. (a) Average s-wave velocity profile, (b) Average p-wave velocity profile](image-url)
4.4 Comparison of Downhole Interpretation Methods

Shear wave velocity profiles produced from a single downhole dataset from one borehole in the 725 crosshole array, using both the interval and direct interpretation methods, are compared in Figure 4(a). The corresponding crosshole velocities are also included for comparison. The two downhole interpretation methods produce different velocity profiles. The direct method velocities match well the independently obtained crosshole profile but is not sufficiently refined to identify the reduced velocity in the upper few metres of the profile. The interval method profile shows somewhat extreme variability beyond that credible for anticipated levels of aleatory variation in the rock mass.
The large variance in the results of the interval method interpretation is a direct consequence of the difficulty in picking the exact arrival time of the waves – these ‘pick errors’ are present even when comparing the ‘first breaks’ of the 180 degree out-of-phase s-wave arrivals because of the relatively long wavelengths produced by the surface sources. Plotting a profile of the difference in picked arrival time from the upper and lower receiver signals when placed at the same elevation, as shown in Figure 4(b), gives an indication of the potential magnitude of pick errors, considering that half the range of time differences approximates the pick error. This suggests the pick error may be around 0.5 to 0.75 msec which, for rock with an s-wave velocity in excess of 2000 m/s and a 2 m separation between the receivers, is a large proportion of the interval travel time (<1.0 msec). These pick errors explain the variability seen in the interval method velocity profile. The combination of high velocity rock and limited receiver separation also makes interval method velocities prone to being skewed by small systematic errors which would not be evident in testing of lower velocity rocks or soils.

Both these epistemic effects are minimised by the adoption of the direct method which in simple terms smooths out the effect of pick errors by assessing velocities from greater numbers of wave arrival times over larger distances in the rock mass. More generally, the downhole seismic testing is considered to be most representative of the rock mass velocities because it tests a large volume of rock therefore capturing the effects of discontinuities and has wavelengths and propagation direction more closely aligned to earthquake seismic waves.

4.5 Sonic and Suspension Logging

The sonic and suspension logging velocities on Figure 2 show smaller reductions in velocity over the upper 20 to 30 m of the profile relative to the downhole direct velocities. Near rockhead this results in differences of around 800 to 1000 m/s in average s-wave velocities.

As discussed in Section 3.3, the sonic and suspension techniques are affected by the presence of discontinuities and give poor results in ‘slow’ formations. Near rock head, greater frequency of discontinuities and the rock mass being ‘slow’ in some locations restricts the sonic and suspension techniques ability to characterise the low velocity rock mass. As a result, the sonic s-wave velocities identified in the upper part of the profile are considered to be over-estimated. Evidence for this was provided by observing that sonic velocities were similar to those measured in the laboratory on intact
unfractured core samples.

As part of the quality assurance process, an independent review of sonic velocity results from 21 boreholes was carried out. This included manual analysis of receiver signals to confirm the s-wave head arrivals and validate the semblance derived velocities. For some of the shallow rock results, no clear s-wave head arrivals were identified. The velocities initially provided were found to be an artefact of the semblance process. Reliable shear wave arrivals were only identified in all 21 of the reviewed sonic velocity results below elevations of -29 mOD (approximately 50mbgl). This review showed the sensitivity of the sonic interpretation, and the importance of robust QA and challenges to the data interpretation.

For the suspension testing, in addition to being subject to some of the limitations of the sonic technique, the six boreholes in which the testing was conducted were where the shallow rock was found to be of better quality. This is considered to contribute to the higher average velocities above about -20 mOD.

4.6 Frequency Effects

Rock mass velocities are dispersive with frequency. Barton (2007) and Sams et al. (1997) indicate that velocity in saturated rocks varies with frequency of the test equipment source signal and that higher velocity measurements are associated with higher frequency source signals. From the Wylfa testing significant variation of velocity with frequency of the body waves generated by the different sources was not identified. At depths where sonic testing was considered reliable, the crosshole seismic testing with source frequencies of the order 0.25 to 3 kHz and the downhole seismic testing with source frequencies of 0.05 to 0.2 kHz, give similar or higher velocities than sonic testing with source frequencies of 20 kHz.

4.7 Dataset Variability

The average and standard deviation profiles of the downhole direct, sonic, and suspension logging site-wide datasets are shown on Figure 5. The variability of the suspension logging is not considered further as the dataset is too small to have significant statistical meaning. The downhole direct profiles generally show greater variability than the sonic profiles. Understanding whether the sources of variability are epistemic or aleatory is critical to reliable interpretation of the rock mass velocities. The downhole direct vs and vp results are seen to have greater variability than the sonic technique. It is considered this is due to epistemic inherent variability in the direct interpretation method and the aleatory variability of the rock mass. The epistemic variabilities include developing a velocity model to fit the determined arrival time profile with depth and the unavoidable pick errors in the dataset. The lower frequency signals generated by the downhole sources results in greater temporal uncertainty in picking arrivals. Whilst these epistemic variabilities cannot be readily removed, the average results well characterise the rock mass velocities. An independent assessment of selected borehole datasets, including independent picking of arrivals, and modelling of velocities, obtained similar overall velocity profiles, albeit with minor differences associated with the interpretation process. The sonic measurement results have less variability, although the technique is considered to provide a less representative measure of the true rock mass velocity in fractured shallow rock.
Figure 5. (a) s-wave velocity variability profile, (b) p-wave velocity variability profile

Figure 6. (a) Average crosshole s-wave velocity profiles, (b) Average crosshole p-wave velocities
The reduced variability relative to the downhole direct velocities is considered due to higher frequency signals enabling greater temporal accuracy of arrival times and a more repeatable semi-automated velocity determination technique to determine first-break arrivals or semblance based velocities. However, detailed review found that subtle variations in the testing equipment, test execution and interpretation methodology, could make differences to the velocity values. Where these differences produced unrepresentative velocities, they were excluded from the interpretation data sets.

### 4.8 Anisotropy

The New Harbour Group rocks have significant potential for stiffness anisotropy, predominantly because of foliation, orientation of discontinuities and stress anisotropy.

Shear wave velocity measurements undertaken to assess stiffness anisotropy at the 725 crosshole seismic array are presented in Figure 6. Typically, in both arms of the array the vertically-polarised s-waves \((v_{s,vh})\) have slightly lower velocities than the horizontally-polarised ones \((v_{s,hh})\). However, the two profiles frequently overlap. This indicates rather limited cross-anisotropy, with any differences small compared to the overall variation in stiffness within the rock mass. Comparing all the different velocity values between the two arms of the borehole arrays, any difference was small compared to overall variations within the rock mass. Similar trends were observed in the 741 array. On this basis, all the velocities were interpreted in an isotropic framework assuming \(v_{s,vh} = v_{s,hv} = v_{s,hh}\) and \(v_{p,v} = v_{p,h}\).

### 5. SITE WIDE CHARACTERISTIC PROFILES

Site wide characteristic velocity profiles were determined using datasets that were considered to provide velocities representative of the in-situ rock mass velocities. The best estimate profile was selected to match the average velocity profiles from these datasets. The lower and upper characteristic profiles were selected to approximately match the ± one standard deviation profiles from the same datasets. A degree of engineering judgement was applied to provide consistent, smooth, integrated profiles. Adopting ± one standard deviation is in line with the recommendations of ASCE (2000) and the deterministic elements of ASCE (2017) for managing uncertainty in seismic soil-structure interaction analysis. Upper and lower characteristic \(v_p\) profiles were calculated from dynamic Poisson’s ratio, and upper and lower characteristic \(v_s\) values. This approach was adopted as it gives \(v_p\) characteristic profiles consistent with the Poisson’s ratio of the rock mass.

The characteristic best estimate and upper and lower characteristic profiles have been selected to be broadly in line with the downhole direct dataset. This dataset, whilst containing some degree of epistemic variability, is considered to provide representative velocities of the rock mass, including in fractured, poorer quality shallow rock. In addition, the downhole direct test is noted to be based on vertically propagating, relatively low frequency seismic waves, similar to earthquake generated seismic waves.

With depth, below approximately -10 mOD (approximately 35 mbgl), the characteristic best estimate profile has been selected in line with the downhole direct and the sonic and suspension dataset. It is considered the increase in stress and reduction in discontinuity frequency lead to the sonic and suspension giving velocity values which converge with the downhole direct and crosshole results. Crosshole velocities were considered representative of the rock mass seismic velocities. However, they only represent the velocities at two discrete locations. Hence, while the data from these two locations was not considered sufficient for the crosshole data set to statistically represent the average rock mass velocity, they provided confirmation of velocities from other testing techniques.

The resulting best estimate and characteristic profiles for the site are presented in Figure 7. Over some elevations, around -20 mOD (approximately 40mbgl) for example, the characteristic range is greater than the ± one standard deviation of the dataset. This is conservative and simply a function of the preference to have relatively uniform or smooth profiles. As an independent check, all the reliable
datasets were combined and an overarching average and ± one standard deviation profiles were
determined. These were a close match to the best estimate and characteristic profiles presented in
Figure 7.

Figure 7. Site-wide characteristic velocity profiles (a) s-wave velocity, (b) p-wave velocity

6. CONCLUSION

The extensive geophysical datasets available from the Wylfa Newydd site have enabled a robust
interpretation of the in-situ rock mass velocities. This interpretation has depended on:

- a detailed understanding of the rock mass quality obtained from extensive drilling, coring and
  optical & acoustic borehole logging;
- establishment of a framework for rock velocity behaviour;
- interrogation of the geophysical tools, techniques and data interpretation process; and
- identification of the limitations of the different techniques as a function of rock conditions.

It is concluded that in lower velocity rock with higher discontinuity frequency and lower levels of in
situ stress as occurring near rockhead, velocities from sonic and suspension logging are less reliable
and have a tendency to over-predict rock mass velocity. Downhole seismic and crosshole seismic
velocities better capture the influence of discontinuities and provide best available estimates of
average rock mass velocity. The effect of pick errors in the downhole data is limited by using the
direct interpretation method. At depth where the discontinuity frequency decreases and the levels of in
situ stress diminish the effect of discontinuities, the velocities from all the techniques converge and all
the techniques were considered reliable. Best estimate and characteristic velocity profiles have been
developed for the Wylfa Newydd site on this basis.

Had a single geophysical testing technique been adopted during the ground investigation, production
of reliable velocity profiles for the rock mass would not have been possible. Using multiple testing
techniques benchmarked against published values and correlations for rock mass velocity is recommended. The interpretation was facilitated by a robust challenge from the client organisation to the interpretation team, through their quality and review regime. This enabled the project team to carry out an appropriate investigation of the seismic testing, and with the clients assistance allowed access to, and challenge from, a wider pool of experts. Finally, detailed understanding of the subsequent use of the data is required. This was obtained through detailed collaboration with the client and other suppliers to the project, including the seismic hazard consultants and the seismic designers of the proposed facilities.

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8. REFERENCES


