Ground Motion Selection for the Integration of Site Response in Probabilistic Seismic Hazard Analyses

M. Papaspiliou
Halcrow Group Ltd., London, UK (formely Imperial College London, UK)

S. Kontoe
Imperial College London, UK

SUMMARY:
This paper examines issues related to ground-motion selection for the performance of site response analysis and the integration of the site-specific amplification function within probabilistic seismic hazard calculations. The, typically, deterministic modification of the probabilistically estimated rock ground motions to consider site effects often leads to nonconservative ground motions at the soil surface. In this paper a methodology proposed by Bazzurro and Cornell (2004b), which allows the transformation of a rock ground-motion prediction equation into a site-specific one by modifying both the median and standard deviation terms of the equation, is used and its sensitivity to different suites of ground-motion records is explored. Suites of 10, 15 and 20 records are used for the performance of the site response analysis in order to examine their impact on capturing the median site amplification and its standard deviation. Subsequently, their impact on the results of a probabilistic seismic hazard assessment is explored.

Keywords: ground motion, site response, PSHA

1. INTRODUCTION

It is common practice to estimate the ground-motion hazards at the free-field surface of a soil deposit using a probabilistic seismic hazard analysis (PSHA) performed for rock site conditions, and subsequently adjusting the estimated bedrock ground motion to account for soil effects. This adjustment is typically done using site factors from a seismic code depending on the site class or V_{s30} or, alternatively, using the median site amplification function estimated from a small set of site response analyses. Both approaches essentially consist a deterministic modification of the probabilistically calculated bedrock ground motions, as the uncertainty in the ground motion associated with the soil amplification is ignored. This procedure leads to probabilistically evaluated ground motions being both nonconservative and with unknown rates of exceedance (Bazzurro and Cornell, 2004a; Goulet and Stewart, 2009).

In order to overcome these shortcomings, site-specific PSHA needs to consider the nonlinear site effects directly within the hazard calculations. This can be done either using a ground-motion prediction equation that includes the effects of nonlinear soil behaviour within both its median and standard deviation terms, or using methods that allow the proper incorporation of the site-specific soil amplification within the hazard calculations – and not just its median value (e.g. Bazzurro and Cornell, 2004b; Baturay and Stewart, 2003). In this paper the methodology proposed by Bazzurro and Cornell (2004b) allowing the transformation of a rock ground-motion prediction equation into a site-specific one, is employed and the sensitivity of this approach to different selected suites of ground-motion records is explored for a NEHRP class D site. Suites of 10, 15 and 20 records are used in order to examine their impact on capturing the median site amplification function and its associated standard deviation. Subsequently, their impact on the results of a PSHA is presented.

2. GROUND-MOTION SELECTION AND SITE RESPONSE ANALYSIS

Results are presented for a sandy site which consists of 90m of alluvial deposits, the water table is located 46m below the surface and has an average shear wave velocity in the upper 30m of about 285m/s (NEHRP class D). Ground-motion records are selected from the NGA database (http://peer.berkeley.edu/nga/), which are subsequently scaled to capture a wider range of spectral accelerations. The examined soil profile, together with the 120 ground-motion records (scaled and unscaled) used in the analyses are shown in Fig. 2.1.

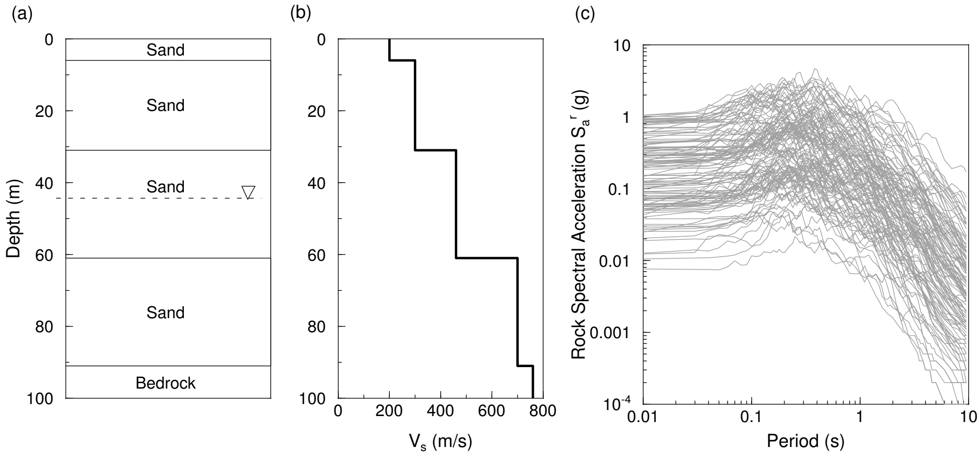

Figure 2.1. Site Stratigraphy, shear-wave velocity profile (after Kottke, 2006) and acceleration response spectra of the 120 rock records used in the ground response analyses

The use of 120 records is considered sufficient to capture the "true" site amplification function and its standard deviation, as far as these can be captured by 1D site response analysis. The site response analysis is performed both with an equivalent linear analysis (SHAKE91) and a nonlinear analysis using the modified hyperbolic (MKZ) constitutive model (Matasovic and Vucetic 1993) and the software DMOD-2000 (Geomotions 2007). In both sets of analyses the dynamic soil properties curves of Darendeli (2001) were adopted. Further details regarding the performance of the site response analyses can be found in Papaspiliou et al. (2012a).

Once the site response analyses are completed, the site amplification function (*AF(f)*) is obtained using nonlinear regression and following the functional form proposed by Goulet (2008):

$$\ln AF(f) = c_o + c_1 \ln\left(S_a^r + c_2\right) + \varepsilon_{\ln AF(f)} \sigma_{\ln AF(f)} \tag{2.1}$$

$$\sigma_{\ln AF(f)} = \sqrt{\left(\frac{c_1 \cdot S_a^r}{c_2 + S_a^r} + 1\right) \cdot \sigma^2_{\ln S_a^r(f)} + \sigma^2_{\ln AF(f)}} \tag{2.2}$$

where *AF(f)* is the frequency dependent amplification function, *f* is a generic oscillator frequency, $S_a^s(f)$ and $S_a^r(f)$ are the 5% damped spectral acceleration values at the soil surface and at the bedrock respectively, $\varepsilon_{lnAF(f)}$ is the standard normal variable, $\sigma_{lnAF(f)}$ is the standard error and c_0, c_1 and c_2 are constants obtained from the regression analysis.

According to Bazzurro and Cornell (2004a) the estimates of the statistics of the amplification function can be obtained by a limited number of site response analyses, irrespectively of the method used for the performance of the analyses (i.e. equivalent linear or nonlinear). Bazzurro and Cornell (2004a; 2004b) performed regressions of *lnAF(f)* on $lnS_a^r(f)$ based on a large dataset of records. This paper evaluates the sensitivity of the Bazzurro and Cornell (2004b) methodology to suites of different numbers of records which span over a wide acceleration and period range. The entire set of 120 records is used to obtain a benchmark site amplification function; subsequently, records are selected to form 11 suites of 10, 15 and 20 records. Records are selected based on their rock spectral acceleration in order to capture a wide range of values, across the period range of interest (0.01s - 3.0s). Initially the 10-record suites are selected and they are subsequently enhanced with a further 5 and 10 records, respectively, to improve the range of accelerations captured.

3. IMPACT OF GROUND-MOTION SELECTION ON *AF(f)*

3.1. Sensitivity of the median *AF(f)*

Fig. 3.1 presents the amplification functions obtained from the 10- 15- and 20-record suites (for PGA, T=0.2s and T=1.0s) of the equivalent linear analysis, while Fig. 3.2 shows the corresponding results from the nonlinear site response analysis. The individual amplification functions are plotted only over their valid range, i.e. each *AF(f)* is plotted only over the range of rock spectral accelerations covered by the records that comprise the suite; therefore not all of them extend through the entire acceleration range covered by the 120-record dataset. A comparison between the equivalent linear and nonlinear results is performed in order to identify whether the same number of records would be required regardless of the method used for the performance of the site response analysis.

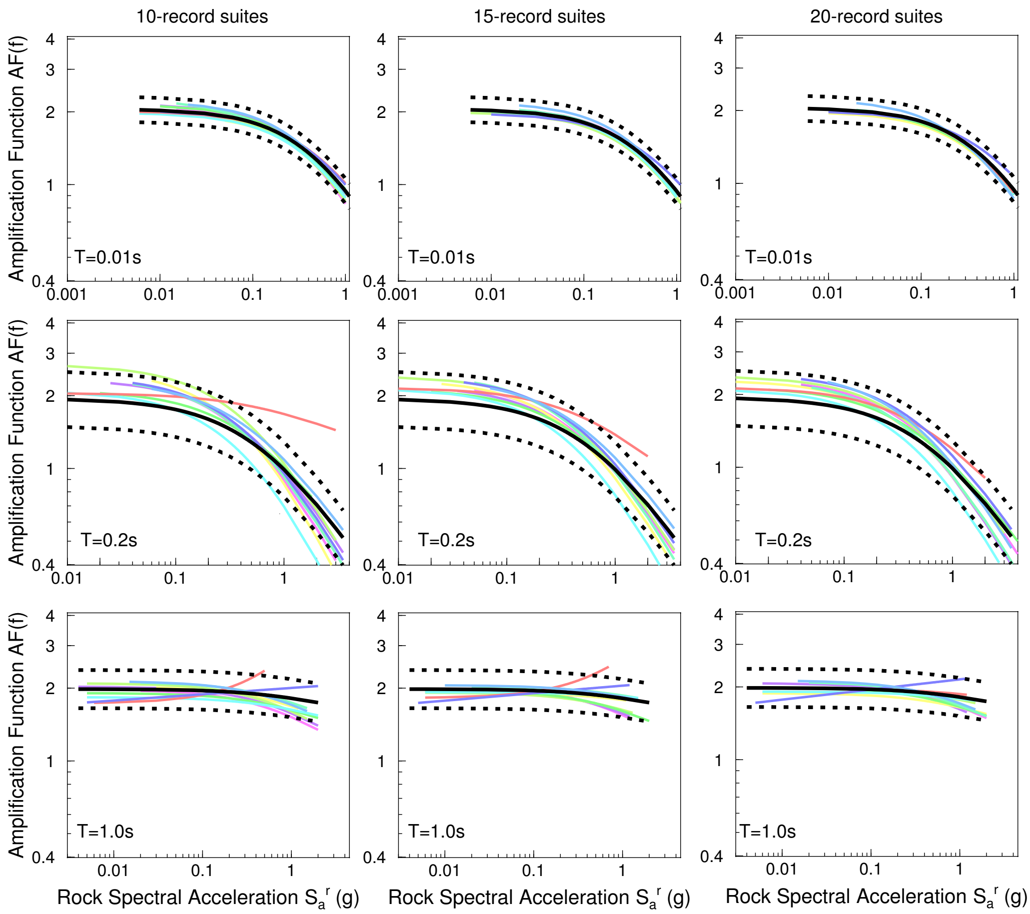

Figure 3.1. Variability of the median amplification function for suites of 10, 15 and 20 records for T=0.01, 0.2 and 1.0s following the equivalent linear site response analysis. Solid black line represents the median *AF(f)* for the 120-record suite and the dashed black lines the +/- one-standard deviation curves

For the nonlinear analysis (Fig. 3.2) the median amplification is captured within the one-standard-deviation interval by almost all suites, even those consisting of only 10 records, with a small deviation at T=0.2s. In the case of Fig. 3.1, it is observed that at PGA, the equivalent linear analysis shows a smaller scatter among different suites than the corresponding nonlinear plot, and amplification functions that are much closer to the benchmark *AF(f)*, even when 10 records are used. However, a significantly larger deviation from the median of the 120 records is noted at T=0.2s and the scatter for all other periods in the amplification functions is larger than that observed in Fig. 3.2. The amplification factor for records with $S_a^r(0.2s)$ larger than about 1g varies by a factor of 4, between 0.5 and 2.0, among the 10-record suites. In this case, at least 20 records are required for the median *AF(f)* to be captured within one standard deviation of the "true" median function across the entire rock acceleration range. At periods longer than 1.0s (not presented herein for brevity) the differences between the standard deviations obtained from the two site response analysis methods for the 120 records are small and hence the different suites are capturing the median *AF(f)* in a similar manner. It is noted that the actual amplification functions are different depending on the method of analysis used and the comparison only refers to the ability of the suites to capture the median of the 120 records corresponding to their respective method of analysis.

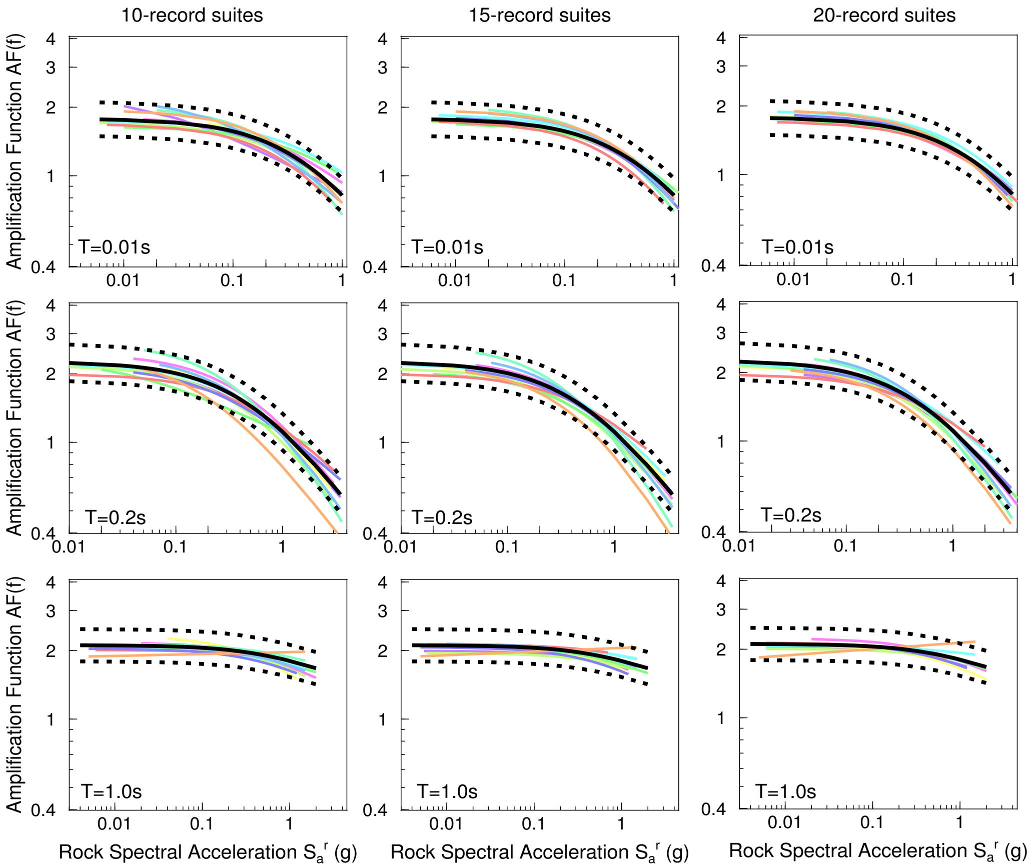

Figure 3.2. Variability of the median amplification function for suites of 10, 15 and 20 records for T=0.01, 0.2 and 1.0s following the nonlinear site response analysis. Solid black line represents the median *AF(f)* for the 120-record suite and the dashed black lines the +/- one-standard deviation curves

The number of records necessary for the site response analyses depends on the expected standard error for the site. Stiffer sites are expected, in accordance with findings of several studies (e.g., Baturay and Stewart 2003; Goulet 2008), to have amplification functions with smaller variability. As a result, a smaller number of records is expected to be required in order to capture both the median amplification function and its standard deviation. On the contrary, softer sites can have amplification functions with significantly higher record-to-record variability, meaning that a larger number of records will be required. In the case of sites that experience variability similar to that of the examined site, the median function seems to be relatively easily captured, with even just 10 records in the majority of cases. This is not the case however for the standard deviation where, as it will be seen in the next Section, individual suites result in larger variation in the estimates of $\sigma_{lnAF(f)}$.

3.2. Sensitivity of the standard deviation, $\sigma_{lnAF(f)}$

Fig. 3.3 shows the variability in $\sigma_{lnAF(f)}$ among different suites and in comparison to the benchmark value for both the equivalent linear and nonlinear analyses. Clearly, capturing the standard deviation is not as straightforward as capturing the median of *AF(f)*. When only a few records are used for the analysis, the ground-motion variability can be significantly under- or overestimated and therefore, a sufficient number of records need to be selected to ensure that the standard deviation estimation is robust and its true value is captured.

It is noted in Fig. 3.3a that the standard deviation for the equivalent linear analysis, $\sigma_{lnAF(0.2s)}$, varies between 0.1 and 0.5 among different suites of 10 records. The increase of the record number to 15, limits the standard deviation fluctuation between 0.15 and 0.38, which is still larger than what is obtained when using the nonlinear analysis and suites of just 10 records (Fig. 3.3b). Additionally, it is noted that the use of 20 records brings only modest additional improvement. At T=0.01s, where $\sigma_{lnAF(PGA)}$ for all records was already relatively low, small variability is noted in the standard deviations of the different suites, independent of the number of records used. At periods longer than 1.0s (omitted herein for brevity) the variability in the estimates increases slightly, with the highest differences noted between the estimates of the 10- and 15- record suites.

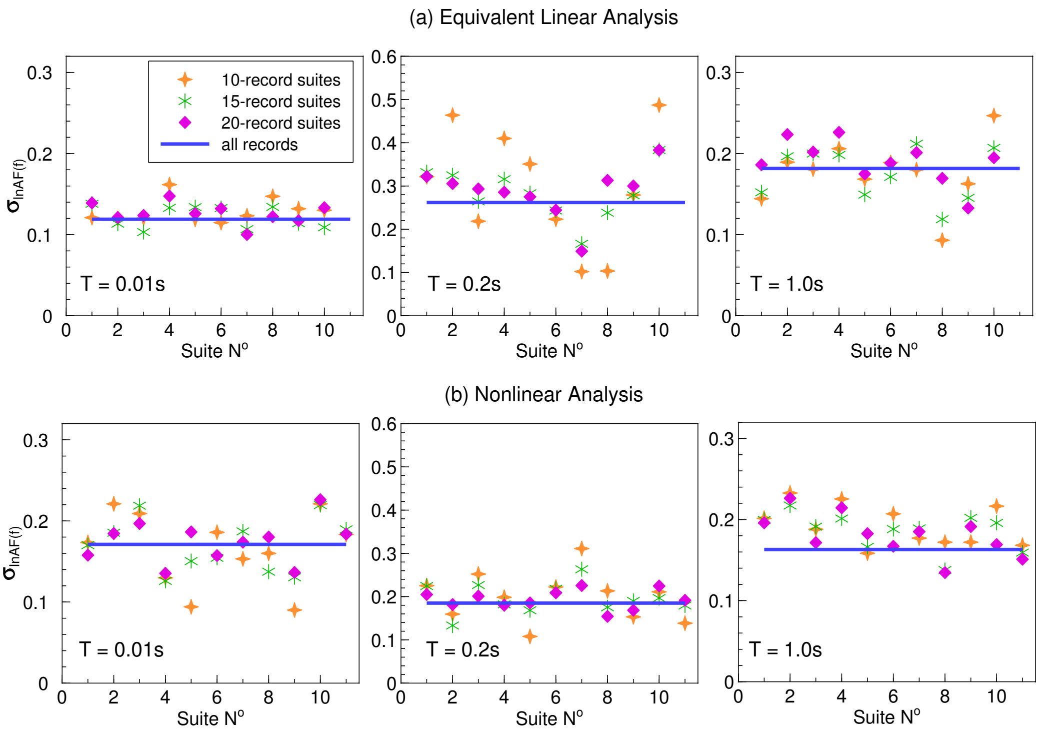

Figure 3.3. Variability of the standard deviation, $\sigma_{lnAF(f)}$, for the different suites of 10, 15 and 20 records following (a) the equivalent linear and (b) the nonlinear site response analysis

In the case of the nonlinear analysis the highest variability is also observed at T=0.2s. At this period, when 10 records are used, $\sigma_{lnAF(f)}$ varies from 0.1 to just over 0.3, while the estimate for the 120 records is equal to 0.185. The use of 15-record suites results in a considerable limitation of the variability in $\sigma_{lnAF(f)}$ across all periods, while increasing further the number of records to 20 leads to relatively smaller improvements. For T=0.2s, the standard deviation varies between 0.14 and 0.25 for the 15-records suites, and between 0.16 and 0.22 for the 20-record suites. In the intermediate period range, T=1.0s, small differences are noted in the standard deviations between the 10-, 15- and 20-record suites.

The above results indicate that, compared to nonlinear analysis, a larger number of records are required for the estimation of the statistics of the site amplification with a similar level of accuracy when equivalent linear site response analysis is to be performed. Therefore, although the equivalent linear analysis has several advantages in terms of the ease of performance and speed of computation, the need for a larger number of records could limit its attractiveness. The significance of this variation among different suites is further evaluated based on the effect it has on a probabilistic seismic hazard analysis. Fig. 3.3 clearly shows that the number of records necessary for the robust estimation of the site amplification depends on the amount of variability. At T=0.2s, where the standard deviation is higher, a larger number of records is needed for the estimation of the statistics of the site amplification. Likewise, it is expected that softer sites would require an even larger number of records.

4. IMPACT OF GROUND-MOTION SELECTION ON PSHA

The selected ground-motion suites and their respective amplification functions are used to evaluate the impact of ground-motion selection on PSHA and the surface hazard curve. The seismic hazard analysis using the different suites of records is performed using OpenSHA (Field et al. 2003), for a location in California (118.135N, 34.696W). The methodology of Bazzurro and Cornell (2004b), which is implemented in OpenSHA, allowing the median and standard deviation of the rock Abrahamson and Silva (1997) GMPE to be transformed using site-specific results, has been used. More details regarding the PSHA can be found in Papaspiliou et al. (2012b). Fig. 4.1 presents the PSHA results when the site amplification function incorporated in the GMPE is obtained from an equivalent linear analysis, while Fig. 4.2 shows the results based on the nonlinear site response analysis. Results are overlapped with the findings of the hazard analysis when the entire 120-record dataset is used for the derivation of the amplification function.

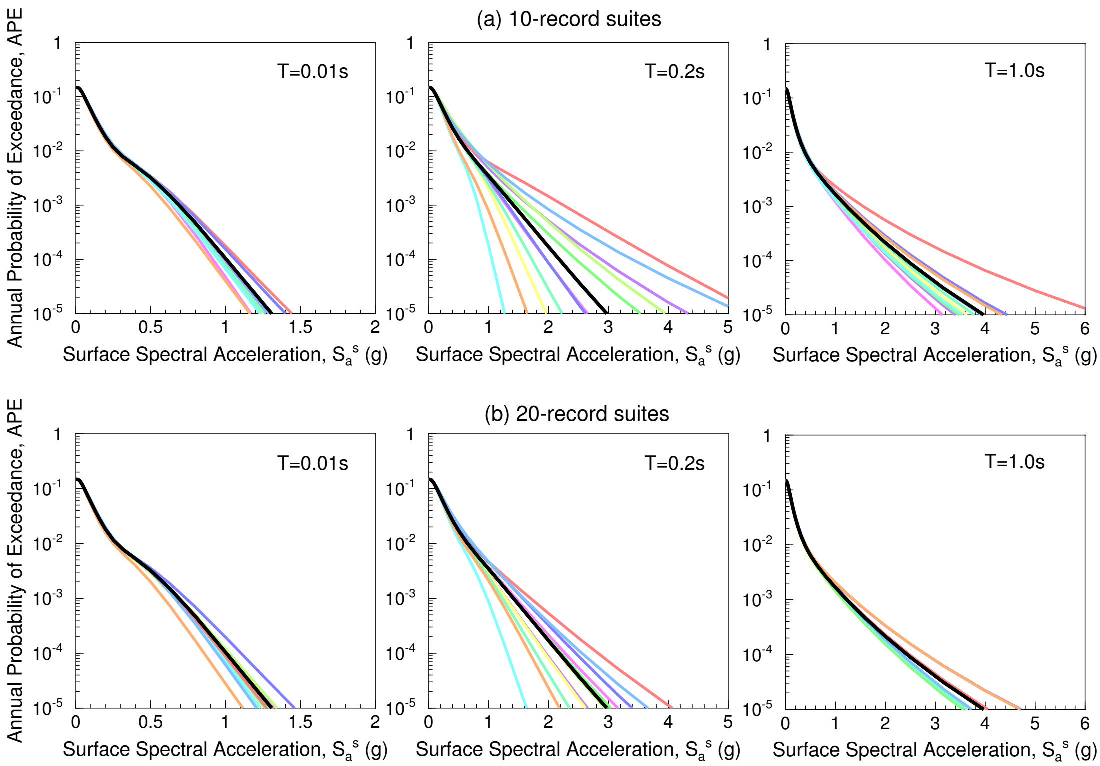

Figure 4.1. Hazard curves for various spectral periods showing the effect of the use of different (a) 10-record suites and (b) 20-record suites for the estimation of the site amplification using equivalent linear site response analysis and its incorporation in PSHA. Black curve is obtained from the use of the entire 120-record dataset

Fig. 4.1 shows clearly that at T=0.2s the variability in the hazard curves of the 10-record suites is vast, with the spectral acceleration at 2% probability of exceedance in 50 years ranging from 0.9g to almost 3.0g, and dramatically increasing with decreasing probability levels. On the other hand, at PGA, where the standard deviation of the "true" amplification function is relatively small, the hazard estimates are considerably closer and the predicted ground-motions vary only between 0.7 and 0.9g. The nonlinear analysis, at the same exceedance level, led to values ranging from 0.6 to 0.9g, as shown in Fig. 4.2.

The use of 20 records offers a significant improvement in the variability of the hazard estimates, in contrast to the 15 records whose use showed limited advantages. A reduction in the spread of the curves was also noted for the longer spectral periods. Despite this improvement, achieved with the use of 20 records, the variability in the hazard curves at 0.2s for the equivalent linear analysis is almost the same as that obtained when the nonlinear site response analysis is performed using only 10 records. This is also true for the hazard curves at T=1.0 (and T=3.0s not shown herein). Comparing Fig 4.1b to Fig 4.2a for T=0.2s, it is seen that at 2% probability of exceedance in 50 years, the ground-motion predictions vary from 1.1 to 2.2g for the equivalent linear analysis using 20 records, with the estimates for the 10-record suites of the nonlinear analysis varying from just 1.4 to 2.0g. It is evident from the above analysis and earlier findings that the equivalent linear analysis requires more records for the estimation of the hazard than the nonlinear analysis.

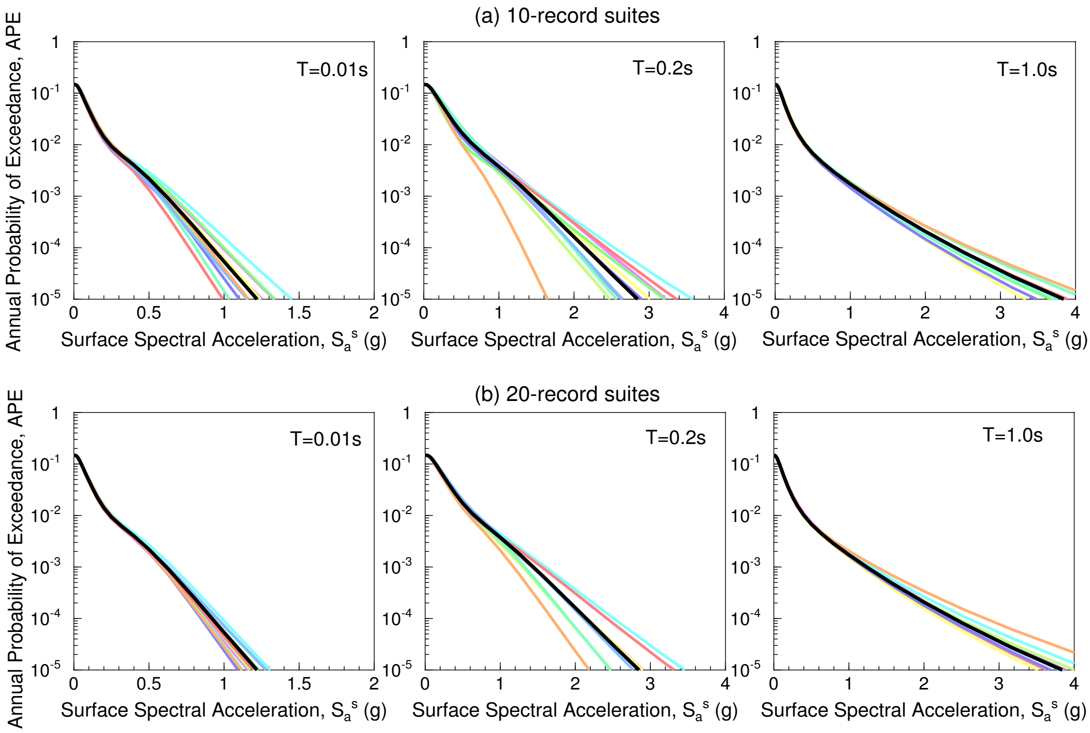

Figure 4.2. Hazard curves for various spectral periods showing the effect of the use of different (a) 10-record suites and (b) 20-record suites for the estimation of the site amplification using nonlinear site response analysis and its incorporation in PSHA. Black curve is obtained from the use of the entire 120-record dataset

Focusing on the nonlinear analysis results and Fig 4.2, at the 2% probability of exceedance in 50 years level (2475yr return period), PGA varies between 0.62 and 0.9g for the 10-record suites and between 0.6 and 0.7 for the 20-record suites. In the case of the nonlinear analysis most suites were able to capture the median *AF(f)* within one standard deviation, irrespective of the number of records, and thus the inclusion of more records mostly offered an improvement in the estimation of the standard deviation. The hazard curves show that the reduction in variability achieved by the addition of more records in the dataset has a relatively small effect for PGA. However, at T=0.2s, where the largest variations in the median *AF(f)* and $\sigma_{lnAF(f)}$ were observed, the use of more records has a clear effect. At this period and for the same APE, it was seen that when only 10 records are used, the surface spectral accelerations range from 1.1 to 2.0g. The inclusion to the suites of five further records limited the range of $S_a^s(f)$ values between 1.3 and 2.0g (the 15 record-suites are not shown for brevity), while the 20-record suites result in values between 1.4 and 2.0g. Although the reduction in the variability of $\sigma_{lnAF(f)}$ was mostly achieved by increasing the number of records from 10 to 15, when the 20-record suites are used, a large number of suites produce hazard curves identical to that of the 120-record dataset. It is thus clear that an improvement is achieved for the majority of suites.

5. CONCLUSIONS

This paper examines the issue of ground-motion record selection for the performance of site response analysis and the sensitivity of the amplification function and its standard deviation when different suites, of different records and numbers, are used. The sensitivity to the above issues was examined for both equivalent linear and nonlinear analysis. Although the median amplification was observed to be relatively easy to capture, the standard deviation was seen to fluctuate considerably, especially when suites of few records were used. The equivalent linear analysis was seen to suffer from larger scatter than the nonlinear analysis, particularly at T=0.2s. As a result, a larger number of records were found to be required for the robust estimation of the median amplification function and its standard deviation, when the site response analysis is performed using equivalent linear methodologies.

The results of the hazard analyses are significantly affected by the use of different suites of ground-motion records for the performance of the site response analysis. The high variation in $\sigma_{lnAF(f)}$ for the equivalent linear analysis led to considerable variation of the hazard estimates, irrespective of the number of records used. The nonlinear site response analysis achieves much more stable results, with a smaller number of records, and prompts for its use for more robust estimates using fewer records. Specifically, it was seen that 10 records provide relatively stable estimates of the hazard curves for the majority of periods, while in the case of the equivalent linear analysis 20 records or more are required to achieve a similar level of accuracy. Use of 20 records in the case of nonlinear analysis can have some advantages and could be used when higher levels of accuracy are thought to be needed.

REFERENCES

Abrahamson N.A., Silva W.J. (1997). Empirical response spectra attenuation relations for shallow crustal earthquakes. Seismological Research Letters. **68**, 94- 127.

Bazzurro P., Cornell C.A. (2004a). Ground-motion amplification in nonlinear soil site with uncertain properties. Bulletin of the Seismological Society of America. **94:6**, 2090-2109.

Bazzurro P., Cornell C.A. (2004b). Nonlinear soil-site effects in probabilistic seismic-hazard analysis. Bulletin of the Seismological Society of America. **94:6**, 2110-2123.

Baturay M.B., Stewart J.P. (2003). Uncertainty and bias in ground-motion estimates from ground response analyses. Bulletin of the Seismological Society of America. **93:5**, 2025-2042.

Darendeli M.B. (2001). Development of a new family of normalised modulus reduction and material damping curves. Dissertation, University of Texas.

Field E.H., Jordan T.H., Cornell C.A. (2003). OpenSHA: a developing community-modeling environment for seismic hazard analysis. Seismological Research Letters. **74:4**, 406-419.

Geomotions (2007). D-MOD2000 - a computer program package for seismic response analysis of horizontally layered soil deposits, earthfill dams, and solid waste landfills. Geomotions LLC, Washington, User's Manual.

Goulet A.C. (2008). Improving the characterization of seismic hazard for performance-based earthquake engineering design. Dissertation, University of California.

Goulet A.C., Watson-Lamprey J., Baker J.W., Haselton C.B., Luco N. (2008). Assessment of ground motion selection and modification (GMSM) methods for non-linear dynamic analyses of structures. *Geotechnical Earthquake Engineering and Soil Dynamics IV*. Sacramento, California.

Goulet C.A., Stewart J.P. (2009). Pitfalls of deterministic application of nonlinear site factors in probabilistic assessment of ground motions. Earthquake Spectra. **25:3**, 541-555.

Matasovic N., Vucetic M. (1993). Cyclic characterization of liquefiable sands. Journal of Geotechnical & Geoenvironmental Engineering, ASCE. **119:**11,1805-1822.

Papaspiliou M., Kontoe S., Bommer J.J. (2012a). On the incorporation of site response into PSHA; part I: issues on the performance of site response analysis. Soil Dynamics and Earthquake Engineering. Accepted for publication.

Papaspiliou M., Kontoe S, Bommer J.J. (2012b). On the incorporation of site response into PSHA; part II: impact on the surface hazard curve. Soil Dynamics and Earthquake Engineering. Accepted for publication.