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CONSISTENCY OF GROUND MOTION PARAMETERS FROM SITE RESPONSE ANALYSES WITH EMPIRICAL PREDICTIONS

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ABSTRACT

Design ground motions are generally developed using spectral matching. Embankment deformations, however, often tend to correlate better with energy or duration rather than spectral amplitude, suggesting Arias Intensity could be used as a target parameter along with spectral matching. Embankment analyses often depend on site-specific considerations such as topography and liquefaction making site response modeling necessary. The variation of Arias Intensity with depth is needed to understand motion characteristics at the base and crest of a dam. Site response analyses for three one-dimensional soil profiles are evaluated and compared to empirical (NGA) predictions. The models use a stiff soil layer of variable thickness overlying hard rock. A suite of 40 ground motions representing two events matched to Arias Intensity and spectral acceleration targets are input at the base of the models. Equivalent-linear and non-linear response analyses are used to calculate Arias Intensities and response spectra at the surface, which are then compared: 1) for each model, 2) across each model, and 3) with empirical predictions. The results show site response analyses should be relied on for the site specific conditions often present for embankments.

INTRODUCTION

The California Division of Safety of Dams (DSOD) manages an inventory of over 1200 dams. Given the implications for public safety, it is necessary for the seismic analyses of embankments to be thorough and efficient. One method of fulfilling these criteria is to fully capture expected loading conditions with a limited number of time histories that give us confidence that we are not compromising dam safety.

In practice, ground motions are typically developed by spectrally matching seed records to a site-specific response spectrum predicted by attenuation relations (e.g. NGA). Spectral parameters, however, only capture peak response, which may not be sufficient to correlate ground motion with analyzed embankment deformations. Arias Intensity, I_a, is a parameter that has been shown to correlate with embankment performance (e.g. Saygili and Rathje 2008), and it captures energy content of a motion. As a result, DSOD has added I_a as a target parameter in addition to spectral amplitude for developing ground motions.

Dam analyses are also complicated by site-specific considerations related to geology and topography that generally require site response analyses using numerical models to determine properties such as crest acceleration and displacement. In such cases, ground motions are input at the base of a model represented by rock (V_s > 750 m/s). Critical DSOD analyses are most common at rupture distances less than 15 km in shallow soil deposits (i.e. $Z_{1.0}$ < 150 m). These conditions stretch the limits of the NGA relations and the associated ground motion database (Chiou et al. 2008).

The goal of this paper is to evaluate the one-dimensional site response for generic site conditions that are typical of DSOD projects. Three generic one-dimensional site profiles are developed with rock bases (V_s = 1000 m/s) overlain by: (1) 150 m soil layer, (2) 50 m soil layer, and (3) 50 m soil layer including 3 m of soft soil at the surface. Two sets of 20 ground motions with identical spectral amplitude and I_a, representing M7 and M8 seismic events in California, respectively, are input at the base of profiles, and site response analyses using equivalent-linear and non-linear methods are used to determine ground motion parameters at the surface of the profiles. The computed I_a and *PHA* are compared (1) for the different modeling conditions (equivalent-linear and non-linear), (2) for the different profile depths, (3) with and without soft soil, and (4) to the predicted surface parameters (NGA and I_a). Finally, observations and conclusions are presented.

SOIL PROFILES

The site conditions underlying dams are variable, so the current analyses are conducted for generic soil profiles representative of those typically evaluated for seismic stability of dams. These generic models are also designed to have a soil V_s profile similar to those potentially used to develop the NGA relations (Walling et al. 2008). Also, the profiles are one-dimensional to facilitate comparisons of site response and modeling to ground motion predictions.

Note that current embankment construction practice removes foundation soils above rock when deposits are shallow, approximately less than 20 m. Once embankment foundations consist of soils more than 20 m thick, it can be impractical to remove all soils above rock, and site response must be considered. Older embankments founded on shallow soil are not uncommon, but seismic re-evaluations are often a result of liquefaction concerns that are beyond the scope of this paper.

For this paper, three soil profiles are developed, two with 50 m and one with 150 m of soil overlying bedrock (V_s = 1000 m/s). The V_s profiles (Fig. 1) are based on a constant shear wave velocity normalized for overburden pressure, V_{s1} (e.g. Andrus and Stokoe 2000), that is truncated at the rock depth, $Z_{1.0}$, with V_s = 1000 m/s. The profiles are similar to V_s profiles in Walling et al. (2008) used in NGA modelling. The modeled profiles here are also constrained by V_{s30}. The first two models have V_{s30} = 350 m/s (V_{s1} = 290 m/s) with $Z_{1.0}$ = 150 m and $Z_{1.0}$ = 50 m respectively. Since $Z_{1.0}$ > 30 m, V_{s30} is the same. The V_{s1} and $V_{s,30}$ values are chosen so V_s > 200 m/s near the surface, which reduces the influence of soft soil behavior on the analyses. These two models are shown in Fig. 1(a & b).

The third model is a variation of the $Z_{1.0}$ = 50 m model, Fig. 1(c) with the top 3 m of soil set to V_s = 135 m/s to evaluate the influence of a soft soil layer. The remaining soil has V_{s1} = 290 m/s as the previous models, but now V_{s30} = 320 m/s.

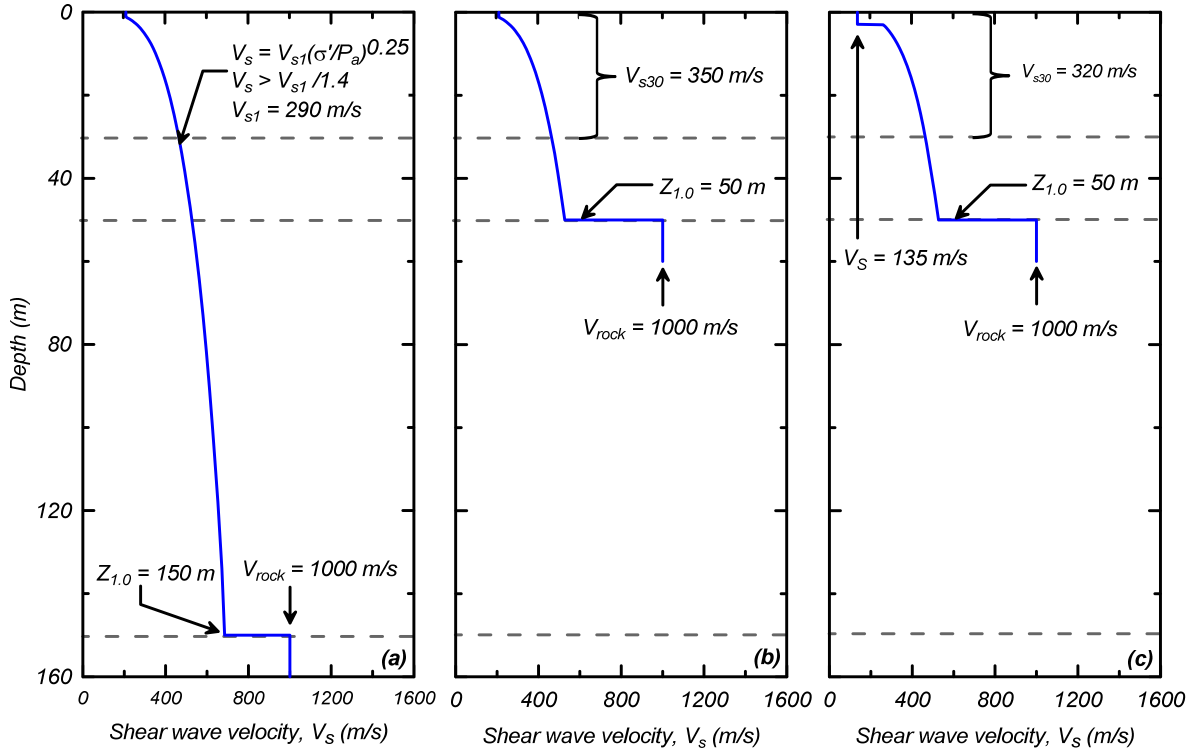

Fig. 1. (a) V_{s30} = 350 m/s, 150 m depth to bedrock (V_s = 1000 m/s), (b) V_{s30} = 350 m/s, 50 m depth to bedrock, (c) V_{s30} = 320 , 50 m depth to bedrock, and 3 m of soft soil (V_s = 135 m/s) at surface.

GROUND MOTIONS

Overview

Two sets of twenty input motions for M7 and M8 scenarios are generated for rock (V_{s30} = 1000 m/s). Target response spectra are developed using the geometric mean of NGA formulas. The Idriss (2008) formula was excluded because it does not apply to the $V_{s,30}$ considered. Arias Intensity (I_a) targets are determined using 84th percentile predictions from Travasarou et al. (2003) and Watson-Lamprey et al. (2006); the latter is evaluated using guidance from Watson-Lamprey (2009). Seed records with conditions similar to those being modeled were spectrally matched and carefully scaled to within 5% of the target S_a and 10% of the target I_a. The looser I_a fit is consistent with the greater variance of I_a predictions. Spectral matching is performed using the RSPMatch module in EZFRISK (Risk Engineering 2009), and the target I_a is obtained by manipulating the initial scale factor, which determines the number of wavelets that participate in reaching target response spectral amplitudes. Spectral matching output is also screened based on whether the non-stationary (time- varying) characteristics of the original seed motions are preserved. The final motions are base-line corrected and rechecked for spectral target fit.

M7 Scenario

The target parameters for the M7 input motions (V_{s30} = 1000 m/s) are developed for a strike-slip, near-source condition with distance, R_{rup} = 5 km. Directivity is not included to avoid complications in the interpretation of results. The resulting M7 84th percentile input motion targets are PGA = 0.56g and I_a = 3 m/s.

The twenty motions representing this scenario were developed using seed records chosen from the PEER database (e.g. Chiou et al. 2008) to best represent the scenario conditions stated. Due to database limitations, the seed record criteria are relaxed to rupture distances within 20 km, M = 6.8 to 7.15, and V_{s30} > 450 m. Dam abutment records, records requiring more than 4x scaling, and adjacent records (i.e. recordings within 500 m) are initially eliminated. To obtain 20 records, however, two records with nearby counterparts and one record requiring 6 x scaling was used. Table 1 and Fig. 2 show the target parameters: peak ground acceleration (PGA), spectral acceleration at 1 sec ($S_{a,1}$), and Arias Intensity (I_a). A statistical summary of the motions including the coefficient of variation, *COV*, are shown.

M8 Scenario

The target parameters for the M8 scenario are determined like the M7 event with R_{rup} < 1 km, and no directivity. The resulting 84th percentile targets for the V_{s30} = 1000 m/s condition are PGA = 0.87 g and I_a = 9.5 m/s.

One near-source M8 strong motion record is available (2002 M7.9 Denali earthquake station PS-10), so to achieve 20 M8 input rock motions, seed records from numerical simulations were required. These seed motions are taken from a set of 30 single-component simulations representing a "rock" site condition 7.5 km from a M8 event, developed by Walt Silva using stochastic finite-fault modeling and randomized slip. This set is one of several simulated motion sets provided to NGA modelers (Wong, 2004). One characteristic of these motions is that they lack long period motion relative to NGA expectations for $4 < T < 10$ sec, thus spectral matching beyond a 4-second response period could add unnatural long-period wavelets with significant peak velocities (e.g., > 50 cm/s). For this analysis, long period motion is not critical, so spectral matching is limited to $T < 5$ sec. Table 1 and Fig. 2 summarize the final suite of motions developed.

It is notable that the *COV* for both *PHA* and I_a are similar, showing that the looser fit to I_a targets still gives consistent ground motions

Table 1. Statistical summary of "outcrop" motion properties used as base (input) motions for modeling

	M7					M8				
	Target	Mean	Median	Std. Dev.	COV	Target	Mean	Median	Std. Dev.	COV
PGA (g)	0.56	0.55	0.55	0.02	0.04	0.87	0.88	0.89	0.04	0.05
I_a (m/s)	3.0	3.04	3.03	0.08	0.03	9.5	9.73	9.77	0.48	0.05

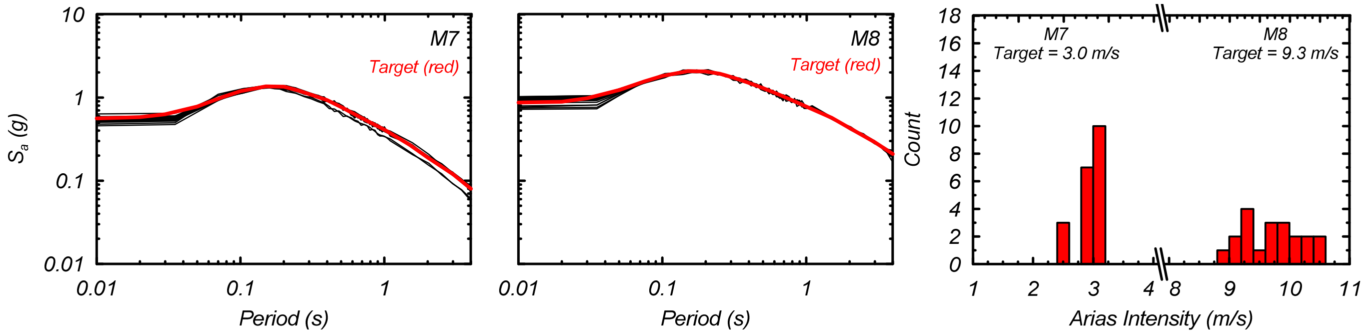

Fig. 2. Spectral accelerations and Arias Intensity distribution for “outcrop” (V_{s30} = 1000 m/s) ground motions for M7 and M8 events.

for both targets. This consistency provides a good basis for evaluating the modeled motion parameters for the surface and the predicted *PGA* and I_a for the motions at the surface.

Predicted Surface Response

Part of the following site response analyses result in a comparison of surface ground motion parameters with those that would be predicted for *PGA* and I_a. These predicted values are determined similarly to the targets used for the outcrop motions determined before. The V_{s30} and $Z_{1.0}$ are set according to the profile evaluated. The predicted values are shown in conjunction with the analyses results that follow (Tables 2 and 3).

SITE RESPONSE METHODS

Equivalent-linear

Two types of site response analyses are conducted for the profiles described. Equivalent-linear analyses are performed using SHAKE91 (Idriss and Sun 1992). The equivalent-linear method is chosen because it is the basis for site response modeling used when developing the NGA formulas. It is also a relatively simple and economical analysis to conduct.

Equivalent linear analyses are conducted by inputting the suite of forty motions at the base of the profiles as within motions. All soils are given a unit weight of 20 kN/m^3. Modulus reduction and damping curves are chosen using curves provided by the Electric Power Research Institute (1993) for sands according to each element’s confinement. For the 3 m of soft soil in the profile of Fig. 1(c), modulus reduction and damping are based on Vucetic and Dobry (1991) to represent clay with $PI \approx 30$. The analyses are conducted, and time histories at the surface are recorded for comparison to surface motion predictions.

Non-linear

One-dimensional finite difference modeling is performed alongside the equivalent-linear analyses. This modeling uses FLAC (Itasca 2009), a finite difference software that uses an explicit solution scheme. It is suited for performing a deformation analyses with non-linear material response, large geometry changes, and instability. The explicit solution satisfies the equations of motion at each nodal mass for every time step. The primary drawback is the small time steps are required to avoid numerical instability.

The analyses here use the Mohr-Coulomb constitutive model for the soil. The Mohr-Coulomb model is elastic-perfectly-plastic with yielding defined by the soil cohesion and friction angle. Modulus reduction and damping are modeled using hysteretic damping features in FLAC calibrated to the modulus reduction and damping curves described for the equivalent-linear models. Rayleigh damping (0.05%) is added to provide numerical stability. Soils are modeled with unit weight = 20 kN/m^3, $\phi = 31^\circ$, and c = 25 kPa. The rock at the base of the profiles is modeled as an elastic material.

Ground motions are input using a “compliant base” to mimic the within condition used in the equivalent-linear analyses. This is accomplished utilizing a procedure in Mejia and Dawson (2006) where the upward propagating wave is assumed as ½ the outcrop motion and converted subsequently to a stress time history. Inputting stress rather than acceleration allows motion to be absorbed by the base, as expected by a half-space, rather than reflected. The time histories at the surface are recorded for comparison to surface predictions of motion parameters. Additionally, the flexibility in FLAC allowed the time histories throughout the profile depths to be recorded for evaluation of the propagation of motion parameters from the base to the surface.

Comparison of Equivalent-linear and Non-linear Analyses

The 150 m profile model of Fig. 1(a) is analyzed for both modeling methods. Figure 3 shows the computed response spectra at the surface for each event and method with the NGA predicted response spectra for V_{s30} = 350 m/s and $Z_{1.0}$ = 150 m and the input spectra. Figure 3 also shows the range in I_a for each analysis alongside the range of base motion I_a, and Table 2 shows the statistical values for each parameter alongside the predicted parameters. The predicted parameters are shown in black on Fig. 3 and are independent of analysis method. Comparisons to the surface predictions will be made later, but it should be noted that for both events neither analysis method meets the expected surface predictions.

The computed surface response spectra from the equivalent-linear (SHAKE91) analysis is slightly higher than those from the non-linear (FLAC) analysis for both the M7 and M8 events whereas the mean (or median) I_a from SHAKE91 is larger for the M7 event but smaller for the M8 event. Attenuation of motion is predicted with both analyses methods with the maximum S_a shifting from around 0.2 seconds for the input motion (Fig. 2) to around 0.3 seconds at the surface for M7 events and to around 0.8 seconds for the M8 events. In terms of standard deviations, σ, and coefficient of variation, *COV*, the computed surface *PHA* or I_a from SHAKE91 is more variable than FLAC for the M7 and M8 events. The differences in computed surface response from the SHAKE91 and FLAC analyses are attributed to inherent differences in modeling approaches and assumptions between equivalent-linear and non-linear analyses. Given the loading levels used for these analyses (PGA = 0.59g and 0.87g), research shows that equivalent-linear analyses can be non-physical at these loading levels (e.g., Stewart and Kwok. 2008). Thus, the remaining analyses discussed and presented are with respect to non-linear FLAC analyses only.

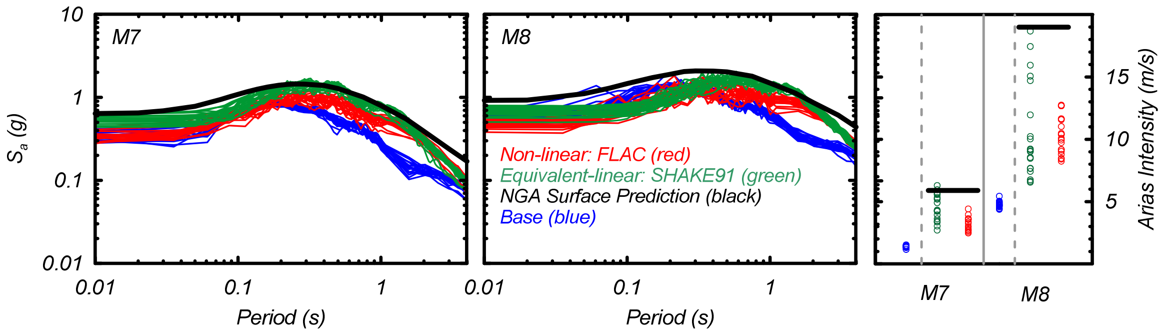

Fig. 3. 150 m profile, SHAKE vs. FLAC response spectra and I_a distributions at the surface for 40 ground motions. Surface response spectra and I_a predictions are shown in black for each event.

Table 2. 150 m profile, site response analyses results at surface for equivalent-linear and non-linear modeling with predicted surface response.

	M7					M8				
	Predicted	Mean	Median	Std. Dev.	COV	Predicted	Mean	Median	Std. Dev.	COV
Equiv. linear (SHAKE)										
PHA (g)	0.64	0.53	0.52	0.07	0.13	0.91	0.67	0.66	0.08	0.12
I_a (m/s)	5.9	4.53	4.30	1.03	0.23	19.0	10.52	9.11	3.68	0.35
Non-linear (FLAC)										
PHA (g)	0.64	0.33	0.33	0.04	0.12	0.91	0.46	0.45	0.04	0.09
I_a (m/s)	5.9	3.23	3.32	0.51	0.16	19.0	10.33	10.25	1.44	0.14

ANALYSES RESULTS AND DISCUSSION

Behavior with depth

Continuing with the 150 m profile, the site response with depth is evaluated. The propagation of *PHA* and I_a as recorded through the profile are plotted in Fig. 4. Comparing the *PHA* of the base input to the surface results, Tables 1 and 2 show the *PHA* at the surface is less than at the base for the M7 and M8 events. At intermediate depths, the *PHA* in Fig. 4 decreases slightly until about the 30 m depth where the *PHA* increases to the value reported in Table 2. For the M8 event, oscillations in *PHA* are shown for some select motions. Since *PHA* is a peak parameter, these oscillations are not necessarily representative of the overall site response for the particular motion as indicated in the I_a profiles, which show a reduced amount of oscillation with depth. It is possible that the synthetic nature of most M8 motions may be a factor with amplification of higher period spectral accelerations. The I_a plots show I_a to be relatively constant until a depth of about 30 m at which point I_a increases. Given the observed minimal amplification of the *PHA*, the increase in I_a is likely due to amplification of spectral accelerations at other periods.

Comparing the σ and *COV* between the base motions and the surface motions, the surface motions are more variable, especially with regard to I_a. The σ for each event seems significant when compared to *PHA* and even the I_a at the base. I_a, however, is an integral measure over time for the full duration of a motion and integrates the square of acceleration ordinates. The apparent discrepancy in σ is less significant when normalized to *COV* where the orders of magnitude difference are not seen.

Never-the-less, one must question the meaning of I_a within a profile because it is a parameter that is not evaluated with depth or in terms of site response. Thus the ability to make any conclusions to be made with it in terms of site response is uncertain. Also, the oscillating results in the *PHA* and I_a with depth are unusual and investigating the effects of mesh density and motion characteristics could help to understand this behavior observed.

50 m profile

Table 3 and Fig. 5 summarize the results for the standard 50 m profile shown in Fig. 1(b). Taken independently, the results and trends of the analysis are similar to those of the 150 m profile. The response spectra are again lower than the surface predictions for the profile near the *PHA* (*PGA*), but they are closer to the predicted spectra for motion content with $T > 0.1$ s. The mean and median I_a evaluated for both events exceed the predicted I_a.

Next, the 50 m and 150 m profiles response are compared. Although the predicted surface *PHA (PGA)* are the same for both profiles, the evaluated *PHA* is larger for the 50 m profile. The σ is also larger for the 50 m profile, but the increase in *PHA* seems to compensate for the increase as indicated by the lower *COV*. The I_a are less clear. The evaluated I_a for the 50 m profile are more than 60% larger than those for the 150 m profile, yet the predicted I_a at the surface are lower for the 50 m profile than the 150 m profile, 17 m/s vs. 19 m/s. The 50 m profile also shows lower σ and *COV* in I_a than the 150 m model.

There are many potential sources of differences between the models. One likely difference is the differing site periods; the 50 m profile has a site period of 0.47 sec, while the 150 m profile has a site period of 1.11 sec (both values reported by SHAKE91). The

Table 3. Non-linear site response analyses results at surface for 50 m profiles (standard and soft layer) with predicted surface response.

	M7					M8				
	Predicted	Mean	Median	Std. Dev.	COV	Predicted	Mean	Median	Std. Dev.	COV
Constant V_{s1} profile										
PHA (g)	0.64	0.47	0.46	0.05	0.11	0.91	0.60	0.60	0.05	0.08
I_a (m/s)	5.7	5.68	5.80	0.70	0.12	17.0	17.68	17.62	1.90	0.11
3 m of soft soil (V_s = 135 m/s)										
PHA (g)	0.63	0.36	0.36	0.01	0.03	0.89	0.37	0.37	0.01	0.03
I_a (m/s)	5.8	7.79	8.20	1.04	0.13	17.1	22.14	22.38	2.42	0.11

site period of 0.47 sec is close to the peak spectral period of the input ground motions, such that the motions are likely to amplify in that spectral range. A look at a closed form transfer function for damped soil on rock shows that the 150 m profile, with a 1.11 s site period, will have minimal amplification over the period range where peak spectral accelerations occur as shown in Fig. 3 with most amplification occurring near 1 sec, which likely explains the shift in peak spectral period seen in Fig. 3.

Another potential factor in the differences in calculated surface I_a are internal reflections of ground motions due to the impedance contrasts between the rock and overlying soil. The impedance contrast for the 50 m profile is much larger since the soil profile is similar resulting in a larger jump to 1000 m/s. This contrast results in downward propagating waves being likely to reflect and remain trapped in the models.

Soft Soil

Table 3 and Fig. 6 summarize the results of the same 50 m profile with 3 m of soft soil at the surface. This represents a condition that sometimes occurs in older dams built before cyclic softening and liquefaction were understood. For the analysis here, liquefaction is neglected. The plots show significantly more amplification in terms of response spectra and I_a. Examination of Table 3, shows that in a comparison to the standard 50 m profile, the *COV* values for *PHA* and I_a are the same or lower for this soft profile. This is not intuitive, but the σ shows that I_a varies more, and the mean and median I_a amplify. On the other hand, the *PHA* decreased for the soft profile, which is likely a result of yielding and an associated increase in damping in this relatively soft material as may be inferred in Fig. 7. Figure 7 shows attenuation of *PHA* above the interface between the softer and stiffer soil. The amplification in I_a may be a reflection of spectral amplification at larger periods increasing spectral content for the associated frequencies and increase in strong motion content during shaking due to wave reflection at the base of the soft soil layer. This shows that I_a, as an integral parameter, does not necessarily correlate with any one spectral parameter such that a change in one parameter, like *PHA*, does not equate to a similar change in I_a. Figure 7 shows a marked change in the propagation characteristics of *PHA* and I_a occurs at the 3 m depth where the soil transitions from the standard V_{s1} = 290 m/s profile to the V_s = 135 m/s soft soil at the surface.

COMPARISON TO PREDICTED RESULTS

The preceding analyses show the predicted *PHA* and I_a in conjunction with the site-response results. As described earlier, the

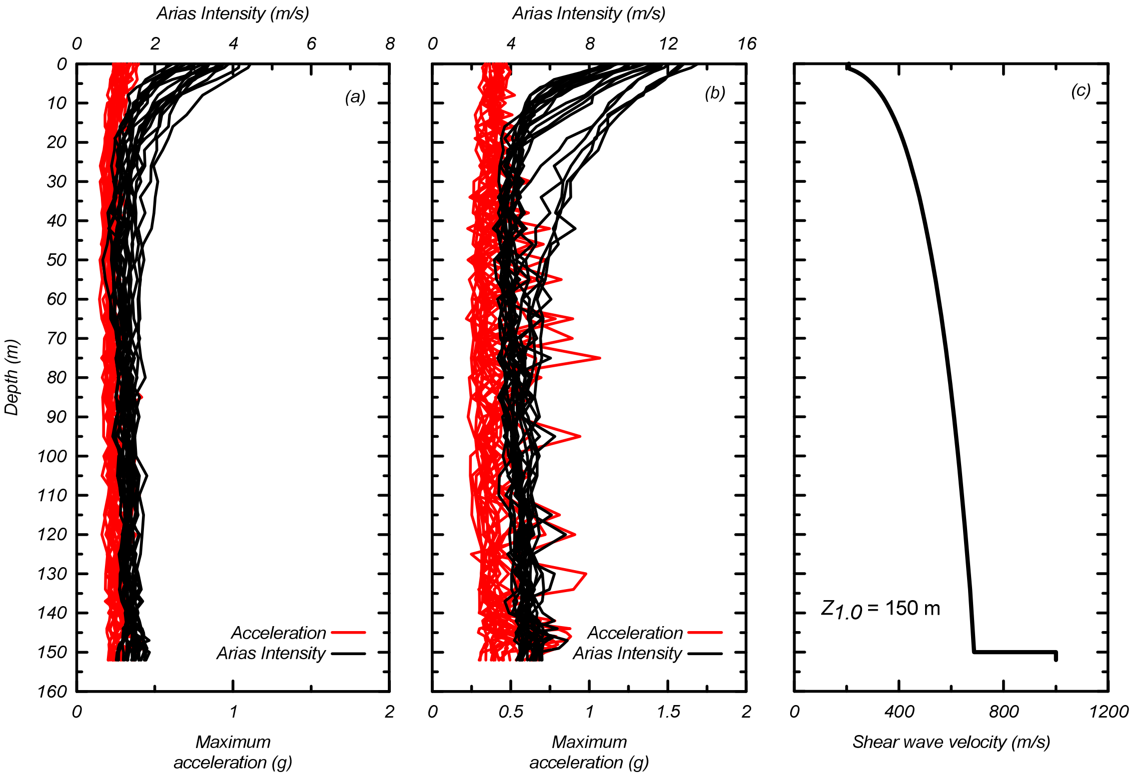

Fig 4. Peak response with depth for 150 m profile from FLAC. (a) M7 events, (b) M8 events, and (c) V_s profile.

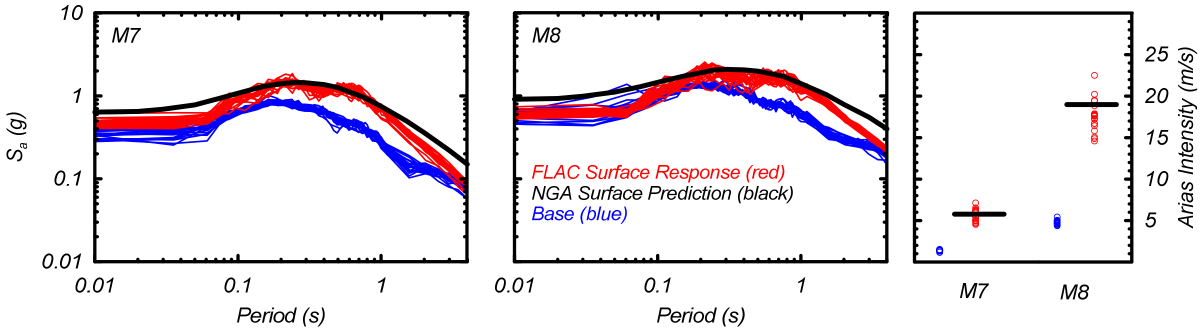

Fig 5. 50 m profile, response spectra and I_a at the surface for 40 ground motions with predicted response parameters.

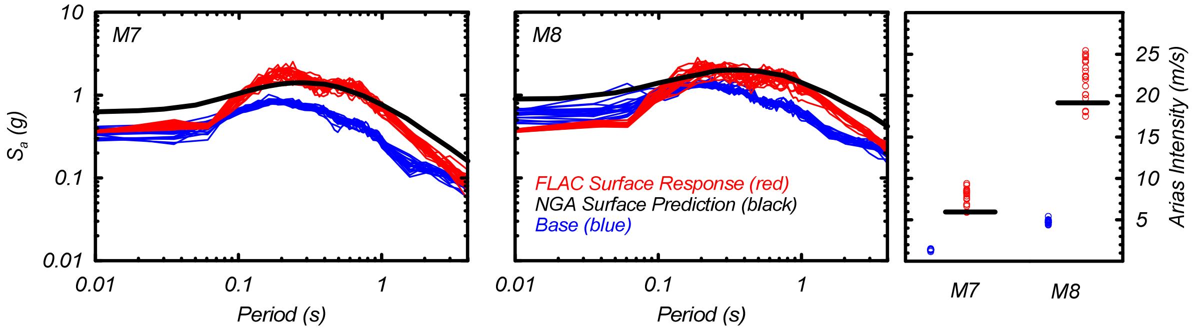

Fig 6. 50 m profile including 3 m of soft soil (Fig. 1.c), response spectra and I_a at the surface for 40 ground motions with predicted response parameters.

predicted spectral parameters for the surface are based on the NGA relations with V_{s30} = 350 m/s or V_{s30} = 320 m/s for the soft soil profile and $Z_{1.0}$ = 150 m or 50 m. The I_a predicted are based on Travasarou et al. (2003) and Watson-Lamprey and Abrahamson (2006) empirical relations.

When looking at the mean and median analyses results in comparison to the predictions, the 150 m profile's response is generally lower than the predictions for *PHA* and I_a. The two 50 m profiles are at or slightly above the prediction for I_a but below for *PHA*. When looking at the profiles over the full response spectra, however, the 50 m profiles do meet or exceed the predicted spectral amplitudes at larger periods.

The differences are not a result of flaws in predictive relations or the site-response analyses but rather due to extrapolation and approximations. The data set used to constrain the predictive relations is limited over the range of conditions often evaluated by DSOD (e.g. $R_{rup} < 15$ km, $Z_{1.0} < 150$ m). The $Z_{1.0}$ term is such that it is usually empirically determined and used to capture basin effects that occur in soil deposits deeper than the 50 m and 150 m evaluated here. As a result, the site response analyses described cannot be used to evaluate the accuracy of the predictive relations but rather as a reason for conducting site response modeling.

This observation can be expanded to the more general case of site specific analysis versus statistical averaging. The predictive relations, by necessity, are based on statistical evaluations over a large and variable number of sites and seismic events. Any specific site, seismic event, or ground motion recording, should not be expected to match the predictions. Site response analyses allow the average statistical predictions to be made site specific.

Differences in results with respect to the NGA relations may also be due to equivalent-linear vs. non-linear site response modeling. It was expected that use of the NGA-like profiles shown in Fig. 1 would provide results similar to the NGA predictions for equivalent-linear conditions. The NGA modelers, however, conducted analyses using equivalent-linear methods on many profiles that were based on Monte Carlo analyses. The authors here do not have the resources available to do similar analysis, but rather look at the exercise here as a site specific evaluation of an embankment foundation. Further, the reliance on non-linear site response modeling shown in this paper is unlikely to be similar to equivalent-linear analysis given the short distance and large loading used. Non-linear site response is implied in the NGA given the likelihood for non-linear behavior contributing to the actual surface recordings in the ground motion database. This makes definitive conclusions about the effects of equivalent-linear vs. non-linear analyses difficult.

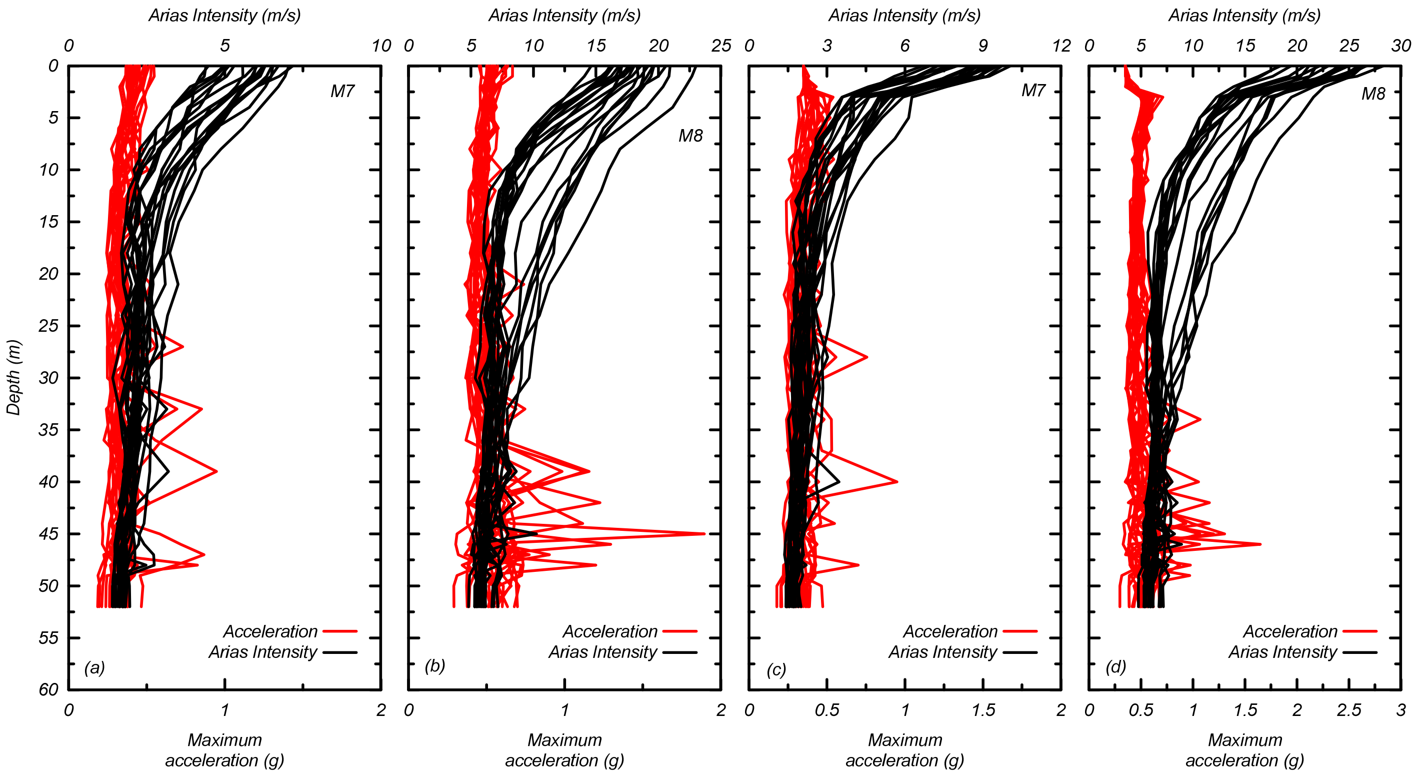

Fig. 7. 50 m profiles site response with depth, (a) & (b) standard profile for M7 & M8 per Fig. 1.b and (c) & (d) 3 m of soft soil for M7 & M8 per Fig. 1.c.

The predictive equations are not designed to handle soft soil conditions. This is dictated by limitations in prescribed use to conditions where $V_{s,30} > 150$ m/s. The profiles used here, however, show that soft soil layers can occur in profiles with large V_{s30} (320 m/s in the case presented). This possibility must be considered when evaluating site response or using the NGA and other predictive relations.

SUMMARY AND CONCLUSIONS

In summary, the preceding paper describes the evaluation of the site response in three soil profiles subjected to two seismic events represented by forty total motions. The conditions used are representative of site conditions that may be evaluated by DSOD in a generic seismic analysis.

The conditions evaluated are limited, but show that even with a one-dimensional analysis, the preferred method of seismic analysis should be to develop input motions for the base (e.g. bedrock) of the site in consideration and rely on site response analyses to evaluate an embankment. Given the breadth of the NGA relations, the predictions should not be used in-lieu of site response analyses or to judge the results of site response analyses. Comparisons of site-response versus predictive equations can be useful for understanding potential differences between the two and may increase the understanding of site conditions. In addition, Dam sites are inherently complicated, and two- and three-dimensional effects will only increase differences in site response from the predicted relations.

Arias Intensity is a parameter that can be useful for developing ground motions by constraining energy content and duration. It is shown here that I_a can change significantly due to site response, and the resulting standard deviation can be seen as a limitation of this ground motion parameter. Evaluation of the *COV* shows that the variation in I_a is not unreasonable and similar to the *COV* observed in *PHA*. The difference in mean and median I_a does not correlate to *PHA* directly since I_a is an integral parameter, which is influenced by the complete response spectra and motion duration. Arias Intensity in conjunction with response will likely give confidence that a thorough analysis can be completed efficiently with fewer ground motions.

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