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ESTABLISHING ROCK OUTCROP TIME SERIES AT VARIOUS DEPTHS IN A NONLINEAR SOIL COLUMN

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ABSTRACT

Nonlinear soil-structure interaction (NLSSI) analysis methods are currently being developed at Idaho National Laboratory (INL). Appendix B in ASCE 4 (2016) includes a framework for performing NLSSI analysis. For NLSSI analysis to be widely implemented in industry, it is important to demonstrate that accurate response in a dynamically loaded, nonlinear soil column can be produced.

In performing NLSSI analysis, one approach is to consider vertically propagating shear and compressive waves that pass through a nonlinear soil column and into a structure. Using finite element techniques, the structure can be placed in a finite volume of nonlinear soil with a rock outcrop seismic time series applied to the bottom of the nonlinear soil. The necessary depth of the nonlinear soil mesh is dependent on the vertical soil stiffness when the model is in static and dynamic equilibrium. Run time, and therefore size of the meshed soil domain, is an important consideration when developing the NLSSI model. An approach is presented in this paper that establishes compatible rock outcrop seismic time series for reduced nonlinear soil mesh depths. To apply the approach, an example is developed using a reasonable soil column with a reasonable top-of-soil response spectrum. The approach is an iterative method that is applied in two steps. The first step is used to establish a reasonable rock outcrop time series at the highest depth considered. The second step is used to establish compatible rock outcrop time series at shallower depths.

INTRODUCTION

Currently, a typical seismic analysis of a nuclear structure in the U.S. is performed with the assumption of vertically traveling, planer seismic waves that are evaluated with linear codes such as SHAKE (Deng et al. 2000) and SASSI (Lysmer et al.1999). In some cases, an appropriate top-of-soil time series is known and, depending on the soil depth to be modelled, an appropriate seismic time series must be established for input at the modelled depth. When using a linear solver such as SHAKE, having a known soil column and an acceleration time series at a given depth is sufficient to establish acceleration time series at any depth with a straightforward, closed form solution. This is true whether the acceleration time series is inlayer (the summation of upward and downward traveling waves) or rock outcrop (an upward traveling wave). Iterations may be necessary with linear analysis if the soil column material properties need to be calibrated to the time series being used.

Using the nonlinear hysteretic soil model that is currently being studied at the INL, a different approach is needed for defining appropriate acceleration time series at different soil depths. A case study is given in this paper to demonstrate one approach. The case study considers a reasonable soil column model and a reasonable horizontal top-of-soil acceleration time series. In the first step of the case study, an approximate rock outcrop acceleration time series is iteratively established 486 feet deep in the soil column. In the second step of the case study, an approximate rock outcrop acceleration time series is iteratively established at 220 feet deep in the soil column based on results from the 486 foot soil column model. The case study only considers one horizontal direction but it is applicable to all three directions.

TIME SERIES

The seismic time series used for this study is a portion of the top-of-soil acceleration time series from the 5.8 magnitude, Mineral, VA earthquake of August 23, 2011 as measured at Corbin, VA (USGS 2011). The entire seismic time series lasts a little over 190 seconds and much of the time series is relatively low amplitude. Consequently, only a little more than 20 seconds of the strong motion portion is used. The resulting time series is transitioned to a second of quiet time at the start and end, is oversampled (using fast Fourier techniques) from a 0.005 second time step to a 0.00125 second time step, and is drift corrected using frequencies less than 0.5 Hz. The resulting acceleration time series produces a very similar 5% damped response spectrum to that of the entire original acceleration time series.

SOIL COLUMN FINITE ELEMENT MODELS

The finite element models (FEMs) used for this study are shown in Figure 1. Figure 1 also shows the low strain shear velocity and density versus depth. These models and material properties are representative of a deep soil site in the Eastern U.S. The 486 foot FEM is defined with 37 nonlinear soil material properties and the 220 foot FEM is defined with 29 nonlinear soil material properties. Both FEMs are free at the top and have a single elastic element at the base. The elastic element has the elastic material properties of the soil layer where it is placed and is used primarily as a boundary condition. It has the rock outcrop seismic load time series applied to its top and a non-reflecting boundary condition on its bottom. Static gravitational loads are also applied to the FEMs and the models are run using LS-DYNA (LSTC 2013). With LS-DYNA, the non-reflecting boundary condition additionally supplies a static pressure to oppose the static gravitational loads.

To mimic an infinite horizontal continuum with the FEMs, each set of four nodes at an elevation is constrained to move together. Additionally, the element heights are set to pass up to 67•Hz waves with at least 10 elements per wave length.

The nonlinear soil constitutive model used in the FEMs is the hysteretic soil constitutive model (*MAT_HYSTERETIC_SOIL in LS-DYNA). This constitutive model is of a form that includes the Drucker-Prager model and is reasonable for nonlinear soil behaviour. The hysteretic soil behaviour results from post yielding shear stress versus shear strain. Each element has “layers” that are each elastic/perfectly plastic with different elastic stiffness and yield stress values. The elastic/plastic behaviour of each “layer” follows a kinematic hardening rule. The response of the “layers” is summed together to produce the post yielding shear stress versus shear strain curve (like those shown in Figure 2). Examples of the shear stress versus shear strain curves used for the case study material properties are shown in Figure 2.

As noted above, the FEMs accept a rock outcrop shear load time series on the elastic element at the bottom of a FEM. Considering only the elastic element, the shear strain in the element is equal to the velocity time series divided by the elastic element shear wave speed of sound. Considering that the shear stress is equal to the elastic element shear modulus multiplied by its shear strain, the shear load time series can be derived as a constant (based on the elastic element material properties) multiplied by the rock outcrop velocity time series (which can be found by integrating the rock outcrop acceleration time series). Consequently, if the nonlinear soil elements are deleted from one of the FEMs (shown in Figure 1), the resulting motion on the top of the elastic element would be the same rock outcrop motion that produced the load time series. However, if the FEMs have the nonlinear soil included, the motion at the top of the elastic element is an inlayer motion including the upward and downward traveling waves. The non-reflective boundary condition at the bottom of the elastic element ensures that downward traveling waves leave the model.

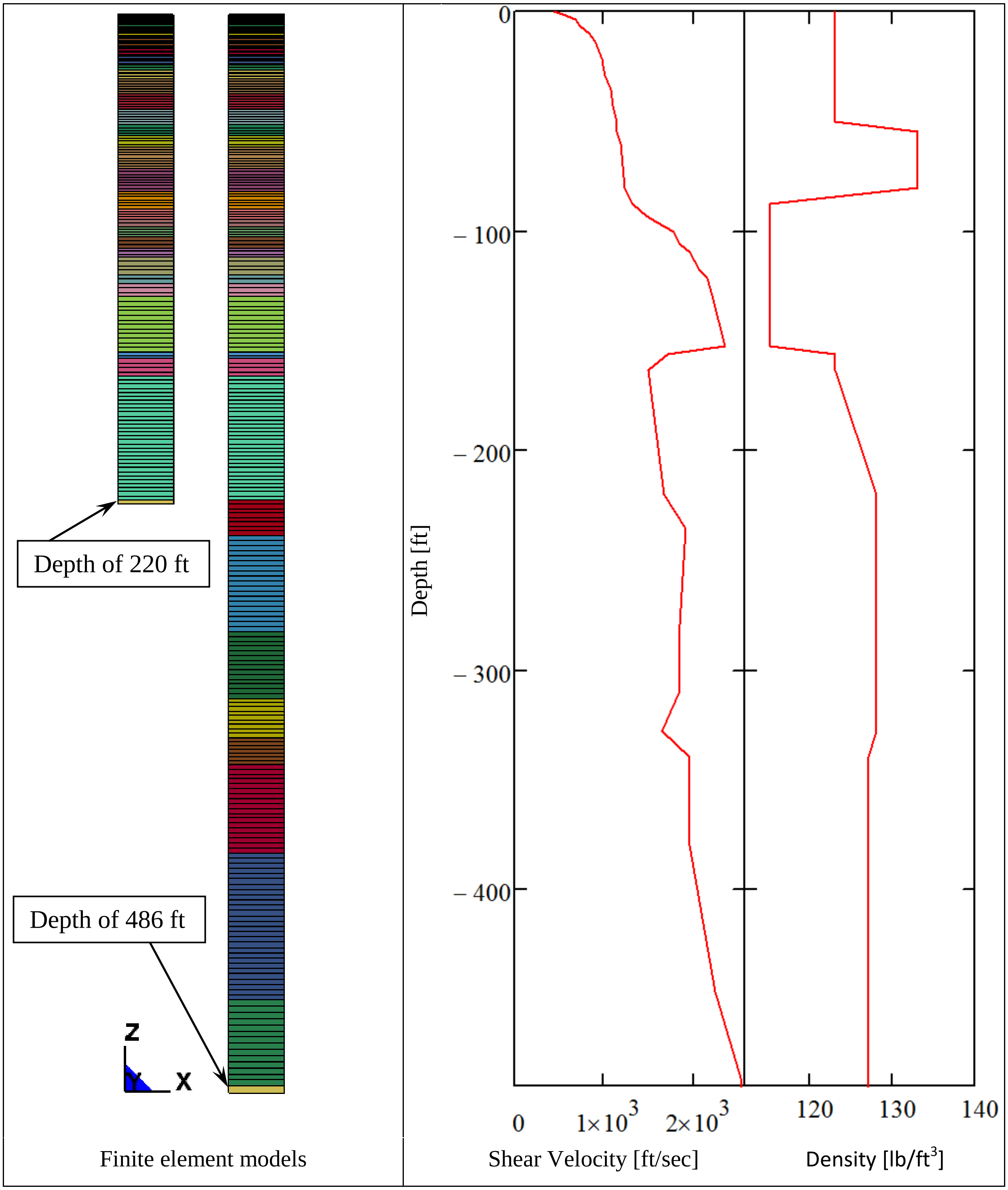

Figure 1. Soil column FEM geometry, low strain shear velocity, and density.

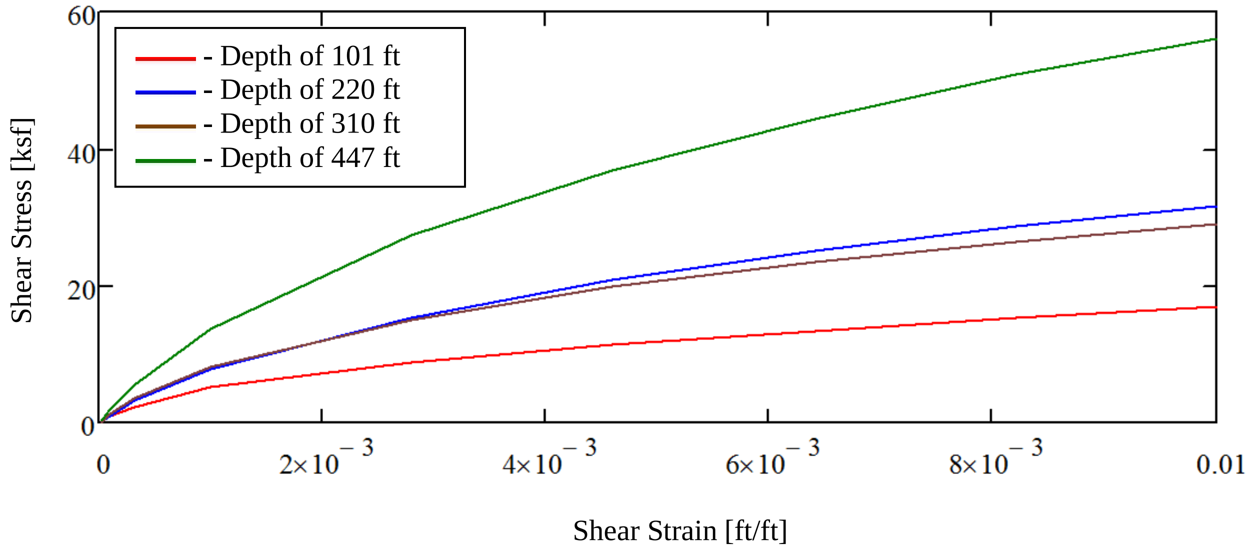

Figure 2. Example shear stress versus shear strain curves use in the soil column FEMs.

DEEP ROCK OUTCROP TIME SERIES (FIRST STEP)

For the first step of this case study, an approximate rock outcrop acceleration time series is iteratively established at 486 feet deep in the soil column. When used with the 486 foot deep FEM, the resulting FEM, top-of-soil motion approximately matches that of the given Corbin, VA (USGS 2011), top-of-soil motion.

The approach used is based on applying a similar time series at 486 feet deep as is desired at the top-of-soil except the frequency content is scaled. By scaling the frequency content, adjustments can be made to counteract amplification and damping that occurs as the waves pass through the soil column. The decision for how much to scale a given frequency amplitude is based on comparing the desired top-of-soil response with the FEM top-of-soil response.

Frequency content is found by taking the fast Fourier transform of the desired top-of-soil time series. The fast Fourier transform provides amplitude and phase angle information for all the sine waves which, when summed, produce a smooth curve through all of the time series data points. Consequently, if a given input time series produces a top-of-soil response that is too high at a given frequency, the frequency amplitude at that frequency could be scaled down. Once scaled, the inverse fast Fourier transform could be taken to produce an adjusted time series.

In this simplest way of scaling, the adjusted time series may drift badly and be difficult to manage. Consequently, the approach used in this study is a variation on this concept. For this study, a fast Fourier transform is performed on the desired top-of-soil time series. Next, the resulting sine waves are defined. Given that there are likely many more sine waves than evaluated frequencies in a response spectrum, sine waves with frequencies in the vicinity of a single response spectrum frequency are summed. Finally, the ends of the sine waves are modified with a smooth polynomial so that they are drift corrected and smoothly transition to zero (as shown in Figure 3). (In this study, the time period where the smooth polynomial is added is limited by the time period where less than 5% of the energy in the full time series is realized.) This process produces a set of modified sine wave time series where each represents a frequency where a response spectrum data point is evaluated. Summing these unscaled modified sine waves approximates the desired top-of-soil time series (with it being close to matching at the ends but exactly matching in the middle). The advantage of this approach is that scaling one of the modified sine waves and then summing them all together produces a modified time series that has adjusted frequency content but doesn't drift.

Having the modified sine waves, iterations can be performed. Initially, a scale factor of one is defined for each modified sine wave and a 5% damped acceleration response spectrum is generated for the Corbin, VA, top-of-soil acceleration (at the frequencies represented with the modified sine waves). For an iteration, the modified sine waves are multiplied by their scale factors and summed, the resulting acceleration time series is integrated to a velocity time series, and the velocity time series is used for the 486 foot FEM input load time series. Upon running the FEM, a 5% damped acceleration response spectrum is generated at top-of-soil. Finally, each scale factor is modified to equal its previous value multiplied by the Corbin, VA, top-of-soil response and divided by the FEM response.

Figure 4 shows the scale factors after two iterations. Figure 5 shows the resulting top-of-soil motion comparison between the Corbin, VA time series and the 486 foot FEM (noting that the Corbin, VA time series are offset by 0.294 seconds to accommodate the time that is required to pass the waves up through the FEM). Figure 6 shows the top-of-soil, 5% damped response spectra comparison between the Corbin, VA time series and the 486 foot FEM (noting that the FEM response spectrum is only plotted to 67 Hz because that is as high of a frequency as the FEM is intended to accurately model).

The response spectrum for this study had a maximum error of 10.6% and only one point (at 31.6 Hz) exceeded 10%. While imperfect, this method produced a reasonable result.

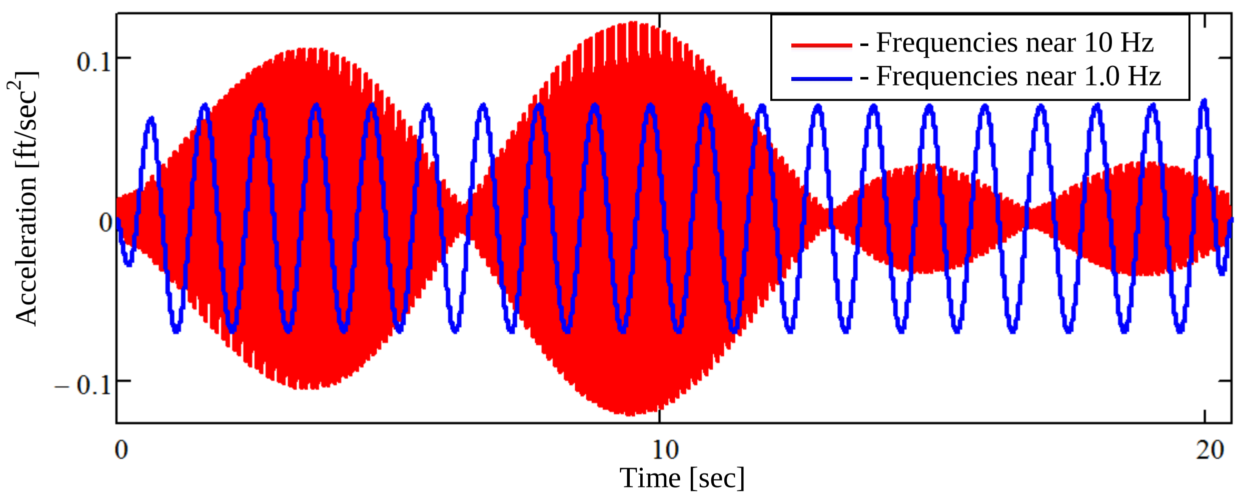

Figure 3. Modified sine waves with frequencies near two of those defined in a response spectrum.

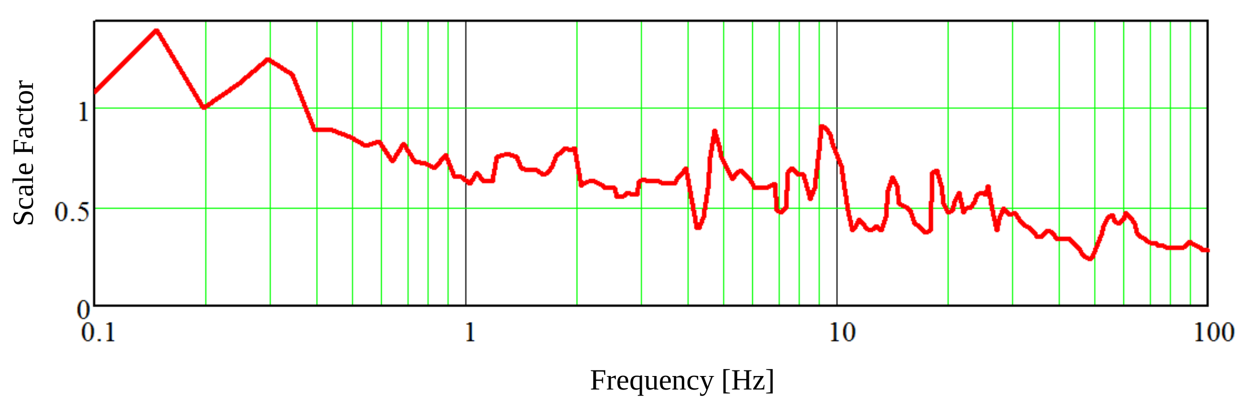

Figure 4. Scale factors after two iterations.

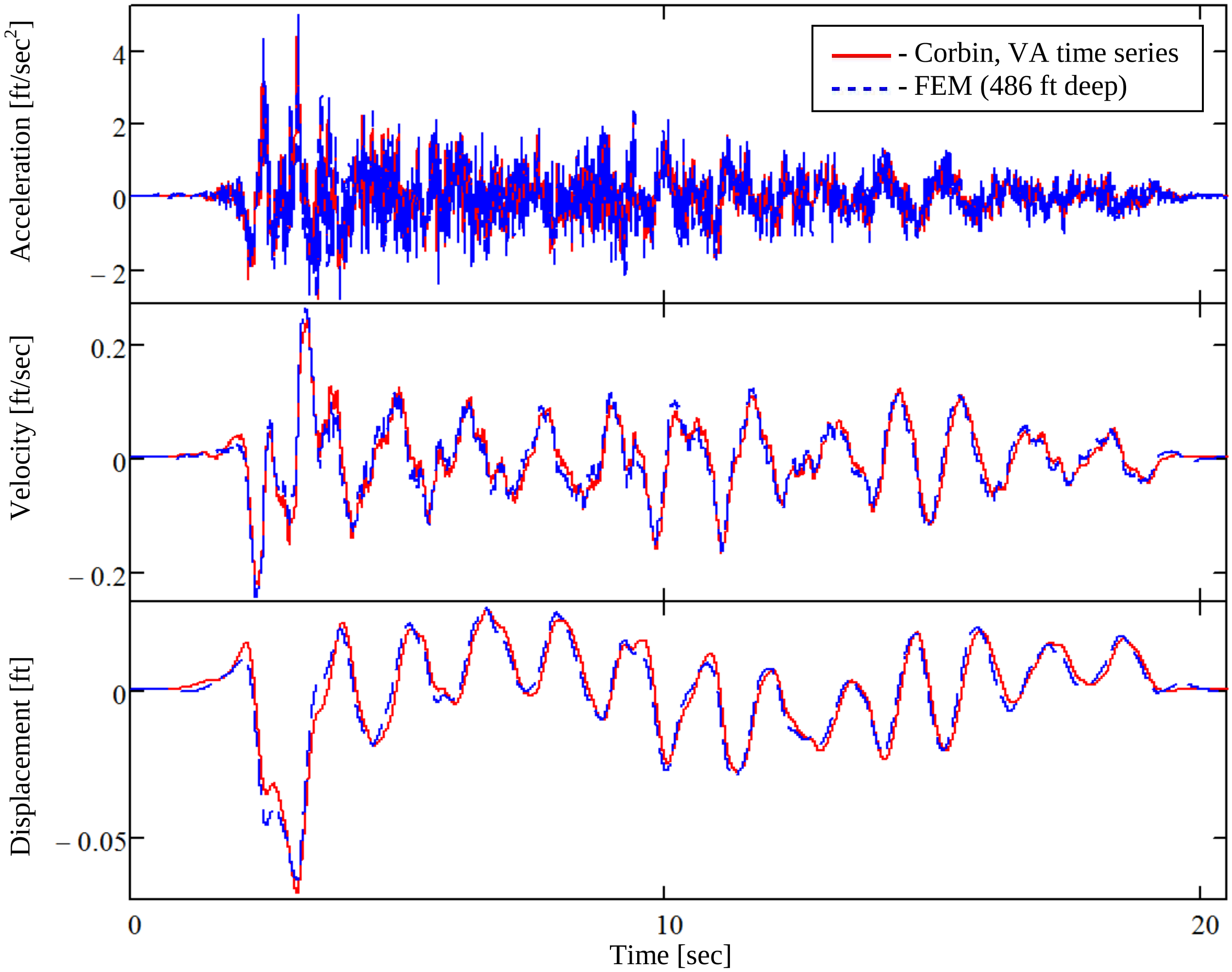

Figure 5. Top-of-soil motion comparison between the Corbin, VA time series and the 486 foot FEM.

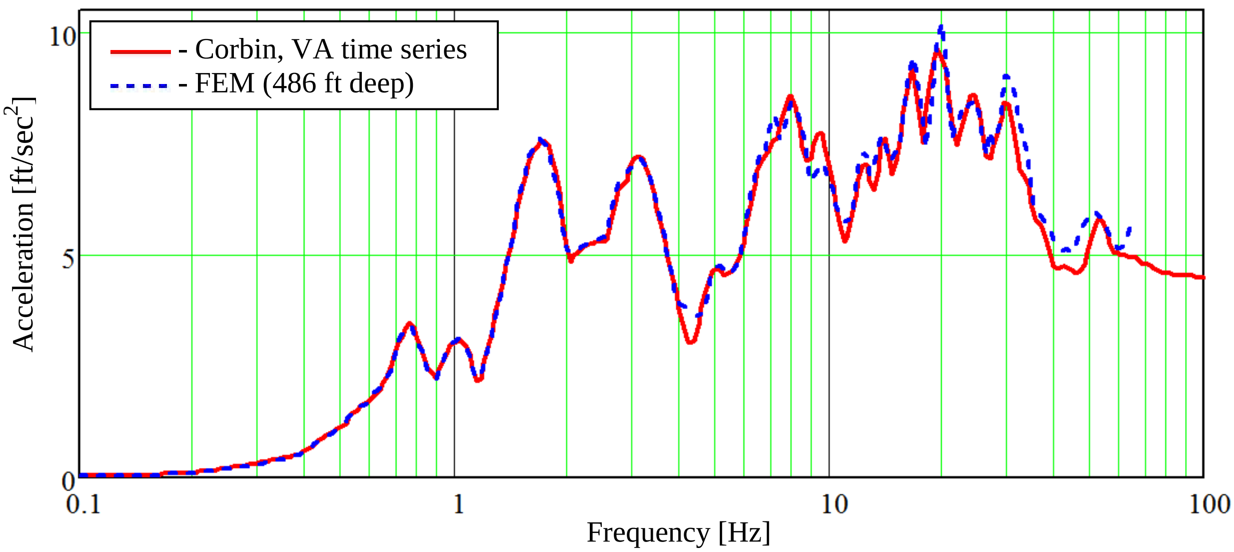

Figure 6. Top-of-soil response comparison between the Corbin, VA time series and the 486 foot FEM.

When comparing the accuracy of this step to a similar process with linear analysis, an important consideration is necessary. This consideration is that a single frequency input to the base of a linear soil model produces a single frequency response at the top-of-soil due to the elliptical shape of the viscous damping hysteresis loop. For a nonlinear analysis (as is used in this study), a single frequency input to the base produces a multi-frequency response at the top-of-soil due to the non-elliptical shape of the hysteresis loop. Considering that neither the linear nor nonlinear models exactly reproduce the stiffness of the real soil, the input rock outcrop time series at the base is not exactly correct for either model. This inexact stiffness may make it necessary to increase (or decrease) the frequency content at various frequencies in the input time series to produce the desired top-of-soil motion. With linear analysis, the added (or subtracted) frequency content can be accommodated without negative consequence because each frequency content modification only affects the top-of-soil response at that frequency. With nonlinear analysis, adding frequency content causes a top-of-soil response at that frequency and other frequencies. Having the frequency content added to the other frequencies can make it difficult to maintain reasonable input frequency content.

As an example, a situation could occur where an actual rock outcrop, low frequency input to a FEM does not produce as much top-of-soil response as the actual soil column (due to the FEM stiffness not being exactly correct). To reduce the top-of-soil discrepancy, more input low frequency content can be added (for either linear or nonlinear FEMs). For a linear FEM, the inaccuracy that this produces is limited to the low frequency content that has been modified. For the nonlinear model, this could additionally cause inaccuracies at higher frequencies. Adding additional high frequency content to correct the higher frequency inaccuracies could lead to inaccuracies at yet higher frequencies. Attempting to address all the resulting inaccuracies could produce an unreasonably inaccurate input time series. Considering this example, few iterations are performed on the nonlinear model and an inexact result that is close to the real top-of-soil motion is considered acceptable.

SHALLOW ROCK OUTCROP TIME SERIES (SECOND STEP)

For the second step of this case study, a rock outcrop acceleration time series is iteratively established at 220 feet deep in the soil column. In this step, the inlayer acceleration at 220 feet is compared between the two FEMs to make adjustments instead of comparing top-of-soil response spectra. This step is relatively simple but can become unstable. Considering the nonlinear soil constitutive model being used, there is a possibility for some erroneous high frequency noise. In reasonably defined soil material properties, this should be at frequencies higher than are of concern and not of significant magnitude. However, the iterative approach described in this study can magnify the high frequency noise issues to the point of making the approach unstable. To reduce the possibility of this instability, an initial modification is performed on the 220 foot, inlayer acceleration time series taken from the 486 foot deep FEM. This first involves taking the fast Fourier transform of the time series. Second, the frequency amplitudes above 100 Hz are ramped to near zero (considering that this is well above the 67 Hz cut off for frequencies that these FEMs can evaluate accurately). Third, the inverse fast Fourier transform is performed to produce a time series with less high frequency content. This modification is likely to cause a small amount of drift. For this this study, this was corrected by adding a quarter second smooth correction (in the shape of a sine wave) to the start of the acceleration time series. The resulting modified acceleration time series is used as the desired inlayer motion for the 220 foot FEM.

Having a target inlayer acceleration time series, iterations can be performed. Initially, the target inlayer acceleration time series is integrated to velocity and used in the 220 foot deep FEM as though it is an input rock outcrop motion. For an iteration, the 220 foot deep FEM is run and the inlayer acceleration time series is output at 220 feet. Next, this inlayer acceleration is subtracted from the desired inlayer motion and the result is added to the acceleration used as rock outcrop for the 220 foot deep FEM. Because of the instability risk, the modified rock outcrop acceleration has the high frequency (above 100 Hz) ramped down and drift correction performed similar to the adjustment originally performed on the desired inlayer motion. Finally, the new rock outcrop acceleration time series is integrated to velocity for the next iteration.

Results shown in Figures 7 and 8 are for the second step of the case study performed with 125 iterations. Figure 7 shows the top-of-soil motion comparison between the 220 foot FEM and the 486 foot FEM. Figure 8 shows the top-of-soil, 5% damped response spectra comparison between the 220 foot FEM and the 486 foot FEM (noting that the response spectra are only plotted to 67 Hz because that is as high a frequency as the FEMs are intended to accurately model).

The response spectrum for this study had a maximum error of 1.5%. Figure 9 demonstrates the convergence of the iterations (based on the velocity time series curves). At 10 iterations, the percent difference for inlayer velocity between the 220 foot FEM and the 486 foot FEM was less than 0.2% until almost 2 seconds and the maximum percent error was 7.4%. At 50 iterations, the percent difference was less than 0.2% until a little more than 8 seconds and the maximum percent error was 1.7%. At 100 iterations, the percent difference was less than 0.2% until a little less than 16 seconds and the maximum percent error was 0.7%. At 125 iterations, the percent difference was less than 0.2% for the whole time series.

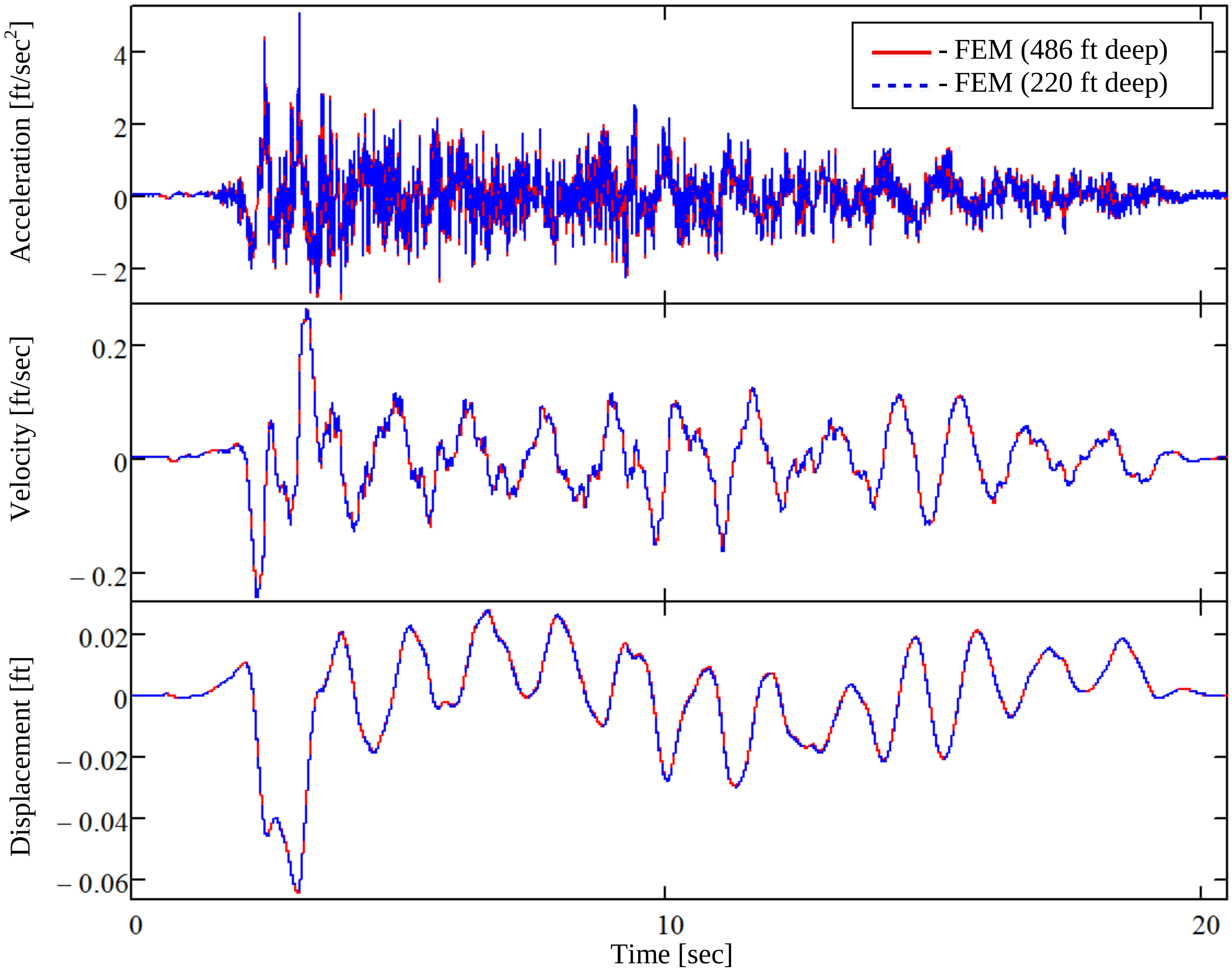

Figure 7. Top-of-soil motion comparison between the 220 foot FEM and the 486 foot FEM.

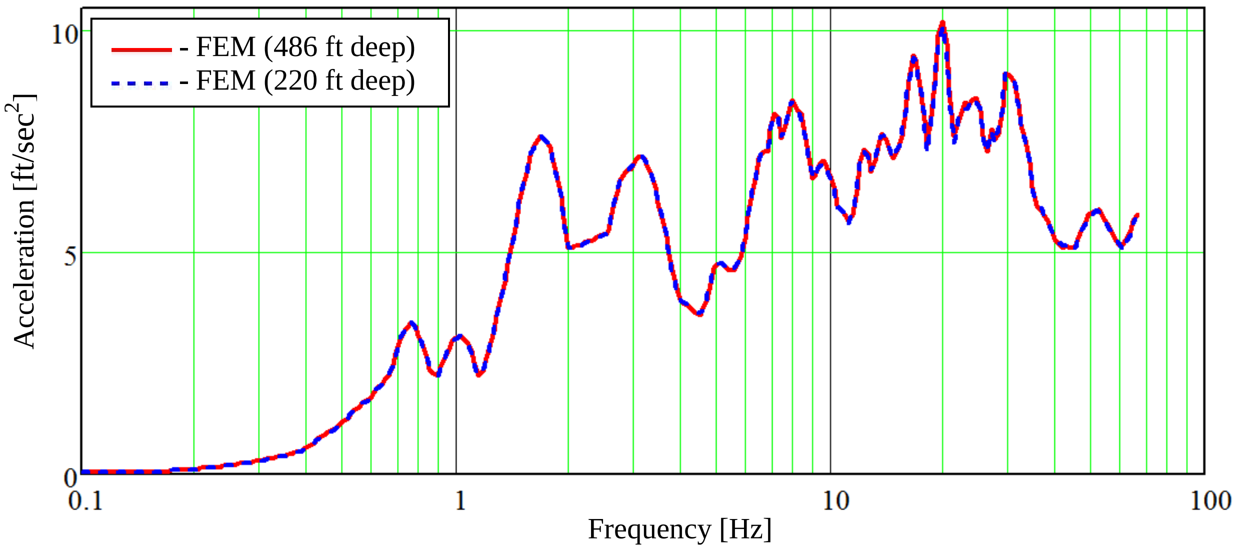

Figure 8. Top-of-soil response comparison between the 220 foot FEM and the 486 foot FEM.

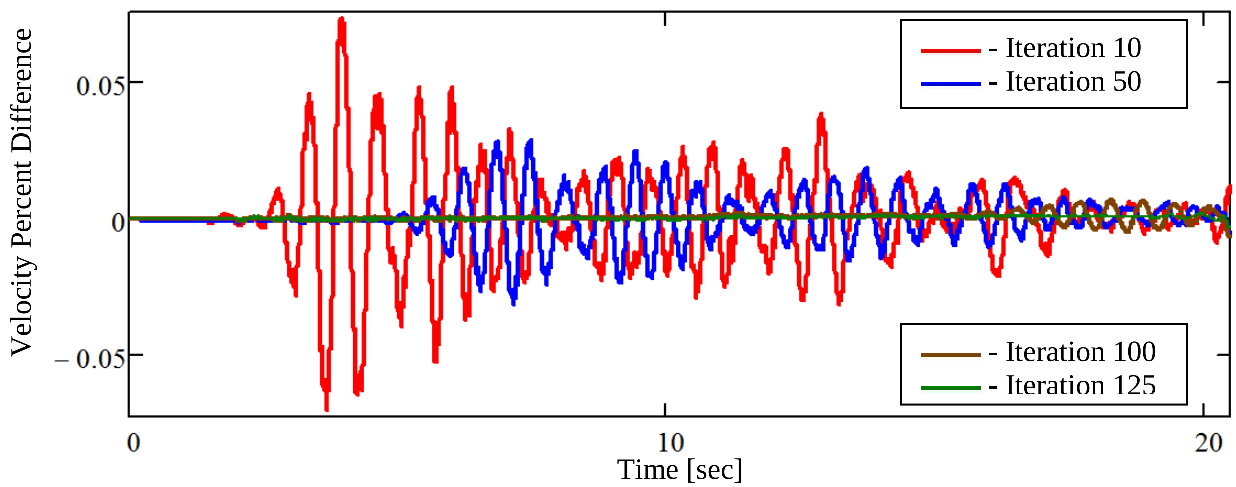

Figure 9. Percent difference of the FEM and desired inlayer velocity curves at specific iterations.

This step produced a stable convergence to an accurate and reasonable time series. The reason this converges better than the first step is that the 486 foot FEM results at the 220 foot depth are used to iterate the 220 foot FEM input. Having the same stiffness definition in both models, an exact match should be possible without the need for added frequency content used to counteract inaccurate frequency content.

CONCLUSION

Using the nonlinear hysteretic soil model that is currently being studied at the INL, an approach has been applied to a case study for defining appropriate acceleration time series at different soil depths. The case study considers a reasonable soil column model and a reasonable horizontal top-of-soil acceleration time series. In the first step of the case study, an approximate rock outcrop acceleration time series is iteratively established 486 feet deep in the modelled soil column. This study showed that the proposed approach for the first step produced reasonable results. However, the accuracy of this approach could possibly be improved with more refinements. In the second step of the case study, an approximate rock outcrop acceleration time series is iteratively established at 220 feet deep in the soil column based on results from the 486 foot soil column model. This study showed that the proposed approach for the second step produced very accurate results when sufficient iterations were performed.

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