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SEISMIC SITE RESPONSE ANALYSIS USING SPREADSHEETS

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ABSTRACT

A spreadsheet-based framework for quantifying local site response due to seismic excitation is presented in this paper. The main focus here is on equivalent-linear one-dimensional analysis, similar to the computer program *SHAKE* or its derivative kin, which by far is the most commonly used approach for performing ground response evaluation. Such analysis involves the computation of the response of a semi-infinite horizontally layered deposit overlying a uniform half-space subjected to vertically propagating shear waves. The bulk of the analysis is actually carried out in the frequency domain, which involves operations with complex-algebraic parameters. Widely available spreadsheet software is typically equipped with sophisticated features, such as programmability and handling of complex-valued data (even Fourier analysis), rendering these productivity tools fully tenable for seismic site response analysis. Since frequency domain analysis is valid primarily for linear systems, an iterative procedure is typically employed to approximate the nonlinear behavior of soil/rock materials. The benefits of performing seismic site response calculations with spreadsheets can be quite substantial, considering their rigorous functionality, dependability, and customizability, in addition to their robustness, user-friendliness, and cost-effectiveness. While the thrust of this paper is directed at the equivalent-linear one-dimensional approach, most of the spreadsheet techniques presented here can also be applied and extended to nonlinear analyses, even in two or more dimensions.

INTRODUCTION

Seismic analyses of structural and geotechnical systems that account for site effects, even in an approximate sense, can often lead to more realistic, efficient, and safer earthquake-resistant designs. Prudent engineering practice calls for a thoughtful consideration of the amplifying effect that the site can have on earthquake-induced ground motions. Such site effects can reasonably be quantified by conducting ground response analyses.

Over the years, various techniques have been developed for site response analysis, the main purpose of which is to estimate the motions near the surface of a soil profile resulting from a given base rock motion. The techniques are often grouped according to the dimensionality of the problems they can address, although many of the two- and three-dimensional techniques are relatively straightforward extensions of corresponding one-dimensional techniques. Both equivalent-linear and nonlinear techniques have been used successfully for site response analysis. Neither can be considered mathematically rigorous or precise, yet their accuracy is not inconsistent with the variability in soil conditions, uncertainty in soil properties, and scatter in the experimental data upon which many of their input parameters are based (Kramer, 1996). The one-dimensional equivalent-linear approach is by far the most common ground response modeling procedure utilized in practice (Kramer and Paulsen, 2004). Nevertheless, several researchers have recently established benchmarks toward validating nonlinear ground response analyses (e.g., Stewart *et al*., 2008).

Why Use Spreadsheets for Seismic Site Response Analysis?

Although seismic site response analysis can be performed using readily available computer software, occasionally the person doing such analysis may rely completely on the output generated by such software, and for various reasons may not bother to perform an independent check of the calculations. Along with the intuitive tabular interface familiar to virtually all users, spreadsheets nowadays contain enhanced standard features, e.g., built-in advanced functions and powerful programmability, such that it is quite practical to perform ground response analysis with these ubiquitous productivity tools. The benefits of performing seismic site response calculations with spreadsheets can be quite substantial, considering that: it would provide a cost-effective means for validating the output results from other ground response analysis program(s); it would enable the user to readily plot the results using the charting capabilities typically integrated with the spreadsheet software package; it would allow the analyst to better understand the underlying concepts and computations involved in the seismic site response evaluation; and, once the inner workings are well understood, the analytical scheme could still be customizable enough for tackling various other types of scenarios as needed.

This paper introduces a novel paradigm for quantifying local site response due to seismic excitation, by leveraging with the advanced functionality and features embedded in modern spreadsheets. While the focus here is on one-dimensional equivalent-linear ground response analysis, the spreadsheet techniques presented in this paper can also be applied and extended to nonlinear analyses, and possibly even to two or more dimensions.

REVIEW OF EQUIVALENT-LINEAR SEISMIC SITE RESPONSE METHODOLOGY

One-dimensional site response analyses are based on the assumption that all boundaries are horizontal and that the response of a soil deposit is predominantly caused by the upward propagation, from the underlying bedrock through the various soil strata, of horizontally straining shear (SH) waves. For one-dimensional site response analysis, the soil and bedrock surfaces are assumed to extend infinitely in the horizontal direction. Procedures based on this assumption have been shown to predict ground response that is in reasonable agreement with measured response in many cases (Kramer, 1996).

Nonlinear soil behavior can quite often be simulated through an equivalent-linear soil material modeling approach. The advantages of equivalent-linear modeling in ground response analyses include minimal computational effort with relatively few input parameters. The most prevalent equivalent-linear computer code used in practice is *SHAKE* (Schnabel *et al.*, 1972), or any of its derivative cousins such as *SHAKE91* (Idriss and Sun, 1992) or *SHAKE04* (Youngs, 2004).

Equivalent-linear modeling is based on a total-stress representation of soil behavior. As shown in Fig. 1, the hysteretic stress-strain behavior of soils under symmetrical cyclic loading is represented by: (1) an equivalent shear modulus (G), corresponding to the secant modulus through the endpoints of a hysteresis loop; and (2) equivalent viscous damping ratio (β), which is proportional to the energy loss from a single cycle of shear deformation. Both G and β are generally functions of shear strain, as shown in Fig. 2. Simplistically speaking, G and β are just about the only parameters required for ground response analyses. As implemented numerically, however, G is evaluated as the product of small-strain shear modulus G_{max} and G/G_{max}, where $G_{max} = \rho V_s^2$ (ρ = mass density, V_s = shear wave velocity) and G/G_{max} is the modulus reduction factor, which depends upon the shear strain level as shown in Fig. 2. Hence, the soil properties actually needed for analysis are the shear wave velocity (V_s), mass density (ρ), and curves for the modulus reduction factor (G/G_{max}) and damping ratio (β) as functions of shear strain.

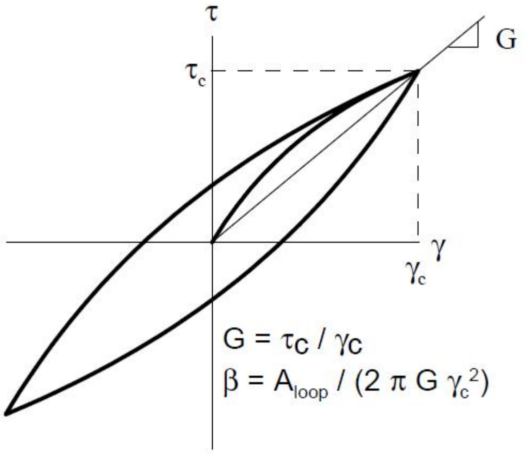


Fig. 1 -- Hysteresis Loop for Soil Loaded in Shear

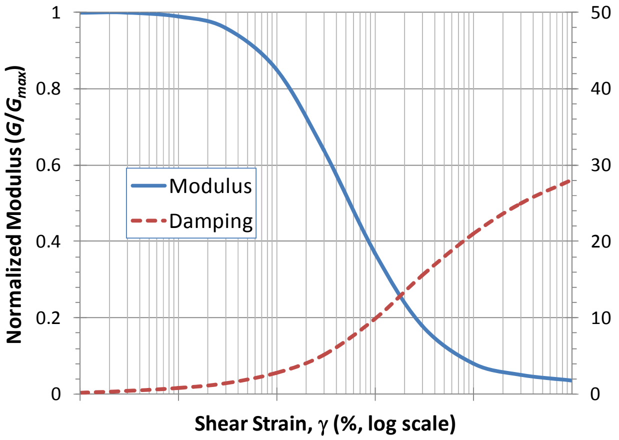


Fig. 2 -- Variation of Normalized Modulus (G/G_{max}) and Damping Ratio (β) with Shear Strain

Wave Equation Theory

Most computer programs developed for one-dimensional equivalent-linear site response analyses have generally been based on the solution to the wave equation, which mathematically describes the oscillating response due to vertical propagation of shear waves through a linear viscoelastic system. Such a system is schematically depicted in Fig. 3, which consists of *N* horizontal layers, inclusive of half-space as the N^{th} layer, with each layer extending to infinity in the lateral direction. Each layer is homogeneous and isotropic, and is characterized by thickness *h*, mass density ρ, shear modulus *G*, and critical damping ratio β.

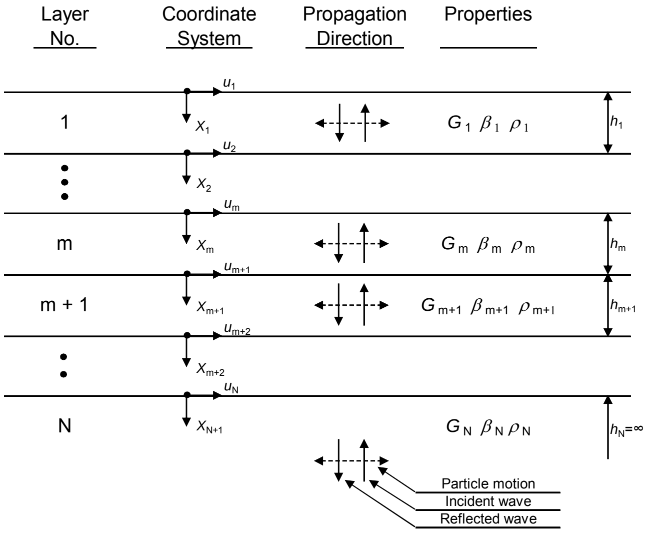


Fig. 3 -- One-Dimensional Viscoelastic System

For the purposes of viscoelastic wave propagation, soils are usually modeled as materials whose resistance to shearing deformation is the sum of an elastic part and a viscous part. Such materials are commonly referred to as Kelvin-Voigt solids. The particle motion due to vertical propagation of shear waves through the one-dimensional viscoelastic system of Fig. 3 is governed by a partial differential equation, called the wave equation, of the form:

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial x^2} + \eta \frac{\partial^3 u}{\partial x^2 \partial t} \qquad (1)$$

where: $u = u(x, t)$ = horizontal displacement as a function of vertical distance *x* and time *t*; and η = material viscosity, which has a strong affinity with both the shear modulus *G* and critical damping ratio β.

If the horizontal displacement *u* is harmonic in character with an oscillating frequency ω, it can be expressed (in complex algebraic notation) in terms of its amplitude *U* by:

$$u(x,t) = U(x) \cdot e^{i\omega t} \qquad (2)$$

The combination of Equations 1 and 2 leads to an ordinary differential equation:

$$(G + i\omega\eta)\frac{d^2U}{dx^2} + \rho\omega^2 U = 0 \qquad (3)$$

which has a general solution epitomized by

$$U(x) = E \cdot e^{ikx} + F \cdot e^{-ikx} \qquad (4)$$

where

$$k^2 = \frac{\rho\omega^2}{G + i\omega\eta} = \frac{\rho\omega^2}{G^*} \qquad (5)$$

E corresponds to the amplitude of the incident wave propagating in the negative *x*-direction (upwards); *F* represents the amplitude of the reflected wave traveling in the positive *x*-direction (downwards); *k* is the complex wave number; and *G** is the complex shear modulus.

The relationship among the material viscosity η, shear modulus *G*, and critical damping ratio β is typically defined for Kelvin-Voigt systems by

$$\omega\eta = 2G\beta \qquad (6)$$

Data from numerous experiments with soil materials indicate that *G* and β are nearly constant over the frequency range of main interest in site response analyses. Thus, it is convenient to express the complex shear modulus in terms of the critical damping ratio instead of the viscosity:

$$G^* = G + i\omega\eta = G(1 + 2i\beta) \qquad (7)$$

About a year after the initial release of the computer program SHAKE (Schnabel *et al.*, 1972), a slightly improved redefinition of the complex shear modulus was proposed (Udaka and Lysmer, 1973):

$$G^* = G(1 - 2\beta^2 + i2\beta\sqrt{1-\beta^2}) \qquad (8)$$

Since then, all subsequent versions of *SHAKE* or its kin have apparently adopted the complex shear modulus as expressed in Equation 8.

Equations 2 and 4 jointly give the solution to the wave equation for a harmonic motion of frequency ω:

$$u(x,t) = E \cdot e^{i(\omega t + kx)} + F \cdot e^{i(\omega t - kx)} \qquad (9)$$

in which the additive components (with leading amplitude coefficient *E* or *F*) represent the incident wave in the negative *x*-direction (upwards) and the reflected wave in the positive *x*-direction (downwards), respectively.

Based on Equation 9, an expression for the shear strain can readily be derived:

$$\gamma(x,t) = \frac{\partial u}{\partial x} = ik \cdot [E \cdot e^{i(\omega t + kx)} - F \cdot e^{i(\omega t - kx)}] \qquad (10)$$

and the corresponding shear stress on the associated horizontal plane is calculable via the appropriate constitutive relation:

$$\tau(x,t) = G^* \cdot \gamma(x,t) \qquad (11)$$

Key conditions that apply here are that the shear stress (and the shear strain) is nil at the free surface (*x* =0), and that stresses and displacements must be continuous at all interfaces. Invoking a local coordinate system for each of the layers in Fig. 3, the amplitudes of the incident and reflected waves in layer *m*+1 can be couched in terms of the corresponding amplitudes in layer *m* by means of accessible recursion formulas:

$$E_{m+1} = \tfrac{1}{2} E_m \left(1+\alpha_m\right) e^{ik_m h_m} + \tfrac{1}{2} F_m \left(1-\alpha_m\right) e^{-ik_m h_m} \tag{12}$$

$$F_{m+1} = \tfrac{1}{2} E_m \left(1-\alpha_m\right) e^{ik_m h_m} + \tfrac{1}{2} F_m \left(1+\alpha_m\right) e^{-ik_m h_m} \tag{13}$$

where α_m is the complex impedance ratio:

$$\alpha_m = \frac{k_m G_m^*}{k_{m+1} G_{m+1}^*} = \left(\frac{\rho_m G_m^*}{\rho_{m+1} G_{m+1}^*}\right)^{1/2} \tag{14}$$

Beginning with the surface layer, repeated use of the recursion formulas in Equations 12 and 13 can lead to relationships, called transfer functions, between the amplitudes in a particular layer and those in the surface layer. By the same token, transfer functions can be established between any two layers in the system. Accelerations can also be obtained through the displacement function (Equation 9), viz.:

$$a(x,t) = \frac{\partial^2 u}{\partial t^2} = -\omega^2 [E \cdot e^{i(\omega t + kx)} + F \cdot e^{i(\omega t - kx)}] \tag{15}$$

or:

$$a(x,t) = -\omega^2 \cdot u(x,t) \tag{16}$$

Solution in Frequency Domain

The appeal of an equivalent-linear approach rests substantially on its natural eligibility to invoke superposition-based techniques, such as the summation of harmonic motions in time and especially within the frequency domain. In a linear system, a complicated loading function such as an earthquake-induced ground motion can be broken down into a series of relatively simple harmonic loading functions (à la Fourier), for which the principle of superposition allows plausible solutions for harmonic loading to be combined to compute the total response. The process of synthesizing the complicated seismic loading function in a linear system into more manageable series of functions is typically executed via Fourier transformation.

By definition, the Fourier transform of a time-dependent function, such as a set of seismic loading *r*(*t*), is given by:

$$R(\omega) = \int_{-\infty}^{\infty} r(t) e^{-i\omega t} dt \tag{17}$$

which essentially converts the effective domain of the function from time *t* into frequency *ω*, through a convolution-type integral operation with a harmonic series (as represented by the exponential term $e^{-i\omega t}$).

Upon transformation of the seismic loading function from the time domain into the frequency domain, multiplicative and additive operations through transfer functions (for a one-dimensional system) can be carried out accordingly. The intermediate goal of these transfer-function operations will typically be to obtain the vector of amplitudes of the desired system response *S* as a function of frequency *ω*. This vector of system response amplitudes can then be teleported back into the time domain by means of the inverse Fourier transform:

$$s(t) = \int_{-\infty}^{\infty} S(\omega) e^{i\omega t} d\omega \tag{18}$$

Numerical implementation of Fourier transformation and frequency domain operations inherently requires the use of discrete, rather than continuous, Fourier analysis techniques. This is usually accomplished through efficient Fast Fourier Transform (FFT) algorithms (e.g., Cooley and Tukey, 1965; Brigham, 1974).

Iterative Procedure to Simulate Nonlinearity

In order to simulate the nonlinear behavior of soil materials, equivalent-linear modeling of local site response involves an iterative procedure, as graphically illustrated in Fig. 4. At the outset, estimates of shear modulus and damping are provided for each soil layer. Using these linear, time-invariant properties, linear dynamic analyses are carried out to quantify the response of the soil deposit. Shear strain histories are obtained from the results, and peak shear strains are evaluated for each layer. Taken as a fraction of the peak strains, the operative shear strains are then used to calibrate and adjust the *G* and *β* values for the respective layers at each iterative step. The process is repeated until the modulus and damping parameters are deemed compatible with the shear strain levels anticipated in the dynamic response analyses. At that point, the analysis is said to have "converged," and is then terminated.

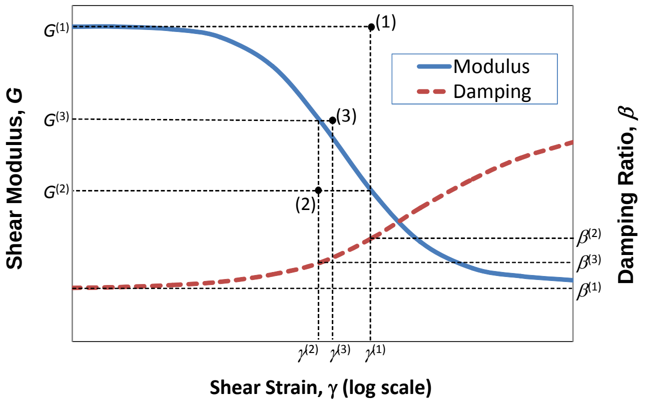


Fig. 4 – Iteration toward Strain-Compatible Soil Properties

Even though, as described above, the process of iteration toward strain-compatible soil properties allows nonlinear soil behavior to be approximated, it is important to keep in mind that the overall methodology is still essentially linear. The strain-compatible soil properties are constant throughout the duration of the earthquake, regardless of the level of straining at any particular time. Such method is incapable of representing the changes in soil stiffness that may actually occur during the earthquake (Kramer, 1996).

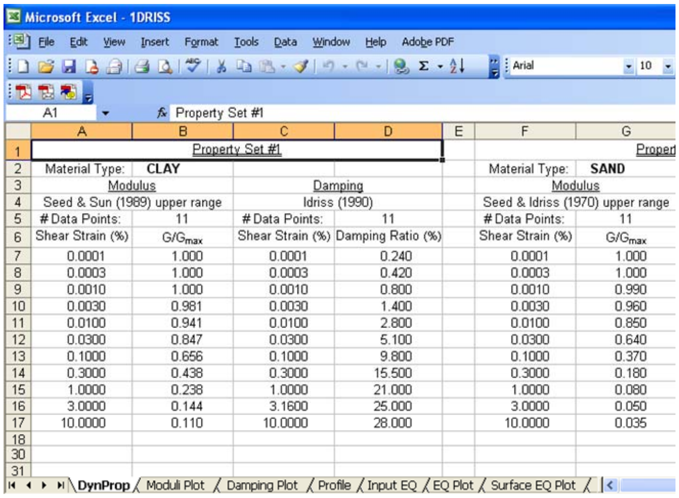
IMPLEMENTATION OF EQUIVALENT-LINEAR APPROACH USING SPREADSHEETS

Given the open-ended nature of most readily available spreadsheet software, the methodology presented here is merely one of several possible approaches for the spreadsheet implementation of seismic site response analysis. The present methodology has specially been dubbed as *1DRISS*, which is an acronym for One(1)-Dimensional Response as Implemented on Spreadsheets. Although current implementation has primarily been on Microsoft® Excel 2003/2007, the approach exemplified in this paper should also generally be applicable to other spreadsheet software with sophisticated features and programming capabilities.

Spreadsheet Architecture

For seismic ground response analysis purposes, a single spreadsheet/workbook file can be organized to contain all the input information relevant to a particular site and scenario, as well as the desired output. Separate tabs within the spreadsheet/workbook itself can be prepared to house clusters of data pertaining respectively to material properties, site profile/stratification, seismic input, and graphic plots of various data sets. Certain rows and/or columns within some of the worksheets/tabs can then be populated accordingly with intermediate calculations and/or analytical results, depending on the structure and nature of the data.

Material Properties. Figure 5 shows a portion of a sample worksheet that contains the data on material properties, specifically, the points that define the curves for the moduli and damping ratios as functions of shear strain for each material type. Although not entirely visible (due to space constraints and readability considerations), the worksheet portrayed in Fig. 5 actually contains three sets of data corresponding to three material types. One can also get some idea as to how the *1DRISS* workbook is organized, by looking at the various tabs on display (at the bottom of Fig. 5) with labels that indicate their respective contents. For example, the tab labeled "Moduli Plot" contains the semi-logarithmic plot of the three sets of normalized modulus curves as functions of the shear strain, as presented in Fig. 6. Similarly, the tab labeled "Damping Plot" has the curves for the damping ratios as functions of the shear strain, as manifested in Fig. 7 (where two of the curves coincide).



	A	B	C	D	E	F	G
1	Property Set #1						Propert
2	Material Type:	CLAY				Material Type:	SAND
3	Modulus		Damping			Modulus	
4	Seed & Sun (1989) upper range		Idriss (1990)			Seed & Idriss (1970) upper range	
5	# Data Points:	11	# Data Points:	11		# Data Points:	11
6	Shear Strain (%)	G/G_{max}	Shear Strain (%)	Damping Ratio (%)		Shear Strain (%)	G/G_{max}
7	0.0001	1.000	0.0001	0.240		0.0001	1.000
8	0.0003	1.000	0.0003	0.420		0.0003	1.000
9	0.0010	1.000	0.0010	0.800		0.0010	0.990
10	0.0030	0.981	0.0030	1.400		0.0030	0.960
11	0.0100	0.941	0.0100	2.800		0.0100	0.850
12	0.0300	0.847	0.0300	5.100		0.0300	0.640
13	0.1000	0.656	0.1000	9.800		0.1000	0.370
14	0.3000	0.438	0.3000	15.500		0.3000	0.180
15	1.0000	0.238	1.0000	21.000		1.0000	0.080
16	3.0000	0.144	3.1600	25.000		3.0000	0.050
17	10.0000	0.110	10.0000	28.000		10.0000	0.035
18							
30							
31							

Fig. 5 -- Worksheet for Modulus and Damping Properties

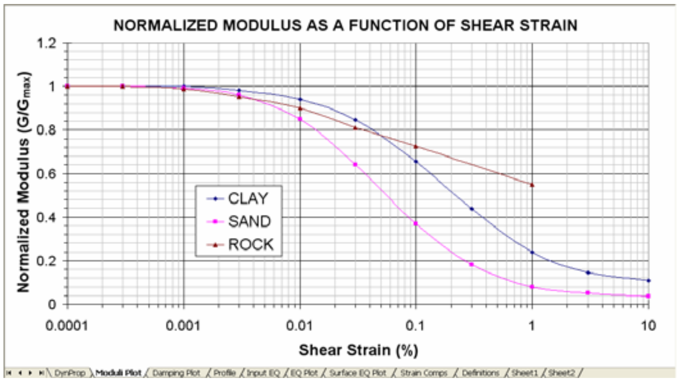


Fig. 6 -- Tab for Normalized Modulus vs. Shear Strain Plot

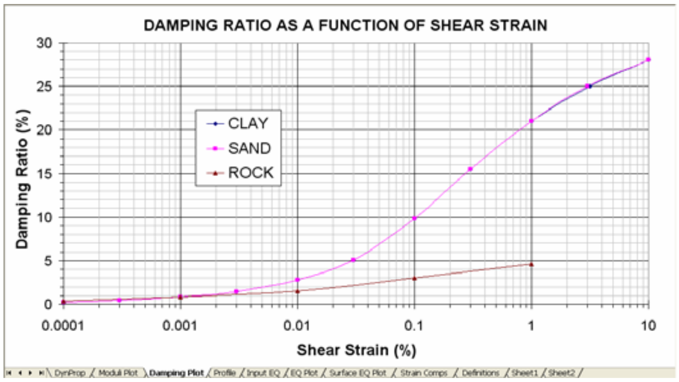
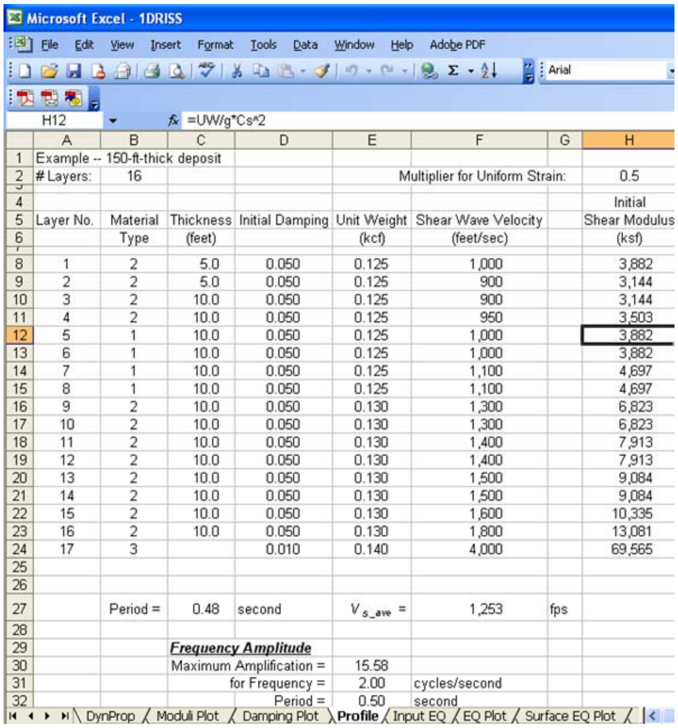


Fig. 7 -- Tab for Damping Ratio vs. Shear Strain Plot

Site Profile. As can be seen in Figs. 5 through 7, there is a tab in the *1DRISS* workbook labeled "Profile," which corresponds to the worksheet containing the data pertaining to the soil stratification at the site. Figure 8 typifies how the soil profile data can be tabulated for each layer at the site in regard to material type, thickness, initial damping ratio, unit weight, and shear wave velocity. Knowing the mass density ρ and the shear wave velocity V_s of the soil, the corresponding shear modulus G for each layer can then be evaluated based on the relation $G = \rho V_s^2$. The average shear wave velocity and overall fundamental period for the site can also be computed.

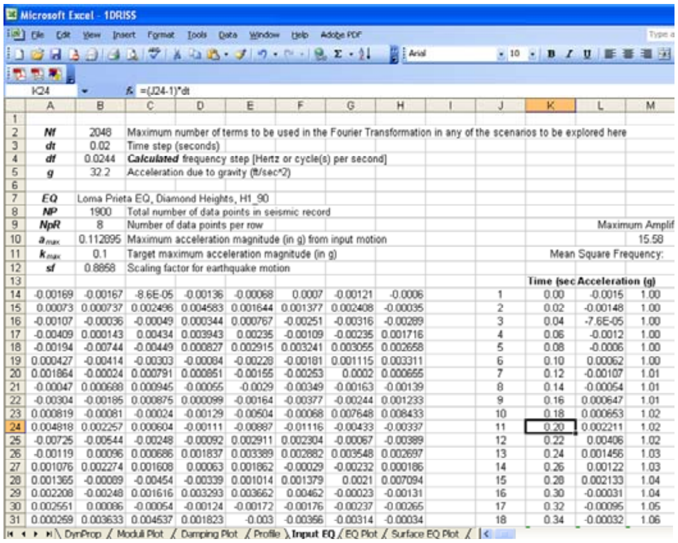


H12 =UW/g*Cs^2

	A	B	C	D	E	F	G	H
1	Example -- 150-ft-thick deposit							
2	# Layers:	16				Multiplier for Uniform Strain:		0.5
4								Initial
5	Layer No.	Material	Thickness	Initial Damping	Unit Weight	Shear Wave Velocity		Shear Modulus
6		Type	(feet)		(kcf)	(feet/sec)		(ksf)
8	1	2	5.0	0.050	0.125	1,000		3,882
9	2	2	5.0	0.050	0.125	900		3,144
10	3	2	10.0	0.050	0.125	900		3,144
11	4	2	10.0	0.050	0.125	950		3,503
12	5	1	10.0	0.050	0.125	1,000		3,882
13	6	1	10.0	0.050	0.125	1,000		3,882
14	7	1	10.0	0.050	0.125	1,100		4,697
15	8	1	10.0	0.050	0.125	1,100		4,697
16	9	2	10.0	0.050	0.130	1,300		6,823
17	10	2	10.0	0.050	0.130	1,300		6,823
18	11	2	10.0	0.050	0.130	1,400		7,913
19	12	2	10.0	0.050	0.130	1,400		7,913
20	13	2	10.0	0.050	0.130	1,500		9,084
21	14	2	10.0	0.050	0.130	1,500		9,084
22	15	2	10.0	0.050	0.130	1,600		10,335
23	16	2	10.0	0.050	0.130	1,800		13,081
24	17	3		0.010	0.140	4,000		69,565
25								
26								
27		Period =	0.48	second	V_{s_ave} =	1,253	fps	
28								
29			***Frequency Amplitude***					
30			Maximum Amplification =		15.58			
31			for Frequency =		2.00	cycles/second		
32			Period =		0.50	second		

Fig. 8 -- Worksheet for Soil Profile Data

Seismic Input Motion. The data set for the input earthquake ground motion is allocated its own worksheet, with a tab labeled "Input EQ" in the current spreadsheet framework. A sampling of such a worksheet is provided in Fig. 9. Most earthquake data come in the form of a text file containing rows of data points (usually eight per row) with specified time step and measurement units. The spreadsheet should be able to readily accept the seismic data from the text file, and to subsequently rearrange the matrix of earthquake data points into a vector array or single column of data. Scaling of the earthquake ground motion should also be possible by specifying the appropriate parameters.



K24 =(J24-1)*dt

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	***Nf***	2048	Maximum number of terms to be used in the Fourier Transformation in any of the scenarios to be explored here										
3	***dt***	0.02	Time step (seconds)										
4	***df***	0.0244	***Calculated*** frequency step [Hertz or cycle(s) per second]										
5	***g***	32.2	Acceleration due to gravity (ft/sec^2)										
6													
7	***EQ***	Loma Prieta EQ, Diamond Heights, H1_90											
8	***NP***	1900	Total number of data points in seismic record										
9	***NpR***	8	Number of data points per row									Maximum Amplif	
10	a_{max}	0.112895	Maximum acceleration magnitude (in g) from input motion										15.58
11	k_{max}	0.1	Target maximum acceleration magnitude (in g)									Mean Square Frequency:	
12	***sf***	0.8858	Scaling factor for earthquake motion										
13											**Time (sec**	**Acceleration (g)**	
14	-0.00169	-0.00167	-8.6E-05	-0.00136	-0.00068	0.0007	-0.00121	-0.0006		1	0.00	-0.0015	1.00
15	0.00073	0.000737	0.002496	0.004583	0.001644	0.001377	0.002408	-0.00035		2	0.02	-0.00148	1.00
16	-0.00107	-0.00036	-0.00049	0.000344	0.000767	-0.00251	-0.00316	-0.00289		3	0.04	-7.6E-05	1.00
17	-0.00409	0.000143	0.00434	0.003943	0.00235	-0.00109	-0.00235	0.001716		4	0.06	-0.0012	1.00
18	-0.00194	-0.00744	-0.00449	0.000827	0.002915	0.003241	0.003055	0.002658		5	0.08	-0.0006	1.00
19	0.000427	-0.00414	-0.00303	-0.00084	-0.00228	-0.00181	0.001115	0.003311		6	0.10	0.00062	1.00
20	0.001864	-0.00024	0.000791	0.000851	-0.00155	-0.00253	0.0002	0.000655		7	0.12	-0.00107	1.01
21	-0.00047	0.000688	0.000945	-0.00055	-0.0029	-0.00349	-0.00163	-0.00139		8	0.14	-0.00054	1.01
22	-0.00304	-0.00185	0.000875	0.000099	-0.00164	-0.00377	-0.00244	0.001233		9	0.16	0.000647	1.01
23	0.000819	-0.00081	-0.00024	-0.00129	-0.00504	-0.00068	0.007648	0.008433		10	0.18	0.000653	1.02
24	0.004818	0.002257	0.000604	-0.00111	-0.00887	-0.01116	-0.00433	-0.00337		11	0.20	0.002211	1.02
25	-0.00725	-0.00544	-0.00248	-0.00092	0.002911	0.002304	-0.00067	-0.00389		12	0.22	0.00406	1.02
26	-0.00119	0.00096	0.000686	0.001837	0.003389	0.002882	0.003548	0.002697		13	0.24	0.001456	1.03
27	0.001076	0.002274	0.001608	0.00063	0.001862	-0.00029	-0.00232	0.000186		14	0.26	0.00122	1.03
28	0.001365	-0.00089	-0.00454	-0.00339	0.001014	0.001379	0.0021	0.007094		15	0.28	0.002133	1.04
29	0.002208	-0.00248	0.001616	0.003293	0.003662	0.00462	-0.00023	-0.00131		16	0.30	-0.00031	1.04
30	0.002551	0.00086	-0.00054	-0.00124	-0.00172	-0.00176	-0.00237	-0.00265		17	0.32	-0.00095	1.05
31	0.000259	0.003633	0.004537	0.001823	-0.003	-0.00356	-0.00314	-0.00034		18	0.34	-0.00032	1.06

Fig. 9 -- Worksheet for Seismic Input Data

Plotting of the input earthquake-induced ground motion can also readily be effectuated within the spreadsheet schema, as depicted in Fig. 10.

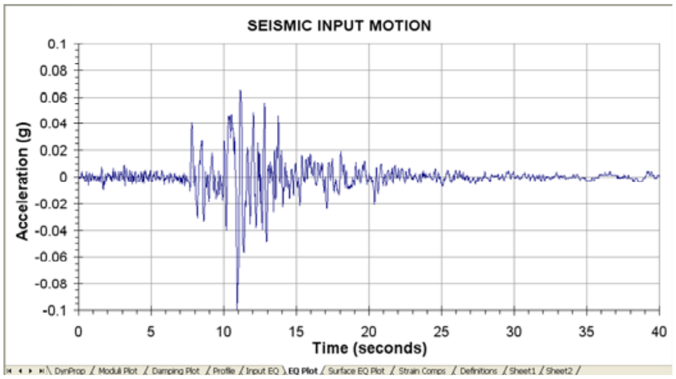


Fig. 10 -- Tab for Plotting Seismic Input Motion

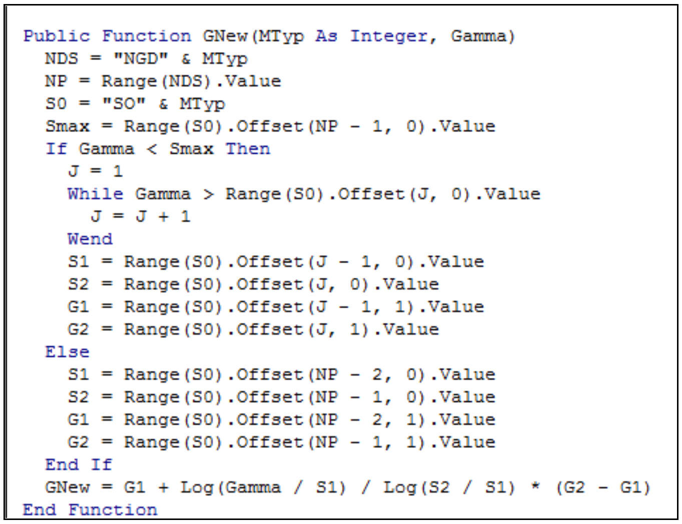
Special Considerations

Beyond the all-important benefits of well-organized handling and rendering of relevant data, the key to satisfactory ground response analysis within the milieu of spreadsheets is the proper utilization of certain advanced features, such as: performing complex-algebra operations, including Fourier analysis; and programming repetitive, iterative, or sophisticated procedures. (In Microsoft® Excel, several of the advanced features and functions are available only upon activation of the "Analysis Toolpak" add-in option from within the spreadsheet application.)

Complex-Algebra Operations. As discussed previously, the solution to the underlying wave equation that describes the site response to seismic excitation involves complex-algebra terms and operations. Modern spreadsheet software like Microsoft® Excel should have specialized functions for proper representation and algebraic manipulation of complex quantities with real and/or imaginary components.

Fourier Analysis. The Fourier Analysis feature in Microsoft® Excel is part of the "Analysis Toolpak" add-in package accessible upon activation by the user. Alternatively, well-established algorithms can be programmed into the spreadsheet to perform FFT computations. Whichever route is taken in this regard, one should evaluate the validity and robustness of the analytical technique employed, by cross-checking against known or verifiable solutions.

Programmability. Microsoft® Excel has a built-in programming language called Visual Basic for Applications (VBA). (Other full-featured spreadsheet software products should have similar programming capabilities.) For example, as part of the iterative process illustrated in Fig. 4, the VBA script shown in Fig. 11 has been adopted for the *1DRISS* scheme, for the purpose of interpolating semi-logarithmically for the normalized shear modulus (for the next round of iteration) corresponding to an operative shear strain.



```
Public Function GNew(MTyp As Integer, Gamma)
  NDS = "NGD" & MTyp
  NP = Range(NDS).Value
  S0 = "S0" & MTyp
  Smax = Range(S0).Offset(NP - 1, 0).Value
  If Gamma < Smax Then
    J = 1
    While Gamma > Range(S0).Offset(J, 0).Value
      J = J + 1
    Wend
    S1 = Range(S0).Offset(J - 1, 0).Value
    S2 = Range(S0).Offset(J, 0).Value
    G1 = Range(S0).Offset(J - 1, 1).Value
    G2 = Range(S0).Offset(J, 1).Value
  Else
    S1 = Range(S0).Offset(NP - 2, 0).Value
    S2 = Range(S0).Offset(NP - 1, 0).Value
    G1 = Range(S0).Offset(NP - 2, 1).Value
    G2 = Range(S0).Offset(NP - 1, 1).Value
  End If
  GNew = G1 + Log(Gamma / S1) / Log(S2 / S1) * (G2 - G1)
End Function
```

Fig. 11 -- Sample VBA Script in 1DRISS Scheme

Miscellaneous Features. Other spreadsheet facets deemed useful and beneficial include: convenient option to assign and invoke names for individual cells and multi-cell ranges; special functions for lookup and referencing, such as *ADDRESS*, *COLUMN*, *INDIRECT*, *OFFSET*, *ROW*, and *VLOOKUP*; versatility in handling and formatting various types of data; and virtually limitless opportunities to experiment with various situations – quite often with minimal risk or penalty.

SAMPLE APPLICATION AND VALIDATION OF SPREADSHEET SCHEMA

The validity of the spreadsheet-based paradigm presented here can readily be tested by comparing the results from the *1DRISS* approach with those from available equivalent-linear codes like *SHAKE91* (Idriss and Sun, 1992).

Input Data

The parameters used in this validation exercise are primarily based on the input data provided in the *SHAKE91* documentation (Idriss and Sun, 1992). The site deposit has a soil overburden depth of 150 feet, and consists of 16 soil layers overlying bedrock, as represented by the information entered into the *1DRISS* worksheet exhibited in Fig.8. The modulus and damping parameters for the various soil types are defined as in Figs. 5, 6, and 7. The seismic input motion is based on recorded accelerogram data at the Diamond Heights station during the 1989 Loma Prieta earthquake, and scaled appropriately such that the maximum acceleration has a magnitude of 0.1*g*, as depicted in Fig. 10.

Equivalent Uniform Strains

In this validation exercise, a multiplier of 0.5 is applied to the calculated peak shear strains to obtain equivalent uniform shear strains, which are then used to iterate for strain-compatible values of shear modulus and damping ratio for each layer. A comparison of results from *SHAKE91* and *1DRISS* is displayed in Fig.12, which plots the respective equivalent-uniform shear strains as a function of depth, as computed after one full iteration and also at the end of eight successive iterations.

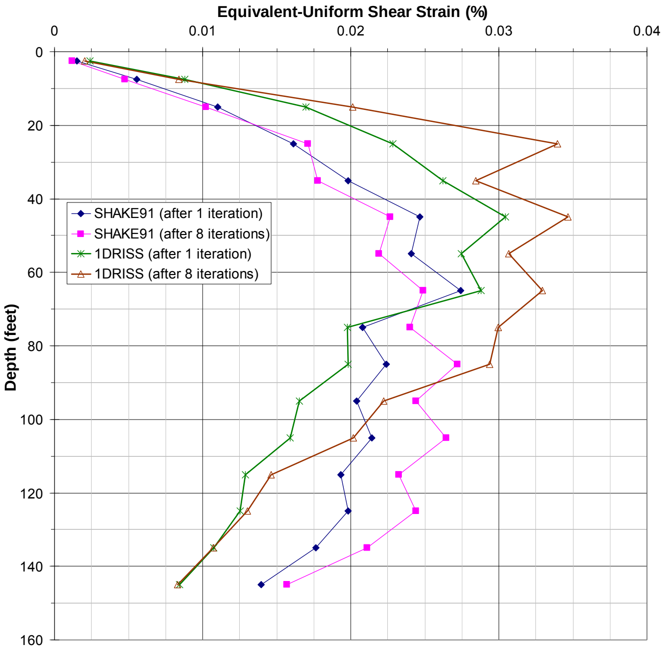


Fig. 12 -- Calculation of Equivalent-Uniform Shear Strains

The calculated shear strains using the *1DRISS* (spreadsheet) approach do not exactly match the corresponding output from *SHAKE91*, but they are reasonably close, considering that the shear strain magnitudes are relatively small. The disparity in the results, in all likelihood, is attributable to the difference in the implementation of the FFT algorithm between these two site-response analytical techniques. Upon close examination, the coding of the FFT routine in *SHAKE* bears little resemblance to other publicized "standard" FFT codes (e.g., Brigham, 1974). On the other hand, no "bugs" are immediately apparent in the Fourier analysis package supplied in Microsoft® Excel.

Strain-Compatible Shear Modulus

Figure 13 shows, along with the initial shear modulus specified for each layer, a comparison of the calculated strain-compatible shear modulus values from the *SHAKE91* and *1DRISS* approaches. Consistent with the modulus curves entered as functions of strain (as in Fig. 6), the shear modulus tends to decrease with increasing shear strain. It is worth noting that, with either approach, the change in the calculated shear modulus from the first to the eighth iteration tends to be pretty minor. Even between *SHAKE91* and *1DRISS*, the differences in the calculated strain-compatible shear moduli seem to be slight (at least in the grand scheme of things), but may again be affected by the dissimilar implementation of the FFT algorithms in each method.

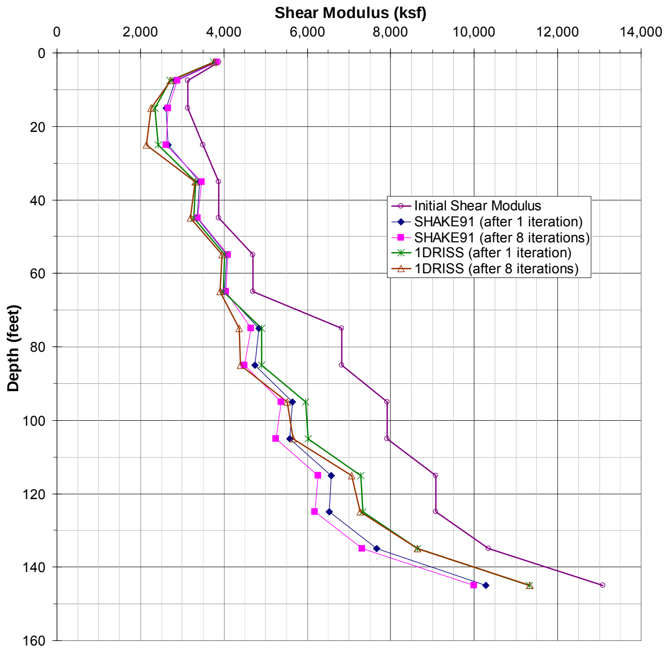


Fig. 13 – Results for Strain-Compatible Shear Modulus

Strain-Compatible Damping Ratio

The calculated results for strain-compatible damping ratios, vis-à-vis the initial damping ratios specified for each layer, are presented in Fig. 14.

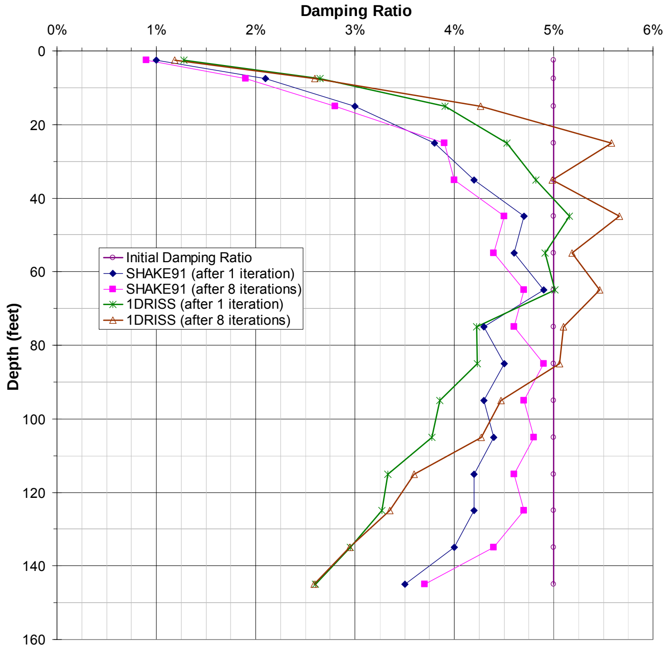


Fig. 14 – Results for Strain-Compatible Damping Ratio

Note that the initial damping ratio of 5% is specified for all soil layers. Based on Fig. 7, for shear strains less than 0.03%, the operative damping ratio will be lower than 5%; if shear strains exceed 0.03%, the operative damping ratio will be greater than 5%. From Fig. 12, the shear strains surpassed the 0.03% “threshold” mostly in the *1DRISS* results for the soil layers ranging between 20 feet and 80 feet in depth. Thus, as can be seen in Fig. 14, the damping ratios were greater than 5% for those soil layers between the depths of 20 feet and 80 feet, based on the *1DRISS* technique. As with the strain-compatible shear moduli, relatively speaking with either the *SHAKE91* or *1DRISS* approach, the strain-compatible damping ratios tend not to change substantially from the first to the eighth iteration.

Surface Motions

Figures 15 and 16 are time-history plots of the calculated surface motions from the *SHAKE91* and *1DRISS* site-response analyses, respectively. There are quite noticeable differences between the two sets of results, including in the magnitudes of the maximum computed acceleration at the surface (0.29*g* from *SHAKE91* vs. 0.24*g* from *1DRISS*). As pointed out previously, the differences in the results are very likely due to somewhat divergent methodologies respectively employed in the implementation of FFT algorithms.

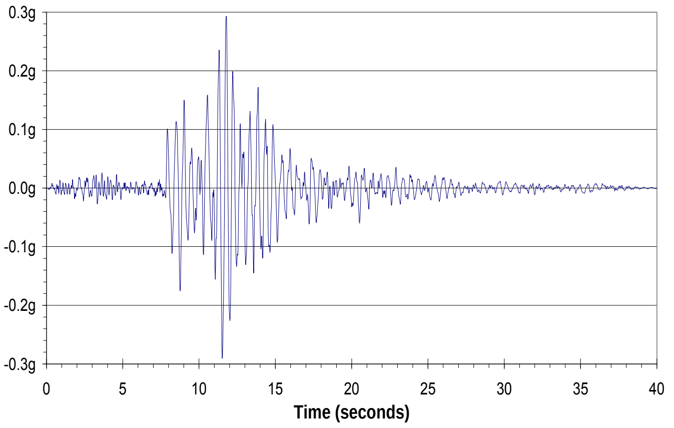


Fig. 15 -- Surface Motion from SHAKE91

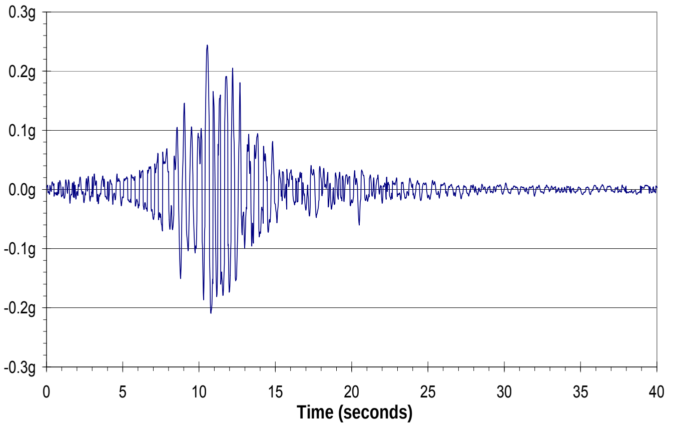


Fig. 16 -- Surface Motion from 1DRISS

Response Spectra

The algorithm used in *SHAKE* for computing the response spectrum due to a specified ground motion is similar to that implemented in the *SPECTR* (Dames and Moore, 1972) program developed primarily for this type of calculation. Such algorithm, which is based on a Duhamel-type integral treatment of impulse loading over short time intervals, can also be programmed into a sophisticated spreadsheet application. Alternatively, one can apply, via some spreadsheet programming, the efficient time-stepping integration procedure recommended by Wilson (1998) for piecewise-linear loading functions, to generate response spectra. For example, Fig. 17 below is a comparative plot of response spectrum results (for 5% damping) from *SHAKE91* corresponding to the surface motion depicted in Fig. 15 and from a corresponding spreadsheet-programmed execution of Wilson's (1998) recommended procedure (as applied to the same ground motion). The nearly perfect match between the *SHAKE91* and spreadsheet-based results tends to strongly validate the efficacy of spreadsheets for these types of analyses.

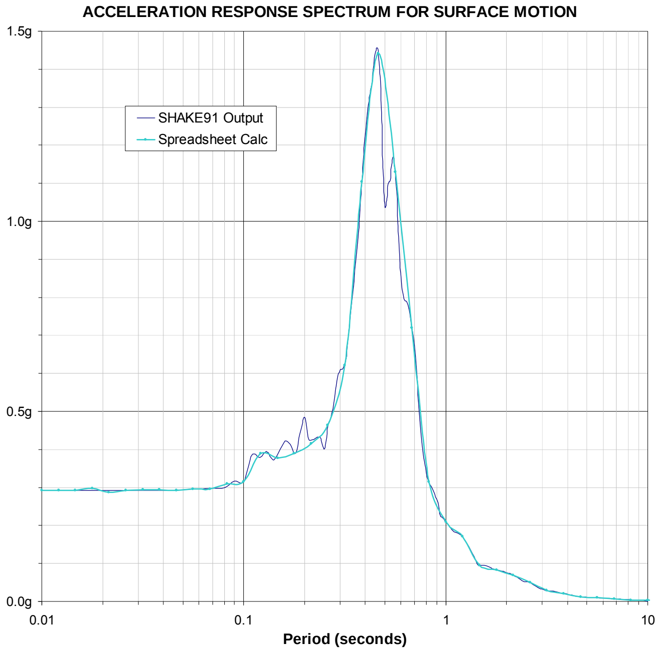


Fig. 17 -- Validation of Response Spectrum Calcs

Having validated the spreadsheet-based methodology for generating response spectra, pertinent results can then be plotted corresponding to the seismic input motion and the surface motion (in actuality, the computed motion within any other layer as well). Figure 18 represents one such set of plotted response spectrum results, factoring in a critical damping ratio of 5%. The response spectrum for the surface motion from *SHAKE91* as shown in Fig. 18 is taken directly from the program output; the counterpart plot from the *1DRISS* schema has been created based on the surface motion displayed in Fig. 16, using a spreadsheet implementation of Wilson's (1998) method; and the response spectrum for the input base rock motion (Fig. 10) has been similarly derived, i.e., using a spreadsheet-based approach.

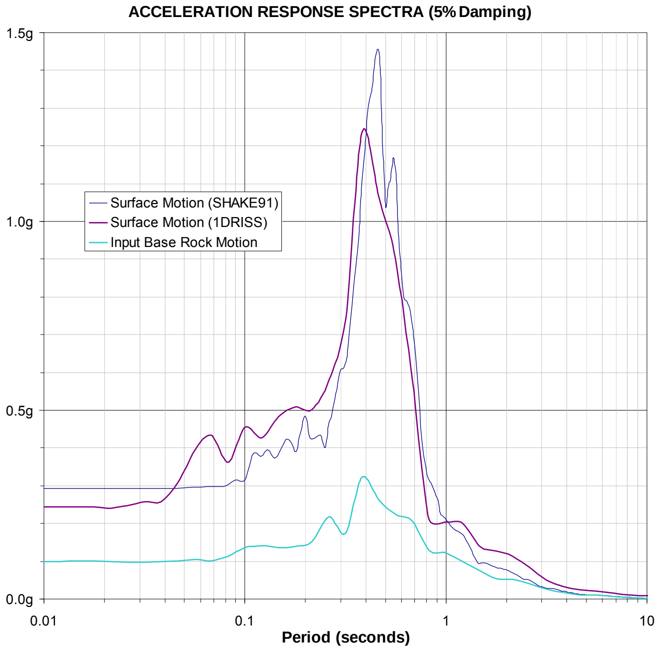


Fig. 18 – Acceleration Response Spectra for 5% Damping

Although the calculated surface motions and corresponding acceleration response spectra from *SHAKE91* and *1DRISS* may not exactly coincide as indicated by Figs. 15, 16, and 18, it seems rather difficult to dispute the reasonableness of a spreadsheet-based framework like *1DRISS* as a potentially useful tool for performing seismic site response analysis.

SUMMARY AND CONCLUSIONS

Beyond the user-friendly interface, structured data handling/processing, and flexible formatting/charting, modern spreadsheet applications apparently have matured to such a level that sophisticated features are commonplace and standard fare. As demonstrated in this paper, by taking advantage of these advanced spreadsheet features, such as complex-algebraic operations, Fourier analysis, and programming capabilities, seismic site response analysis using spreadsheets is both viable and valuable as a supplement to existing practices. Because of the wide availability and affordability of spreadsheet software, their use for seismic site response analysis is highly recommended for both academic and practical endeavors.

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