Opinion Paper for the International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response.

Jamison H. Steidl – U.C. Santa Barbara

A goal of earthquake engineering research is to generate analytical and empirical models for accurate prediction of ground response and ground deformation and to understand how these ground motion predictions affect the built environment. A required element for the development of these models is well-instrumented test sites where actual ground response and deformation, can be monitored during earthquake shaking to provide benchmark case histories for model development and verification. In addition the use of active methods to shake the test sites can also provide benchmarks that can be compared with actual earthquake motions.

Through my work at UC Santa Barbara I have been involved with the deployment of instrumentation at test sites throughout California for the purpose of collecting this control data that can be used to further develop and validate our models for wave propagation in soils, at all strain levels, and over a wide range of frequencies. Borehole instrumentation provides a unique opportunity to directly measure the effects of surface geology. While one must still rely primarily on single point observations of ground motion and deformation at the surface due to the high cost of drilling and downhole sensor instrumentation, geotechnical arrays provide critical constraints for our methods of interpreting observed ground motions. Direct evidence of the magnitude and effect of nonlinearity in soil response; the frequency and strain dependent amplification and attenuation of seismic waves, the effects of smooth versus discontinuous variation of geotechnical material properties, and the effects of water saturated versus dry soil conditions, all depend on *in situ* borehole measurements at varying depths within the soil column.

One of the main issues when modeling nonlinear soil dynamics is the lack of knowledge of the soil properties. Indeed, one of the reasons why the equivalent linear method is so popular is due to the limited number of parameters needed. If a more sophisticated and complete method is used, that also translates into more parameters that must be specified. Unfortunately, the cost of laboratory and *in-situ* field tests is quite expensive, so a complete geotechnical description of a site is a rare and precious commodity.

In more complicated nonlinear methods for simulation of dynamic soil response, model parameters should be chosen such that they are closely related to the rheology that describes the material properties at various strain levels. Unfortunately, in some previous cases these rheological models do not necessarily have physical parameters. Sometimes there are indirect parameters that cannot be measured in the lab, but rather must be found in a statistical sense, or by trial and error (Lopez-Caballero, 2003). Therefore, one important line of research in earthquake engineering corresponds to understanding how the nonlinear behavior can be modeled using the least number of parameters, maintaining a physical relationship between the model parameters and the material properties, and without loosing accuracy in the simulated predictions of ground motions.

There are a large number of soil models in the literature. Most studies about soil nonlinearity vary from simple state equations with few parameters (e.g. Hardin & Drnevich 1972a,b, Pyke 1979, Prevost & Keane 1990) to complex formulations with dozens of parameters (e.g. Zienkiewicz et al. 1982, Ramsamooj & Alwash 1997, Prevost & Popescu 1997). The former follow the so-called Masing rules (Kramer 1996) for simulating the hysterestic behavior of soils; whereas the latter include hysteresis in their formulation. In addition, several international tests have been conducted to determine the advantages and limitations of the different codes available (e.g. Arulanandan & Scott, VELACS, 1994).

The propagation of seismic waves directly depends on the mechanical properties of the material were they travel through. As indicated above, there are several powerful models, but the number of parameters makes their use difficult. For example, SUMDES (Xi et al, 1992) goes from 10 to 20 parameters depending on the chosen rheology. Similarly, CyberQuake (BRGM, 1998) uses 14 parameters in their formulation (Lopez-Caballero, 2003). Those codes are based on plasticity theory to describe the material nonlinear behavior. Conversely, the Iwan model (Iwan, 1967) simulates well the nonlinear behavior based on a series of springs, which obey a given modulus reduction curve. Joyner and Chen (1975) describe this method and its application to compute nonlinear soil response. Furthermore, the work in Japan approximates the nonlinear and hysteretic behavior by a phenomenological approach: the so-called extended Masing rules (Masing, 1926). One of such models is the one developed by Towhata and Ishihara (1985) and further modified by Iai et al (1990), which simulates well the nonlinear hysteretic behavior of dilatant soils under undrained conditions. This model is used in the commercial code FLIP in Japan, and it has been implemented in the research code NOAH (Bonilla, 2000) developed at UCSB using borehole observations at a variety of locations as a constraint on our model.

The advantage of this model is that it needs only one parameter to describe the nonlinear behavior under dry conditions, and five more that describe the dilatancy under undrained conditions. This, of course, makes the model attractive because of its simplicity. The model formulation includes nonlinear effects such as anelasticity and hysteretic behavior, and pore pressure generation. The technique developed is a **NO**nlinear **A**nelastic **H**ysteretic (NOAH) finite difference code, which computes the nonlinear wave propagation in water saturated soil deposits subjected to vertically incident SH ground motion. The constitutive equation implemented in this code corresponds to the strain space multishear mechanism model developed by Towhata and Ishihara (1985) and Iai *et al*. (1990). The code is able to perform total and effective stress analyses.

There have been several attempts to describe the stress-strain space of soil materials subjected to cyclic loads, and among those models the hyperbolic is one of the easiest to use because of its mathematical formulation as well as for the number of parameters necessary to describe it (Hardin and Drnevich, 1972b; Pyke, 1979; Ishihara, 1996; Kramer, 1996; Beresnev and Wen, 1996). Hysteresis behavior can be implemented with the help of the Masing and extended Masing rules (Vucetic, 1990; Kramer, 1996). However, these rules are not enough to constrain the shear stress to values not exceeding the material strength. This happens when the time behavior of the shear strain departs from the simple cyclic behavior, and of course, noncyclic time behavior is common in seismic signals. Inadequacy of the Masing rules to describe the hysteretic behavior of complicated signals has been already pointed out and some remedies have been proposed (e.g., Pyke, 1979; Li and Liao, 1993).

Some acceleration time histories -primarily recorded in dense and saturated deposits- show a characteristic waveform that differs completely from the predictions inferred from the classic nonlinear site response. These records show an increase in duration of the ground motion with high-frequency spikes in acceleration arriving after the direct S waves. They are characterized by intermittent behavior, high-frequency peaks riding on low-frequency carrier. Examples of this behavior are records at Kushiro, Wildlife Refuge, Bonds Corner, and Van Norman Complex among others. To understand the behavior of the soil during strong shaking this general formulation of hysteresis based on the Masing rules is used. The generalized Masing rules provide a framework for understanding the non-uniform dilation and translation of stress-strain loops for a material subjected to non-periodic stresses; they also provide a means for understanding anelastic damping as function of the stress-strain loops. Finally, the generalized Masing rules, coupled to a pore pressure generation, are able to reproduce the characteristics of the hysteretic and dilatant behavior of soils such as those mentioned in the waveform records above.

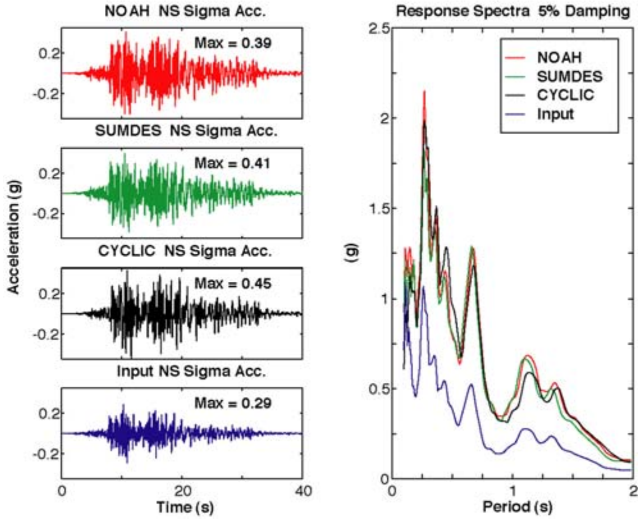

Figure 1. Comparison of simulation method NOAH with CYCLIC and SUMDES.

Figure 1 shows as a first pass validation, an example of the NOAH simulation code relative to two other nonlinear codes, Cyclic and SUMDES, each having more complicated material parameterization than NOAH. Here the same synthetic input motion is used at the bottom of an identical soil profile for all three codes. Note that the simulated motions from each method are very similar in both time domain and in response spectra.

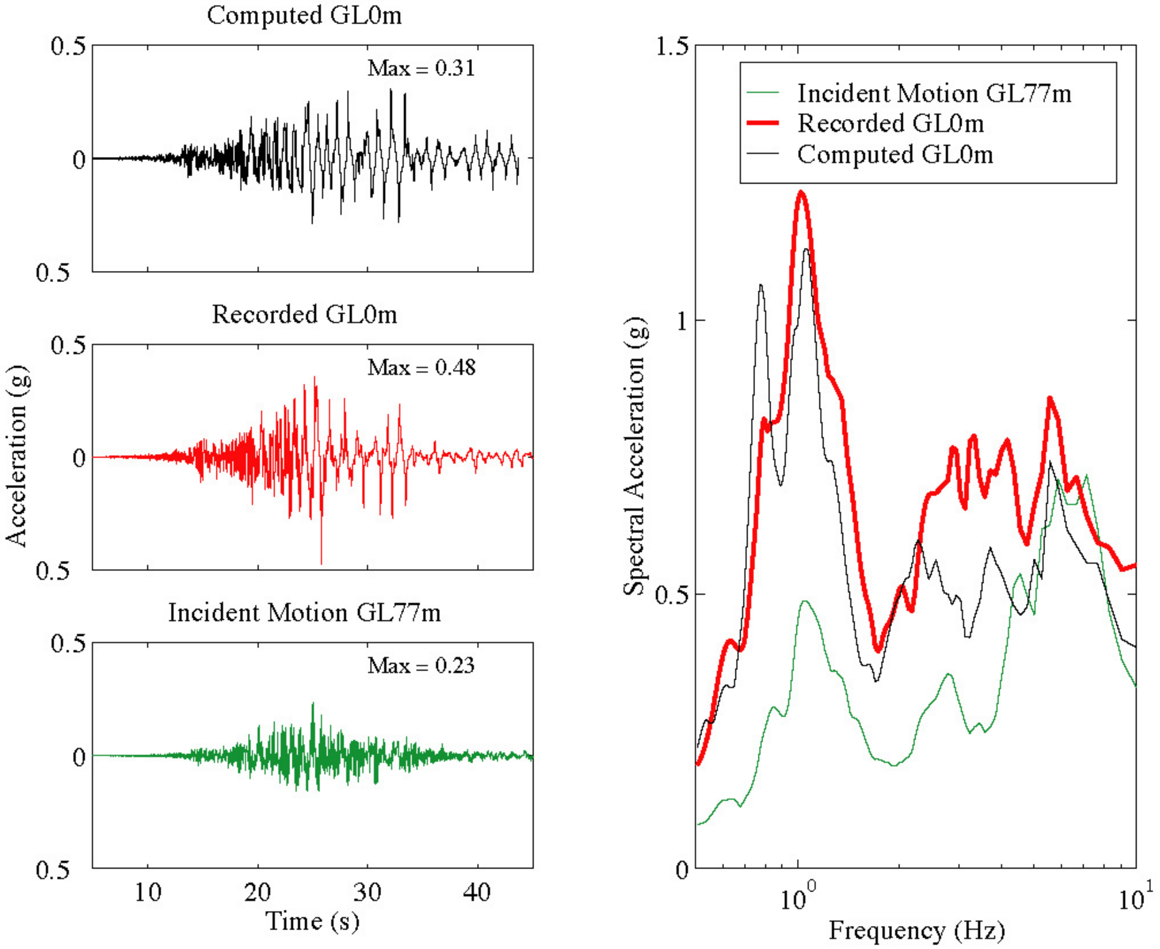

Figure 2a. Example of NOAH simulation using the 1993 Koshiro-Oki Port Island data. Observed borehole motion at GL-77m is used as input to NOAH and the surface simulation is compared with the observed surface record.

After validation with other published nonlinear simulation techniques, we test the NOAH technique using the 1993 Koshiro-Oki Port Harbor data. This data is representative of the hysteretic and dilatent soil behavior mentioned above that produces the high frequency intermittent peaks riding on the low-frequency carrier. Figure 2 (a&b) shows the simulation results for this event using NOAH.

The generalized Masing rules propose that the hysteresis shape factor is no longer constant and equal to 2 as in the case of the classic Masing rules. On the contrary, it will depend on the stress-strain level acting on the medium at any time. If the strain is fixed at infinity, from the hyperbolic model the maximum stress is reached, this corresponds to the Cundall-Pyke hypothesis (Pyke, 1979). In the NOAH approach, the strain is iterativelly fixed to its maximum value during the total loading process. The effect on the hysteresis is that extended behavior is naturally produced (the computed stress follows the backbone if this is reached). The soil is represented as a collection of multiple anelastic springs each following the generalized Masing rules.

NOAH is a simple model that represents laboratory and field data with only few parameters, and the use of generalized Masing rules. The nonlinear effects observed in wave propagation include the wellknown shift toward lower frequencies, large amplifications of the signal at frequencies different than the resonance frequency, increment in the duration of the strong motion as the input motion amplitude is augmented, and development of intermittency. The last three effects have not been predicted by simple nonlinear models in the past.

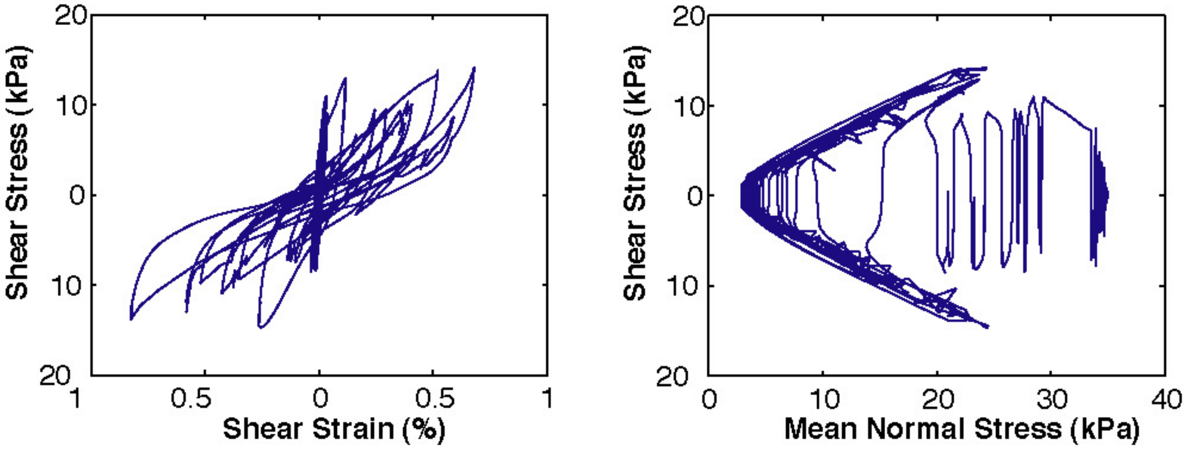

Figure 2b. Computed Stress-Strain Phase Space and Stress Path for Kushiro-Oki at GL-3.5m

Summary of NOAH Method:

1. The generalized Masing rules capture the essentials of soil nonlinearity. They describe analytically the hysteresis of soils. In addition, by choosing the correct constraint the computed stress will not exceed the maximum strength of the material as the classic Masing rules do.

2. The coupling of the hysteresis operator with pore pressure produces different results depending if the material is dilatant or not. When the material is not dilatant, as in the case of cohesive soils, the mean stress is reduced monotonically towards zero. As a consequence, the computed stress has lower amplitude and smaller duration. Thus, the computed acceleration (spatial derivative of the stress) presents the classical amplitude reduction.

3. When the material presents dilatant behavior (cyclic mobility), the stress path shows partial strength recovery. The computed stress develops large amplitudes and larger duration. As a consequence, the acceleration also shows large amplitudes beyond the direct S-wave, and longer duration of the strong motion.

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