Nonlinear Site Response: Where We're At (A report from a SCEC/PEER seminar and workshop)

E. H. Field Dept. of Earth Sci., Univ. of Southern California

S. Kramer Dept. of Civil Eng., Univ. of Washington

A.-W. Elgamal Dept. of AMES, U.C., San Diego

J.D. Bray Dept. of Civil Eng., U.C., Berkeley

N. Matasovic Project Engineer, GeoSyntec Consultants

P.A. Johnson Los Alamos National Laboratory

C. Cramer Calif. Division of Mines and Geology

C. Roblee Senior Research Engineer, Caltrans

D.J. Wald U.S. Geological Survey, Pasadena

L.F. Bonilla Inst. for Crustal Studies, U.C., Santa Barbara

P.P. Dimitriu Egnatia 311, Thessaloniki 54249, Greece

J.G. Anderson Seismological Lab., Univ. of Nevada, Reno

Although the fact that sediments can amplify earthquake ground motion was recognized at least 100 years ago (Milne, 1898), there has been a lingering uncertainty as to whether the degree of amplification varies with the level of input motion. This issue remains as one of the most important questions with respect to understanding and predicting earthquake ground motion.

In accordance with the conservation of energy, seismic-wave amplitudes generally increase in sediments due to lower densities and and/or lower seismic velocities. In addition, resonance effects can occur where abrupt impedance contrasts exist. If sediments were perfectly elastic, their response would be independent of incident-wave amplitudes. As with any real material, however, sediments begin to yield at some level of strain, and this violation of Hooke's law will give rise to a nonlinear response.

The engineering community has long believed that sediment nonlinearity is significant. This perspective was based almost entirely on laboratory studies, where observed stress-strain loops imply a reduced effective shear modulus and an increased damping (lower Q) at higher levels of strain. A reduced shear modulus alone implies an increased amplification, depending on how it is measured. However, the increased damping generally tends to dominate, resulting in reduced amplification factors (and even possible deamplification), which in turn implies less stringent building requirements.

Nonlinear effects have been applied in engineering practice since the early 1970s and are accounted for in current building codes. One manifestation of this perspective was that peak ground acceleration (PGA) was believed to be reduced (or deamplified) at sediment sites when rock-site

PGA exceeds 0.1g (Seed and Idriss, 1983). The 1985 Michoachan and 1989 Loma Prieta earthquakes changed that perspective, shifting the threshold between amplification and deamplification to ~0.4 g for deep, soft clay sites (Finn, 1991; Idriss, 1991). Furthermore, data obtained during the 1989 Loma Prieta and 1994 Northridge earthquakes indicates a threshold of ~0.6g for deep, stiff soil sites (Chang and Bray, 1997). The 1997 Uniform Building Code employs amplitude-dependent site factors that attempt to capture these differences between hard and soft soil sites. Although the engineering profession generally accepts this approach, they acknowledge that further refinements may be in order depending on future observations.

Seismologists have traditionally been skeptical of the significance of sediment nonlinearity, in spite of the fact that one of their very own (Reid, 1910) recognized and described the potential effect some 90 years ago (in the same paper that introduced the elastic-rebound theory of faulting). The prevailing seismological perspective as of 1988 was reflected in a seminal review paper by Keiiti Aki (1988), who wrote that:

> "...except for the obvious case of liquefaction, ...the amplification factor obtained using weak motion data can be used to predict... strong ground motion...."

The reason for this view was either that nonlinear effects were indeed insignificant or that they could not be resolved among the myriad of other effects complicating a very limited number of strong-motion observations. Seismologist were also skeptical that laboratory studies reflect *in situ* behavior, both because of well-known difficulties in obtaining undisturbed samples and because such studies do not include the effects of scattering attenuation. Given a lack of direct evidence for sediment nonlinearity, seismologist naturally opted for the simpler linear model (which is also generally more conservative in terms of predicted ground motion).

Keiiti Aki turned out to be one of the earliest seismological converts. In a follow-up review paper he wrote that "Non-linear amplification at sediment sites appears to be more pervasive than seismologists used to think" (Aki, 1993). This new perspective was based largely on a study by himself and one of his graduate students, where they claimed to see a pervasive nonlinear effect in data from the 1989 Loma Prieta earthquake (Chin and Aki, 1991). Although the study was certainly provocative, it left seeds of doubt for many seismologists and was formally challenged in the literature (Wennerberg, 1996; Chin and Aki, 1996). Other studies have appeared showing evidence of nonlinear effects (see Beresnev and Wen, 1996, for a review; or the Proceedings of the International Workshop on Site Response held in Yokosuka, Japan, January 16–17, 1996 for some more recent examples). However, diehard skeptics could still point out that these were isolated cases and/or associated with liquefaction (as at Treasure Island during the Loma Prieta earthquake and in Kobe, Japan during the 1995 earthquake). The overall prevalence, especially with regard to relatively dry and stiff soils that typify southern California, therefore remained in question. However, a recently published seismological study now claims to have identified a pervasive nonlinear effect at these types of sites as well (Field *et al.*, 1997); sediment amplification factors inferred from the 1994 Northridge earthquake main shock were up to a factor of two less, on average, than for relatively weak-motion aftershocks. Although this nonlinear interpretation seems the most reasonable, it remains to be seen whether the conclusion holds up to additional scrutiny.

Given recent progress, the time has been ripe to reassess our present understanding (or lack thereof) with respect to nonlinear sediment response. On January 29–30 of this year, the Southern California Earthquake Center (SCEC), in cooperation with the newly established Pacific Earthquake Engineering Center (PEER), sponsored a seminar and workshop on this important topic. Also in attendance were members of the Los Alamos National Laboratory, government officials, members of the private sector, and a representative from the Japanese Ministry of Transportation. Over 60 individuals participated, and the diversity of disciplines in attendance (including physics, seismology, engineering, and practicing professionals) was unprecedented with respect to previous meetings on this topic.

Everyone agrees that Hooke's law is only an approximation, especially because some degree of nonlinearity is apparent in laboratory studies at even the lowest detectable strain levels. The question is more a matter of degree, or the adequacy of the linear model under various conditions, especially in comparison with other commonly made approximations (such as isotropy). In other words, when is sediment nonlinearity a first-order effect in terms of understanding or predicting earthquake ground motion? To address this question the workshop concentrated on five specific issues, each of which is outlined and discussed below.

1. Do lab studies reflect *in situ* behavior?

The answer seems to be: sometimes yes, and sometimes no. Laboratory and field technicians go to great lengths to avoid sample disturbance. Nevertheless, some level of disturbance is virtually unavoidable when the sampler is inserted into the ground. Another problem is the effect of stress relief associated with bringing the sample to the surface (on rare occasions specimens literally burst when taken out of the confinement tubes). To evaluate the influence of sample disturbance, the shear-wave velocity inferred from low-strain tests can be compared with that obtained from weak-motion field studies (*e.g.* down-hole, cross-hole, or surface-wave velocity measurements). The difference is typically a factor of between 1 and 2, with *in situ* velocities being greater. This factor can then be applied as a correction to the laboratory results. However, given a lack of high-strain *in situ* shear-wave measurements, it is presently unknown whether this correction factor applies at higher levels of strain.

The issue of sediment damping (or *Q*) is especially problematic. The degree of attenuation predicted by engineers has traditionally been much lower than that observed by seismologist (*e.g.*, Cramer, 1995), and the difference has been attributed to the influence of scattering attenuation from heterogeneities larger than the test samples. Laboratory studies include only intrinsic attenuation, so the question naturally arises as to the relative importance of this versus scattering attenuation (not to mention any possible sample disturbance effects). The evaluation of lab results is further exacerbated by the fact that only weak-motion *in situ* observations are generally available and that weak motion (or low strain) damping values are particularly difficult to measure in the lab. However, significant advances in laboratory procedures have recently been made (*e.g.*, Doroudian and Vucetic, 1995), which should allow a more precise comparison of weak motion results. Such studies will hopefully reveal the influence of both sample disturbance and scattering attenuation. The comparison of damping at high strains awaits the acquisition of more *in situ* strong-motion data.

2. "...there is no nonlinear model of any kind established on a sound physical basis" (Ishihara, 1996, pg 28). Is this true?

The point here is that models of sediment nonlinearity are generally based on curve fitting of stress-strain loops (or of shear-modulus reduction or damping increase as a function of strain) where the form of the curves are not based on any first principles of physics. This is of no consequence for practical purposes as long as the models predict ground motion faithfully. From a scientific perspective, however, a more physically based model is more elegant and therefore preferable. In terms of what's applied in practice, Ishihara's statement appears to remain valid.

This issue reflects an interesting distinction between engineering and scientific approaches to the problem. Engineers have a job to do; they want accurate estimates of ground motion so they can design buildings accordingly, and they work under strict time constraints with limited information. They have developed advanced ground-motion simulation techniques which are well calibrated with respect to previous observations. Seismologists, however, are primarily interested in understanding how nature works and in developing physical models of observed behavior. They are quite comfortable with presenting hypotheses, publicly debating the issues, and even admitting they are wrong if subsequent evidence implies such. Engineers typically have multi-million dollar decisions made on the basis of their results and, due to liability issues, are often prohibited by their clients from performing subsequent tests and analyses.

Having more scientific or physically based methodologies will be an obvious benefit to engineers, especially with respect to predicting ground motion under conditions not currently represented by the observational database (*e.g.* near-source effects for large earthquakes). However, one needs to be careful that implementing such changes in a ground-motion simulation does not upset the balance established among other factors (*e.g.*, source and path effects) during the calibration process.

3. Under what conditions is the equivalent-linear model adequate? Is this methodology outdated?

One of the most widely used approaches to model sediment nonlinearity is the equivalent-linear model (Idriss and Seed, 1968; Schnabel *et al.*, 1972). Here, the sediment response is treated as linear-viscoelastic. However, the shear-wave velocities and damping levels are changed from their original weak-motion values to be compatible with what laboratory results suggest for the particular strain level induced by the input motion. Because the strain is not known a priori, the response is obtained in an iterative manner. That is, shear-wave velocities and damping factors are successively adjusted to be compatible with the level of strain implied from the previous calculation until further iterations do not significantly change the result.

This equivalent linear modeling produces a systematic shift in resonant peaks toward lower frequencies as the level of strain increases. It also predicts a more dramatic reduction in amplification factors at higher frequencies. However, fully nonlinear calculations, where the actual stress-strain loops are represented numerically, are beginning to reveal much more complex and interesting behavior. For example, one study has found that as strain levels are increased, the fundamental resonance does not simply shift toward lower frequencies but actually bifurcates into two lower amplitude peaks, with a third peak growing up at an even lower frequency (presented by Paul Johnson of the Los Alamos National Laboratory).

Another study (Yu *et al.*, 1993) found that a truly nonlinear calculation predicts a transition frequency, above which amplification factors actually increase relative to the linear response (in direct contrast to an equivalent-linear prediction). This effect was previously unanticipated with respect to sediment amplification but is now understood as a manifestation of "harmonic doubling" and "sum- and difference-frequency" interactions. In essence, each frequency interacts with all others, thereby shifting the distribution of energy across the spectrum. Although such effects have been observed in the laboratory (*e.g.*, Johnson *et al.*, 1996), in an active-source field experiment (Dimitriu, 1990), and are well understood in terms of classical nonlinear theory, the increased amplification above some transition frequency has not yet been unambiguously observed in the field. However, this effect may explain one of the most often cited objections with the recent study that inferred nonlinear sediment amplification from the Northridge earthquake (Field *et al.*, 1997): that the difference between weak and strong motion is largest between 2 and 4 Hz and is reduced at higher frequencies.

The lesson here is that we should not be surprised if the equivalent-linear model does not capture all relevant aspects of site response, especially at high ground-motion levels. The full range of nonlinear effects remains to be explored, especially with respect to conditions under which the equivalent linear model will lead one seriously astray. Given the present speed of computers, the equivalent linear model does not seem to provide any practical advantage. However, it is deeply rooted in engineering practice and will remain so until an easily parameterized and well-tested alternative is available.

4. Are there any novel ways of examining our limited seismic data? What should we be looking for?

A major impediment to our understanding sediment nonlinearity has been a shortage of strong-motion observations. The Northridge earthquake provided an abundance of data, and by carefully removing source and path effects, the significance of sediment nonlinearity has apparently been identified (Field *et al.*, 1997; Su *et al.*, 1998; Beresnev *et al.*, 1998). However, this inference has generally required the combination of data from several sites, each of which differ in their local structure, so details regarding the physics of the response (such as resonant-peak shifts) have usually been washed out in the averaging.

Resolving the physics requires a good estimate of the input motion. By far the best, although not perfect, source of information on input motion comes from downhole arrays. In fact, perhaps the first convincing seismological evidence for sediment nonlinearity came from up- to down-hole spectral ratios at the SMART1 array in Taiwan (Wen *et al.*, 1994), where interference peaks (sometimes mistaken as resonant peaks) were clearly shifted toward lower frequencies for the stronger input motion. The value of vertical arrays for inferring actual stress-strain time histories at various depths has also been demonstrated (Elgamal *et al.*, 1995; Kazama, 1996). Such recording are clearly the key to improving our understanding of *in situ* soil dynamics. Short of that, the acquisition of more weak-motion recordings at strong motion sites will also be helpful.

Another important source of information is the actual structure below the recording sites. In recognition of this, aggressive efforts are ongoing in southern California to drill, log, and test samples at existing strong-motion stations (*e.g.*, Schneider *et al.*, 1997). Interestingly, about half of those drilled so far have produced surprises relative to how the sites had previously been classified. This underscores the need for borehole studies at as many recording sites as possible.

5. Is nonlinearity in rock or very stiff soil significant?

For many years now, laboratory studies have shown that unconfined rock exhibits nonlinearity at strain levels as low as 10^{-8} (*e.g.*, Johnson and Rasolofosaon, 1996). However, questions have remained whether this significantly influences strong ground motion, especially compared to the myriad of other complicating effects. In field studies, this often hinges on exactly what is meant by rock. For example, many "hard rock" outcrops have a significant weathered zone near the surface. As shown in a presentation by Robert Nigbor (of Agbabian Associates), this weathered region can behave very much like sediment (both in terms of resonance and nonlinear effects).

Another problematic case is so called "weak rock", which is present at more than 20% of construction sites in southern California. These materials are neither soil nor rock, but consist of gravels, cobbles and boulders embedded in a soil matrix that is cemented (although more weakly than in conglomerate rocks). Unfortunately, the particle size and cementation make sampling and testing almost impossible, so little is known on the non-linear characteristics of such material.

6. Are multi-dimensional effects (in terms of sediment-deposit geometries) and P/SV-wave coupling effects important? Are we ready to tackle these problems?

Most models of nonlinear sediment response assume vertically incident *S* waves and one-dimensional velocity structures. There was widespread agreement that *P/SV* wave coupling for non-vertically incidence waves, as well as multidimensional effects, are likely to be important. However, there was no clear conclusion as to whether we are ready to tackle this issue. The question is whether we will learn anything by adding these complications now or whether we are better off with a more piecemeal approach.

In terms of theory and computational requirements, modeling such complexities is not problematic. However, such models require additional parameters, such as Poisson's ratio, for which there is relatively little information on the strain dependence. Therefore, our computational tools are ahead of the testing and understanding of material behavior under cyclic loading.

7. Is sediment nonlinearity significant at long periods (greater than one second)? Will it reduce the severity of near-source effects?

It is now recognized that sites adjacent to the surface projection of a fault can experience a large displacement pulse during earthquakes (Heaton, 1990). According to some, this previously unanticipated level of motion may exceed the design capacity of certain structures. Not surprisingly, the news media has taken a big interest in this issue. In an unfortunate lack of insight, one reporter recently used the evidence for sediment nonlinearity as an argument against the potential severity of any near-source displacement pulse. However, the study showing significant nonlinearity (Field *et al.*, 1997) was restricted by instrument limitations to frequencies above 1 Hz, whereas near-source pulse effects are generally thought to be significant at lower frequencies. It is nevertheless an interesting question. To the extent that nonlinearity manifests as a reduction of shear modulus and that increased damping effects are less influential at low frequencies, one could reason that a long-period displacement pulse might even be enhanced. However, one could alternatively envision the sediments as yielding, making the ground surface naturally base isolated from a large displacement pulse. At this point we do not know what happens, although the Northridge and Kobe earthquakes have taught us that near source effects can be quite significant regardless of the influence of nonlinearity.

To summarize, we are making rapid advances in our understanding of nonlinear site effects. The degree of sediment nonlinearity appears to reside somewhere between the traditional seismological and engineering perspectives, as each new study seems to make a step toward intermediate ground. We have along way to go, however, and nonlinearity remains as one of the final frontiers in our understanding of site effects. In particular, there is a rich parameter space waiting to be explored in fully nonlinear models, which will presumably give us more insight as to what to look for in our limited observations. Furthermore, we need to conduct more direct and candid evaluations of laboratory results in terms of their ability to reflect *in situ* sediment behavior. Finally, we need more broadband and wide dynamic-range recordings in order to infer behavior at all frequencies of interest, particularly at downhole arrays which constitute our best hope for understanding the physics of nonlinear site effects.

REFERENCES

Aki, K. (1988). Local site effects on strong ground motion, *Proc. of Earthq. Eng. and Soil Dynamics II*, 103–155.

Aki, K. (1993). Local site effects on weak and strong ground motion, *Tectonophys.* **218**, 93–111.

Beresnev, I.A., and K.-L. Wen (1996). Nonlinear soil response—A reality?, *Bull. Seism. Soc. Am.* **86**, 1964–1978.

Beresnev, I.A., G.M. Atkinson, P.A. Johnson, E.H. Field (1998). Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California earthquake. II Widespread nonlinear response at soil sites, Subm. to *Bull. Seism. Soc. Am.*

Chang, S.W. and Bray, J.D. (1997). Implications of recent strong motion data for seismic building code design at deep, stiff soil sites, *Proc. CUREe Northridge Earthquake Research Conference*, Los Angeles, CA, in press.

Chin, B., and K. Aki (1991). Simultaneous study of the source, path, and site effects on strong ground motion during the 1989 Loma Prieta earthquake: A preliminary result on pervasive nonlinear site effects, *Bull. Seism. Soc. Am.* **81**, 1859–1884.

Chin, B.-H., and K. Aki (1996). Reply to "Comment on Simultaneous study of the source, path, and site effects on strong ground motion during the Loma Prieta earthquake: a preliminary result on pervasive nonlinear effects" by L. Wennerberg, *Bull. Seism. Soc. Am.* **86**, 268–273.

Cramer, C.H. (1995). Weak-motion observations and modeling for the Turkey Flat site effects test area near Parkfield, California, *Bull. Seism. Soc. Am.* **85**, 440–451.

Dimitriu, P.P. (1990). Preliminary results of vibrator-aided experiments in nonlinear seismology conducted at Uetze, F.R.G., *Phys. Earth Planet. Inter.* **63**, 172–180.

Doroudian, M. and M. Vucetic (1995). A direct simple shear device for measuring small-strain behavior, *Geotech. Testing J.*, March, 1995, 69–85.

Elgamal, A.-W., M. Zeghal, and E. Parra (1995). Identification and modeling of earthquake ground response, *First Int. Conf. on Earthq. Geotech. Eng.*, Tokyo, Japan, **3**, 1369–1406.

Field, E.H., P.A. Johnson, I.A. Beresnev, and Y. Zeng (1997). Nonlinear ground-motion amplification by sediment during the 1994 Northridge earthquake, *Nature* **390**, 599–602.

Finn, L.D. (1991). Geotechnical engineering aspects of microzonation, *Proc. Fourth Int. Conf. Seism. Zonation*, Stanford, California, **1**, 199–259.

Heaton, T.H. (1990). Evidence for and implications of self-healing pulses of slip in earthquake rupture, *Phys. Earth and Plan. Int.* **64**, 1–20.

Idriss, I.M. and H.B. Seed (1968). Seismic response of horizontal layers, *Proc. Am. Soc. Civil Eng., J. Soil Mech. Found. Div.* **94**, 1003–1031.

Idriss, I.M. (1991). Earthquake Ground Motions at Soft Soil Sites, Special Session in Honor of H.B. Seed, *Proc. Second Int. Conf. on Recent Advances in Geotech. Earthq. Eng. and Soil Dyn.*, St. Louis, B.

Ishihara, K. (1996). *Soil Behavior in Earthquake Geotechnics*, Oxford University Press, New York.

Johnson, P A., and P.N.J. Rasolofosaon (1996). Manifestation of nonlinear elasticity in rock: convincing evidence over large frequency and strain intervals from laboratory studies, *Nonlinear Processes in Geophysics* **3**, 77–88.

Johnson, P.A., B. Zinszner, and P.N.J. Rasolofosaon (1996). Resonance and nonlinear elastic phenomena in rock, *J. Geophys. Res.* **101**, 11,553–11,564.

Kazama, M. (1996). Nonlinear dynamic behavior of the ground inferred from strong motion array records at Kobe Port Island during the 1995 Hyogo-Ken Nanbu Earthquake, *Proc. Int. Workshop on Site Resp. Subj. to Strong Earthq. Mo.*, Yokusaka, Japan, **2**, 185–200.

Milne, J. (1898). *Seismology*, 1st ed., London, Kegan Paul, Trench, Truber.

Reid, (1910). The California earthquake of April 18, 1906: Report of the state earthquake investigation commission, *Carnegie Inst. of Washington*, pub. 87, vol 2, Washington, D.C.

Schnabel, P., H.B. Seed, and J. Lysmer (1972). Modification of seismograph records for effects of local soil conditions, *Bull. Seism. Soc. Am.* **62**, 1649–1664.

Schneider, J.F. , C.J. Roblee, B.L. Nigbor, W.J. Silva, and R. Pyke (1997). Resolution of site response issues from the Northridge earthquake (ROSRINE), *Proc. CUREe Northridge Earthquake Research Conference*, Los Angeles, CA, in press.

Seed, H.B. and I.M. Idriss (1983). *Ground motions and soil liquefaction during earthquakes*, Earthq. Eng. Res. Inst., El Cerrito, California.

Su, F., J.G. Anderson, and Y. Zeng (1998). Study of weak and strong ground motion including nonlinearity from the Northridge, California earthquake sequence, Subm. to *Bull. Seism. Soc. Am.*

Wen, K.-L., I.A. Beresnev, and Y.T. Yeh (1994). Nonlinear Soil Amplification Inferred from Downhole Strong Seismic Motion Data, *Geophys. Res. Lett.* **21**, 2625–2628.

Wennerberg, L. (1996). Comment on "Simultaneous study of the source, path, and site effects on strong ground motion during the Loma Prieta earthquake: a preliminary result on pervasive nonlinear effects" by B.-H Chin and K. Aki, *Bull. Seism. Soc. Am.* **86**, 259–267.

Yu, G., J.G. Anderson, and R. Siddharthan (1993). On the characteristics of nonlinear soil response, *Bull. Seism. Soc. Am.* **83**, 218–244.

Edward (Ned) H. Field
Dept. of Earth Sciences/SCEC
University of Southern California
Los Angeles, CA 90089-0740
field@usc.edu

SEISMOLOGICAL RESEARCH LETTERS

Volume 69, Number 3

May/June 1998

SEISMOLOGICAL SOCIETY OF AMERICA