Engineering and Science Needs for GSMA Sites: An Invited Opinion Paper

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In responding to the organizers' request for an opinion paper on engineering and science needs for GSMA sites, I have attempted to identify issues that I see as being significant for the advancement of both research and practice from my perspective as a researcher, educator, and user/developer of site response analysis tools. I have chosen to focus on a subset of a wide range of possible topics – those that I consider to be both important and amenable to resolution with data from strong motion arrays. I am expecting that others will address soil-structure interaction issues, so my comments will deal primarily with free-field issues.

Over the years, there has been a growing understanding of site effects and concurrent development of procedures to account for their effects. We understand the main differences in the ways that stiff and soft soil profiles respond to earthquakes in general, although some disagree on the best ways to classify various sites. Site effects can be accounted for in attenuation relationships, by the use of empirical amplification functions, and by site response analysis. Estimation of these effects by any of these methods could be improved with additional data from geotechnical strong motion arrays.

In a somewhat broader interpretation, site effects can be taken to include ground failure, or at least the accumulation of permanent strain due to cyclic loading. There is relatively little available array data from sites on or near slopes where the presence of a initial driving stresses would lead to the accumulation of permanent strains, and hence to the development of permanent deformations. Since performance depends so strongly on permanent deformations, the availability of field data that include permanent deformations would be extremely valuable.

STATES OF ART AND PRACTICE IN SITE RESPONSE PREDICTION

As frequently lamented by both researchers and practitioners, there is a substantial gap between the state-of-the-art and the state-of-practice in the prediction of site response. In the state-of-the-art, which we see being used in research settings and in highest-level (e.g. nuclear industry, large dams, etc.) practice, we have access to numerical tools for one-, two-, and three-dimensional linear, equivalent linear, and nonlinear analyses. We can simulate fault rupture and account for path effects deterministically at frequencies up to about 0.5 Hz. We can simulate soil failure and its bounding effects on ground surface motions in nonlinear site response analyses. We can simulate the generation, redistribution, and dissipation of excess porewater pressures in potentially liquefiable soils, and at least identify the mechanisms by which permanent deformation develop if not accurately predict the magnitude of those deformations.

The use of these advanced analytical tools in practice is generally quite low. As part of the March, 2004 International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response, a graduate student and I conducted an informal survey of practitioners in the U.S. and abroad on their use of site response models (Kramer and Paulsen, 2004). The results of the survey indicated that one-dimensional equivalent linear analyses were far and away the most commonly used procedures for site response analysis in North America – equivalent linear analyses appeared to the primary approach taken by about 80% of responding North American practitioners. Only about 30% of the overseas respondents indicated equivalent linear as their predominant approach, but the sample size of that response was quite small. For these analyses, a number of equivalent linear soil models are used, with the relatively old Seed-Idriss sand and clay curves retaining a striking level of popularity. Dynamic soil properties appear to be most commonly determined by field testing and empirical correlation in North America; the use of laboratory testing was much more commonly reported by overseas respondents.

Most of us recognize that we live in a nonlinear world, at least site response-wise, and that nonlinear analyses model actual soil behavior more accurately than equivalent linear analyses. We also recognize the good reasons behind the historical use and enduring popularity of the equivalent linear approach to site response analysis. This popularity stems, in my opinion, from the facts that: (a) equivalent linear analyses are relatively easy to perform, and (b) practitioners trust the results they produce. The ease of use issue follows from the ready availability of various equivalent linear soil models (i.e. matched pairs of modulus reduction and damping curves) that have been published in the literature. The previously described survey indicated that relatively few practitioners obtained dynamic soil properties from laboratory tests; instead, they obtained them by empirical correlation to insitu and/or index tests. The trust aspect of their popularity comes from the fact that equivalent linear analyses have been shown to produce good estimates of site response in past earthquakes for many of the site conditions that practitioners commonly encounter.

In situations when soils are stiff and/or motions are weak, equivalent linear and nonlinear analyses are known to produce very similar results. In such situations, there is little doubt that the convenient and familiar will win out and equivalent linear analyses will continue to be used until someone develops a nonlinear code of equal convenience. Where we, as researchers, can most beneficially focus our attention is on (a) identifying and documenting the conditions under which nonlinear effects are not approximated adequately by the equivalent linear approach, (b) developing practical and convenient tools for nonlinear analysis, and (c) developing, where possible, procedures for correcting the results of equivalent linear analyses for the nonlinear effects they do not capture. The commercial software marketplace is probably where Item (b) will be addressed, and if it is done well there, then Item (c) will not be necessary. Nevertheless, the timing will probably be such that efforts toward Item (c) will be required. In my opinion, geotechnical strong motion arrays will play a key role in moving the states of both art and practice forward.

NONLINEAR RESPONSE

Nonlinear site response analyses can be used to address the two main types of problems we deal with in geotechnical earthquake engineering – response problems and ground failure problems, which can be distinguished on the basis of permanent deformations. Response problems are those in which we are interested in estimating the amplitude, frequency content, phasing, and duration of ground motions and in which permanent deformations are insignificant. Response problems typically arise in sites with level ground surfaces and can be addressed with equivalent linear or nonlinear analyses. Ground failure problems are those in which permanent deformations are significant and may control the performance of structures and facilities of interest. Ground failure problems involve initial, static stresses and therefore are frequently associated with sloping or irregular ground surfaces or with the presence of structures. Direct analysis of ground failure problems requires nonlinear analyses. Advances in the treatment of both types of problems will require the validation of nonlinear analyses. The type of validation that will be accepted by practitioners, and thereby adopted in practice, will undoubtedly involve the type of full-scale, insitu data that only strong motion arrays can provide.

The extent to which nonlinear response is significant depends on the degree to which the stiffness of the soil is reduced by earthquake shaking. This reduction is associated with two aspects of soil behavior – the nonlinear stress-strain behavior of the soil itself, and excess pore pressure generation. The former is primarily responsible for nonlinear effects in clayey soils and the latter can strongly influence the behavior of saturated coarse-grained soils.

Soft Clay Sites

Soft to medium stiff clay soils are often found on top of stiffer sediments. The impedance contrast associated with such stratigraphy gives rise to increased spectral amplification in the vicinity of the fundamental frequency of the softer layer, which is usually addressed by means of site-specific site response analyses. These are prime situations for the use of site response analyses, and nonlinear response can become quite significant when soft clay profiles are subjected to strong shaking.

Strong shaking at sites underlain by very soft clays can lead to large strains with stresses that approach the shear strength of the soil, particularly in the vicinity of strong impedance contrasts. Although nonlinear response is known to differ significantly from that assumed in commonly used equivalent linear analyses in such cases (Figure 1), equivalent linear analyses are still used to predict ground surface motions. Geotechnical strong motion arrays at sites where very soft clays are underlain by much stiffer materials could provide field evidence of the effects of strong nonlinearity that would convince practitioners of the errors involved in using equivalent linear analyses beyond their range of applicability, and provide needed data for validation of nonlinear models under conditions of extremely high nonlinearity.

Development of nonlinear soil models that closely approximate the laboratory-measured modulus reduction behavior of soils is not a particularly difficult task; approximating the corresponding laboratory-measured damping behavior simultaneously is considerably more difficult. For most nonlinear models, the shape of the hysteresis loop (which controls damping behavior) is controlled by the manner in which the shear modulus degrades with increasing strain amplitude; in most cases, nonlinear models that match modulus reduction behavior typically produce damping ratios higher than the experimental values associated with the matched modulus reduction curve. For stiffer sites, nonlinear analyses using models calibrated to simultaneously approximate the modulus reduction and damping curves used in equivalent linear analyses have been shown to produce "underdamped" response when applied to actual cases. Better agreement with field data is typically obtained with the higher-than-laboratory damping produced by calibrations against modulus reduction behavior only. Identification of the source of the apparent "extra damping," which may result from scattering or other non-damping mechanisms, would be useful. Geotechnical strong motion array data would help resolve this issue.

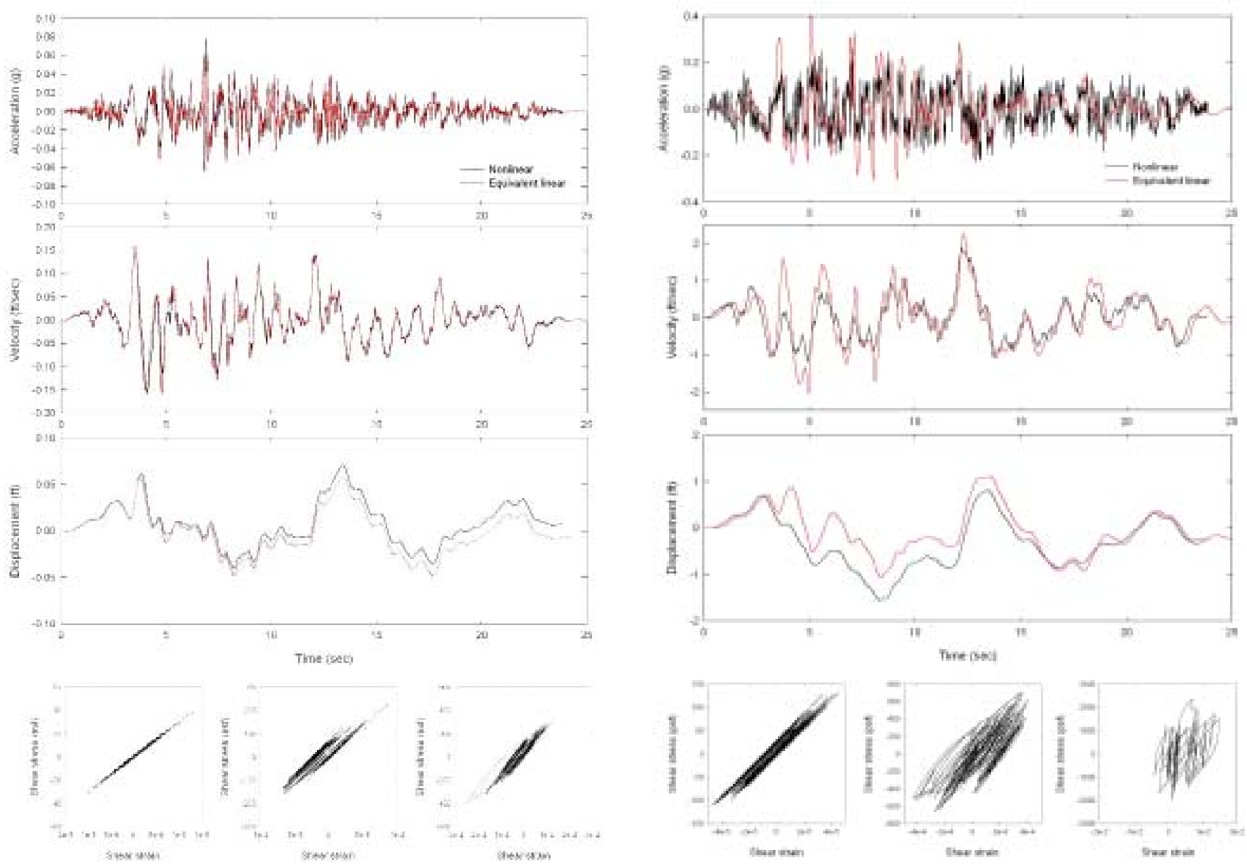

Figure 1. **Illustration of computed nonlinear and equivalent linear response for soft clay subjected to very strong shaking (left) input motion scaled to 0.05 g, and (right) input motion scaled to 0.30*g*. Stress-strain curves are from top, middle, and bottom of soft clay layer.**

A densely instrumented soft clay site would offer the potential for evaluating nonlinear effects directly – in terms of stress-strain behavior – rather than by inference through frequency shifts, etc. Establishing a "cell" of strong motion instruments of the form suggested by Zeghal (Figure 2) would allow evaluation of average stress and strain within the cell. Data from such a cell, measured during both weak and strong motions, would help validate constitutive models for soft clay response including the significant problems of rate dependence and low-strain damping, and numerical models for nonlinear site response analysis. It could also help clarify the relationship between actual hysteretic damping and other mechanisms that we might interpret as apparent damping in a one-dimensional analysis. The installation this type of array in both high- and low-plasticity clays, which would be expected to exhibit different degrees of nonlinearity and rate-dependence, would be very useful. This type of nonlinearity is closely related to the shear strength of the soil, so instrumentation of very soft sites would be expected to yield useful information in ground motions of even moderate strength; the use of very soft sites would maximize the amount of useful information from a geotechnical strong motion array.

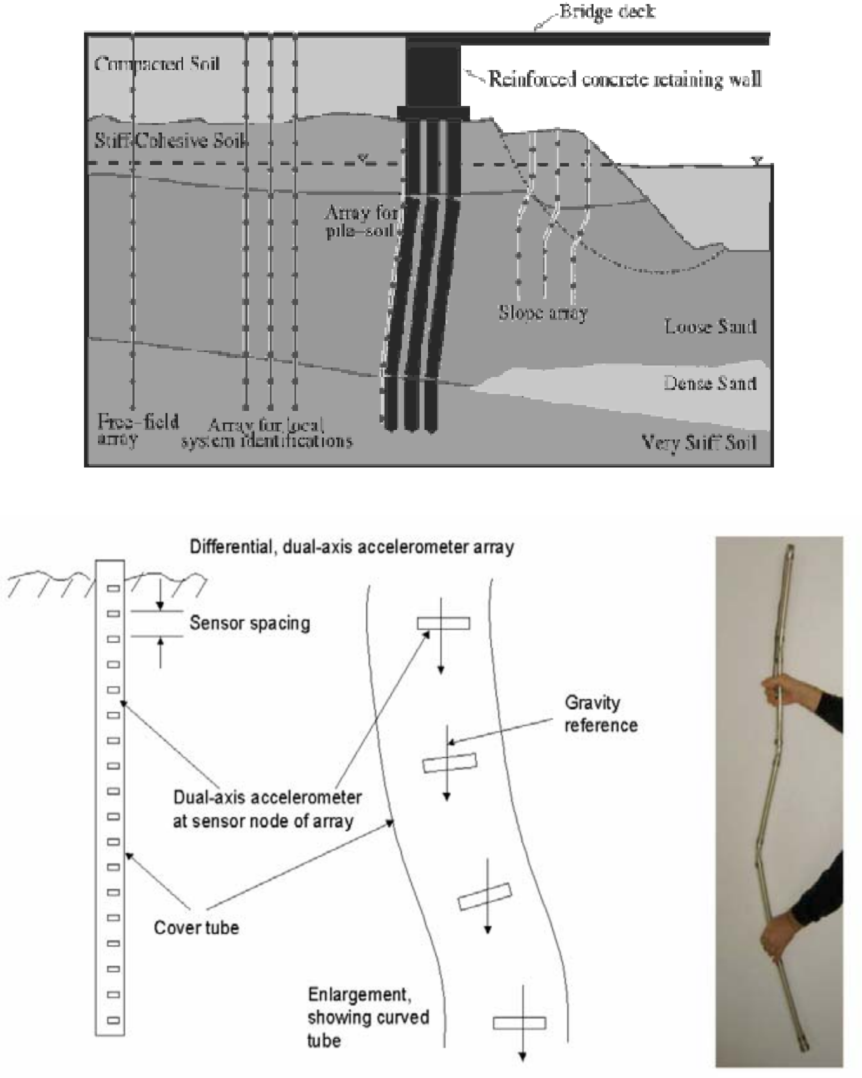

Figure 2. **Illustration of (a) potential array instrumentation schemes, and (b) novel dual-axis flexible accelerometer array (Zeghal et al., 2004).**

Liquefiable Soil Sites

The response of liquefiable soils remains a topic of great interest to geotechnical engineering researchers and practitioners. While empirical procedures for evaluation of liquefaction potential and the effects of liquefaction are available, the development of performance-based approaches to earthquake engineering suggests that future practice will likely involve more numerical analysis of liquefaction and its effects. Such analyses will require validation of their ability to predict pore pressure generation considering both contractive and dilative response, the effects of the resulting changes in effective stress on ground motions and structural response, the redistribution and dissipation of porewater pressure, and both vertical and horizontal deformations during and following earthquake shaking.

The most common forms of damage associated with liquefaction are likely lateral spreading and post-liquefaction settlement. The phase transformation behavior of liquefiable soils, which leads to their dilation-induced stiffening during shearing, undoubtedly plays an important role in controlling the cyclic and permanent deformations associated with liquefaction. Aside from the Wildlife array, which produced the first field evidence of phase transformation behavior (Figure 3), we have very little field data with which to validate the many numerical models being developed to handle this aspect of liquefiable soil behavior. There is a pressing need for more arrays of this type, instrumented with accelerometers and pore pressure transducers in such a way that post-liquefaction stress-strain and stress path behavior can be identified. It may be necessary to have multiple accelerometers within a single liquefiable layer including very closely spaced pairs to resolve behavior when wavelengths become very short as the soil softens dramatically. Arrays installed in both level-ground and sloping ground sites would be desirable. The degree to which dilation-induced stiffening occurs depends on the density of the soil – soils that are too loose will not exhibit this type of behavior. Therefore, geotechnical strong motion arrays intended to capture this type of behavior should be installed at sites with liquefiable sand layers that are loose enough to liquefy in ground motions weak enough to occur relatively frequently, but dense enough to exhibit significant dilation-induced stiffening. The identification of such profiles will require careful study and evaluation.

Current procedures for evaluation of liquefaction potential characterize ground motions based on peak acceleration and earthquake magnitude. Advances in procedures for evaluation of liquefaction hazards, specifically the *effects* of liquefaction, require improved understanding of the timing of liquefaction, which may require characterization of ground shaking by integral, rather than peak, parameters. Arias intensity is an example of an integral parameter – it increases with time in a relatively continuous manner from the beginning to the end of the earthquake. Liquefaction criteria expressed in terms of an integral parameter allow description of the strength of shaking *after* initiation of liquefaction in terms of that parameter. Given that

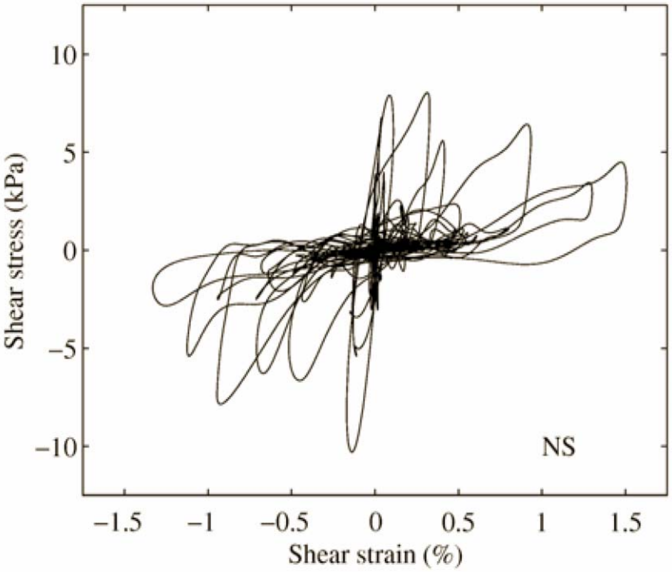

Figure 3. Illustration of insitu dilation-induced stiffening at large strains due to phase transformation behavior at Wildlife array (Zeghal and Elgamal, 1994).

most permanent deformations develop after initiation of liquefaction, characterization of the level of ground shaking following initiation may provide improved prediction of the effects of liquefaction. Understanding the effects of timing will require additional data on the phasing of ground motions, i.e. on the order in which acceleration pulses of different size arrive at a site and their effects on pore pressure generation and development of permanent strain. Additional geotechnical strong motion arrays at liquefiable sites could provide very useful data for this application.

There currently exists some degree of uncertainty in the best metrics for evaluating the liquefaction susceptibility and potential of fine-grained soils. It is widely recognized that non-plastic silts are eminently liquefiable and that highly plastic silts are not (which does not imply that they cannot behave poorly in earthquakes, although by mechanisms other than liquefaction). Strong motion arrays with pore pressure transducers located in soils that would be classified as non-susceptible by some schemes and as potentially liquefiable in other schemes would be very useful for improving our understanding the behavior of these "transitional" soils.

SOIL DAMPING

The propagation of waves through thick sequences of relatively stiff soils, which occurs in many seismically active areas, can be significantly influenced by the damping characteristics of those layers. If the materials are stiff, the low-strain damping is important. A number of laboratory studies have investigated low-strain damping, and available numerical models treat it differently (e.g. as viscous damping, using Rayleigh damping, and as hysteretic damping). The nature of insitu low-strain damping could be investigated with the aid of geotechnical strong motion arrays, both through the recording of weak tremors and through the generation of surface vibrations; such studies would require identification of a layer in which low-strain damping is to be studied and installation of high dynamic range instruments near the top and bottom of the layer. To determine the extent to which reduction in high frequency amplitude is associated with scattering (due to spatial variability of stiffness/density, for example), the ability to measure motions laterally as well as vertically would be useful.

GEOTECHNICAL SCALE BASIN EFFECTS

Basin effects on ground motions have been increasingly recognized in recent years. Site amplification studies (e.g. Baturay and Stewart, 2003) have shown that conventional one-dimensional site response analyses systematically underpredict the long-period components of ground motions recorded within basins, presumably due to their inability to account for surface waves. This unconservative bias is not widely recognized in practice and could potentially lead to problems for structures and facilities sensitive to the low frequencies of the surface waves.

Due to the manner in which geologic materials are often deposited, basins occur at many different scales – basins within basins (Figure 4) are not uncommon. Improved understanding of basin effects, and data with which to calibrate multi-dimensional models and/or develop correction factors for one-dimensional models, could be obtained from a strong motion array spanning a relatively small "geotechnical-scale"

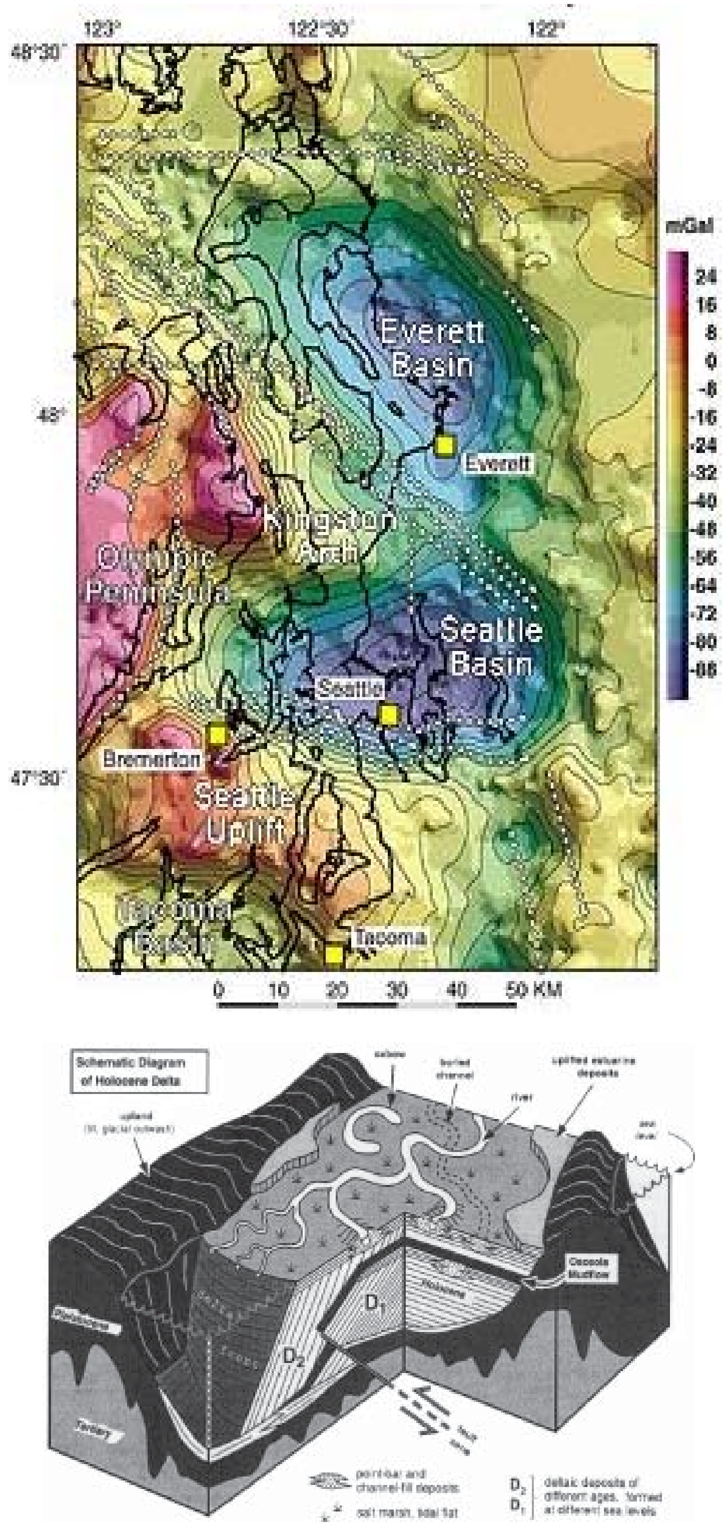

Figure 4. Basins in Seattle area: (left) large-scale Seattle basin (sedimentary rock on volcanic basement rock), and (right) small-scale Duwamish River basin (soft Holocene deposits on Pleistocene till; Kayen et al., 1998).

basin. The frequency range of surface waves in a small basin will be different from that in a large basin, but the basic phenomena involved are similar so an instrumented basin would provide useful information on the modification of ground motion frequency content and duration by basins.

SUMMARY

There are a number of geotechnical earthquake engineering issues that could be better addressed with additional data from geotechnical strong motion arrays. These issues relate primarily to the nonlinear response of soils during strong shaking – data is required to better understand basic aspects of soil behavior and to further the development and validation of nonlinear models for prediction of site response and ground failure.

This paper has attempted to identify and describe a number of these issues, which include the insitu stress-strain behavior (at low and high strain levels) of soft clays of low and high plasticity, the behavior of liquefiable soils (before and after initial liquefaction), low-strain damping of all types of soils, and basin effects. Many of the soft clay issues could be addressed by data from arrays in extremely soft clays that would be expected to exhibit nonlinear behavior in moderate motions that may be expected to occur relatively frequently. Many of the most important liquefaction-related issues, however, deal with the dilation-induced stiffening that occurs in moderately dense liquefiable soils; because such soils require stronger motions to liquefy and develop the strains required for dilatant response, data from those arrays will likely be produced less frequently.

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