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Soil Amplification During Earthquakes and Microzonation

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CLASSIFICATION OF PAPERS

The seventeen papers of this session could be classified under the following topics:

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MODELS AND MODEL DEVELOPMENT

Towhata and Islam in their paper, "Pseudo-Three-Dimensional Analysis of Cyclic Deformation of Ground Subject to Seismic Liquefaction," present a methodology to assess differential cyclic movements between two points on the ground surface due to earthquake motions. The difficult, three-dimensional nonlinear analysis is avoided by adopting a pseudo-three-dimensional approach. This is accomplished by coupling a plane-stress finite element model representing an unsaturated surface layer with a spring and dashpot (Voigt) model representing an underlying liquefiable layer. Both the finite element model of the surface and the Voigt model of the underlying layer are assumed to have visco-elastic properties. Elastic properties of the model are a time-dependent function of maximum shear-strain and pore water pressure build up.

In two trial applications of the method, predicted dynamic displacements were small and could not account for observed piping failures. This may be due, in part, to the simplified assumption of coherent base motion. Also, the model cannot, in its current state of development, take account of surface waves.

Another hybrid methodology is put forward in the paper, "BEN-FEM Hybrid Analysis for Topographical Site Response Characteristics" by Takemiya, Ono and Suda. Their paper investigates the conditions of site geometry under which 2-D analysis must be applied to assess dynamic site response to incident seismic waves. This methodology couples a finite element model with a boundary element model and accepts both incident harmonic body waves (P and S) and Raleigh waves.

The hydrid methodology is used to conduct a parametric study using a hypothetical trapezoidal-shaped, layered soil on a uniform half space. The analysis sheds very real insight into the conditions of site geometry that require 2-D analysis. It is found that for a site aspect ratio (width of basin sediments over depth) greater than three, 1-D analysis is adequate to predict site response around site resonance. It is found that both wave type and wave field incidence are important parameters in predicting site response. Observations supporting these conclusions are presented in an experiment discussed by Jongmans and Campillo, to be discussed later in this summary.

Nishigaski and Baba qualify an extension of Aki and Larner's site response model by Baba, Inoe and Nishigaki, using simplified geometries of a basin over a half space. The Aki and Larner model involves simplifying assumptions which were relieved by the extension of their model developed by Baba, Inoe and Nishigaki. Qualification of these models was accomplished by benchmarking them, using basin models having simple geometry, against results obtained using the closed form solution of Wong and Trifunac. It is shown that the Baba, Inoe and Nishigaki extension of Aki and Larner's method, gives results that are in excellent agreement with closed-form solutions.

The model is then applied to several hypothetical basins having different geometries. It is shown that basin geometry has an important effect on response results. Depending on a basin's aspect ratio (width/depth) 2-D modeling may be required to accommodate the affects of irregular or complex basin geometry. This finding is in keeping with the findings of Takemiya, Ono and Suda and with experimental results discussed later in this summary.

The cellular normal mode method for modeling site response discussed by Stephenson, appears to offer some insights about local variations in damage. Indications are that this method should be most useful in explaining damage patterns at large distances from an earthquake source where incident motions are small and response is within the linear range. It is expected to be least applicable in explaining variability of damage under conditions of strong incident motion that are likely to induce non-linear behavior. Future tests of the method may identify more fully the conditions under which the method may be usefully used for forward assessments of site response to earthquake motions.

USE OF DENSE ARRAY DATA

Dense, 2- and 3-dimensional arrays of strong motion seismographs have been installed in a number of places during recent years. Many of these arrays have high quality synchronized timing, common triggering and digital recording. Now the large data sets accumulating from dense arrays are being used to address important site response issues ranging from characterizing the behavior of seismic wave fields to attenuation of earthquake-induced ground strains. Vertical arrays of strong motion instruments closely nested laterally provide data particularly useful to address a number of issues related to site response assessment.

Abe, Terada, Kasuda and Shimizu use data from the three-dimensional KASSEM array to compare observed site amplification for both incident P-waves and incident S-waves to theoretical results obtained using a model developed by Silva. The model results appear to be in good agreement with observed amplification for both P and SV-waves at frequencies around the fundamental resonant frequency for any instrument pair. Differences between predicted and observed amplification may be due to a combination of factors, including partitioning of energy between P and SV, unquantified strain-dependent damping and simplifying assumptions on site geometry. In general, however, the Silva model appears to give quite good site amplification results.

Analyzing data obtained from the vertical array at Garner Valley, California, Seale and Archuleta compute amplification from 16 earthquakes. All recorded motions were within the elastic response range. Site response was derived empirically by fitting the low frequency asymplate of normalized source displacement spectra at the surface and at 220M. By this method, the low frequency, (< 5 Hz) amplification of the integrated geologic section between ground surface and -220M was found to be 12.8.

Niazi tested the method of assessing site response by taking the ratios of soil site recordings with a recording of the same earthquake at proximate rock site. He analyzed recordings of six earthquakes taken at rock site and soil site elements of the SMART-1 array, separated by a distance of about 2 km. Amplification of peak spectral ratios ranged between 1 and 3, while overall spectral ratios were found to vary with frequency and with components.

An important test of the use of this approach also is contained in the paper by Abe, Terada, Kasuda and Shimizu. They compare observed responses at the ground surface and at depth to responses on the same rock at two nearby sites, to predicted results using the rock site motions as input. Reasonable comparisons were seen at near resonant frequencies, but not at higher frequencies (> 10 Hz). One could conclude that both wave field coherency and possibly simplifying assumptions on site geometry contribute to the observed differences.

Another potentially very valuable use of dense array recordings is presented by Tokida, Tamura and Aizawa in their paper, "Attenuation Characteristics of Ground Strains Induced During Earthquake[s]." Knowledge of earthquake-induced ground strains is particularly important for assessing a site's geotechnical stability and for design of buried lifeline facilities. Using a computational approach developed by the authors, ground strains were obtained from the recordings of 78 earthquakes on the Public Works Research Institute (PWRI) dense strong-motion arrays. The computed strains were resolved into maximum normal and maximum shear and empirical attenuation equations were derived by assuming the form of the model long used to develop empirical ground motion attenuation relations.

This is a particularly valuable use of dense array data. Data from other dense array data sets should be analyzed and compared with the results obtained by the authors.

USE OF MICROTREMOR MEASUREMENTS

Recordings of 26 earthquakes at the three-dimensional Chiba Strong Motion Array were analyzed by Lu, Yamazaki and Katayama to assess site amplification. Results are compared with site amplification derived from microtremor recordings and the wave field coherency was analyzed to assess spatial correlation characteristics. The authors present potentially very important findings for the analysis of embedded structures: amplification of peak ground acceleration for the Chiba site occurs dominantly in the upper five meters while amplification of ground displacement is not observed between measurements taken at the ground surface and a depth of 40 meters.

Coherence between component motions is often a consideration. Based on an ensemble of 16 events, quite good coherence was found for the two horizontal components, but not for the vertical motions. This suggests that vertical amplification is dominated by P-wave arrivals. In addition, the holes in the coherence function around the resonant frequencies of the soil column are interpreted to confirm vertically incident wave fields. The authors further point out that the amplitude of the transfer function is much lower than the actual site amplification near the resonant frequencies of the soil column, due to the drop-in coherence at these frequencies.

Analyses of microtremor recordings have long been suggested as a rapid, inexpensive method to determine site resonant response characteristics. However, the full potential for use of this method continues to be a subject of debate. Recordings at the Chiba Array provided a valuable opportunity to assess the reliability of microtremor results for this application. A significant correlation was found between the peak of microtremor and earthquake ground motion power spectra at about 2.5 Hz. This very important finding appears to confirm the potential value of microtremor recordings for determining site resonant response.

Bouckovlas and Krikeli, provide a further evaluation of the use of microtremors for microzonation. Their paper compares microtremor predictions of site response with analytical predictions using a 1-D model, at eight locations with well-established soil profiles. The main focus of these comparisons is on predictions of the fundamental period of the soil column response to seismic wave excitation. It was found that the fundamental period of ground response derived from analysis of microtremor recordings is significantly influenced by local soil strategraphy. Shallow, thin, stiff layers in a soil column may set up conditions for a very shallow wave guide that results in erroneously low fundamental site resonance periods as estimated from microtremors.

ANALYTICAL ASSESSMENT OF SITE AMPLIFICATION

Analytical models to assess the effects of local site geology on the spectral characteristics of seismic waves are now widely developed. Local site geometry and soil material properties may affect site amplification in ways that are not intuitively predictable. For simple site geometries, 1-D models may be adequate; but for more complex geometries, 2-D analysis may be required.

Chiang and Chang examined the local geologic conditions that influence site response in Mexico City to the 1985 Michoacan earthquake motions. Amplification of motions at three sites having different distances from the edge of the lake deposits in Mexico City were examined using both 1-D (SHAKE) and 2-D (FLUSH) analytical models. The models were excited by a nearby rock site recording of the Michoacan earthquake and an artificially-generated motion with similar peak motion values.

It was found that site geometry does significantly influence particularly, the amplitude of site response. The influence is greater near the edge of the lake bed, but persists to a distance of about a mile from the edge of the lake bed. Thus, 2-D analytical models appear to be needed to predict site response, particularly at sites near the lake bed edge.

The influence on site response of the spectral properties of the input motion appears to be relatively slight. The amplitude spectrum used in this case appears to be relatively flat over a broad period range. The soil dynamic properties, however, were found to have a very important influence on site response characteristics, changing both the predominant response period and amplitude. Better understanding of the non-linear behavior of sites under strong ground motion loading is clearly an important need.

Jongmans and Campillo investigated the application of 1-D and 2-D analytical models to predict site responses at sites in a well-developed 2-D, sediment-filled valley. Analytical and observed results were compared for a site on rock and four sites nearby within the valley for a number of nearby, small earthquakes. The computed results obtained using 1-D models were not able to explain the observed experimental results. Although results using a 2-D model resulted in a somewhat improved comparisons with observations, significant differences remained. These differences suggest that waves propagating from the edge of the basis and incidence angles of incoming waves also have an important role in site response for sites having complex geometries, and lateral variation in site material properties also may play a role.

In a somewhat different application of theoretical analyses, Athanasopoulos compared site response to observed variations in damage caused by a local earthquake near the city of Kalamata, Greece. Response analyses were performed at nine sites having known soil dynamic properties, using the 2-D finite element code LUSH in a 1-D mode. A calculated strong motion accelerogram was used as model input. The ground response was found to vary in both amplitude and frequency content among the nine sites. The intensity of motion and site fundamental response were found to correlate well with observed damage.

INTEGRATED PROCEDURES FOR GROUND MOTION ESTIMATION

Site-specific estimation of strong ground motion based on interpreted earthquake source, seismic wave attenuation and local site response models is a desirable goal. In practice, these site-specific spectra are derived either: 1) empirically by taking an appropriately conservative representation of an assemblage of ground motion recordings representing analog combinations of source magnitude, distance and site conditions, or 2) theoretically or semi-theoretically by combining earthquake source, seismic wave attenuation and local site response models.

Ahmad, Gazetas and Desai in their paper "Study of Site Response at Memphis Due to a Large New Madrid Earthquake," take the latter approach. A source model representing a M7 earthquake on the New Madrid fault together with a regional seismic wave attenuation model are used to simulate bed rock motions at Memphis, at a 65 km distance. The Hanks-McGuire model is used to generate source motions and the 1-D SHAKE and DYNA1D codes are used to model site response. Very significant modeling uncertainties, known to exist at each stage of such a site-specific ground motion modeling methodology are not addressed by the authors.

EMPIRICAL STRONG GROUND MOTION ATTENUATION

Means of estimating strong ground motion as a function of earthquake magnitude and source distance is fundamental to earthquake engineering practice. Empirical attenuation relationships historically have been most commonly used to estimate strong-ground motion in practice. These are highly region-specific and it is well known that both magnitude and distance are uncertain. Huo and Hu have derived an empirical attenuation relationship that accounts for errors and uncertainty in both magnitude and distance determinations. Approaches, such as suggested by the authors should lead to improved empirical ground motion attenuation models.

POINTS TO CONSIDER

The papers contained in this Session raise some very real challenges for future research. This is particularly true with respect to more fully defining conditions under which 1-D site response modeling is sufficient and conditions under which more complicated models are required. Dense, three-dimensional strong motion seismograph arrays are providing excellent, high quality data to directly validate site response models and to address a wide range of site response modeling issues. Such arrays also are providing data for the direct computation of ground strain and for developing strain attenuation relationships. Two key issues in microzonation mapping addressed in this Session are the usefulness of microtremors and of proximate rock motion recordings for predicting site response. The points emerging from these papers for further discussion are as follows:

- A number of site response computational models now exist, ranging from 1-D to 3-D modeling approaches. It is important now to make coordinated use of the very powerful dense array data being accumulated to systematically validate these models.

- In practice, site response usually must be obtained using empirical or forward modeling approaches, often with limited information about site and soil properties and their geometry. More clarification is needed about conditions that can be satisfactorily analyzed using less costly 1-D approaches as opposed to those conditions that require use of more complex 2-D or 3-D approaches. Simplified procedures should be the ultimate goal.

- Dense arrays also provide data suited to assessing the properties of the seismic wave field, including scattering and coherency. The importance of the properties of the wave field on site response is only beginning to be explored.

- Microtremor recordings appear to offer very real promise as a means for rapid microzonation. The geologic confidently provide site response information need to be better understood and guidelines for application are needed.

- Nearby rock motions also are often used to assess the general amplitude and resonant properties of soil sites. Work is needed to determine under what spatial separations this technique can be applied.

- Understanding non-linear behavior of soil is perhaps the most important need. In practice, site geology is extremely heterogeneous for a given site and is highly variable from site to site. Means of obtaining strain-dependent properties in-situ or by a combination of field and laboratory techniques are needed.

- Finally, there is a strong need to better understand and account for the uncertainty in determination of bulk site geotechnical properties.