Nonlinear Soil Properties and their Use in Dynamic Analysis

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Computational Models for Dynamic Analysis

For the last 40 years, research on the development of constitutive models for soils has been conducted around the world and a large number of models have been developed. The most successful models have been the suite of programs based on the equivalent linear soil model. Since the early 70's, these have been the main methods used in practice. They are robust programs, not overly sensitive to reasonable variations in soil properties. They are likely to continue to be the methods of choice for analyses where major yielding does not occur and where the effects of pore water pressures are not significant. For these problems, nonlinear methods which are not formally based on plasticity theory and are not based on Biot's equations tend to be used. Full plasticity models based on Biot's equations are used infrequently because of perceived theoretical complexity and the difficulty of calibrating the models in a commercial environment.

By far the largest number of constitutive models is based on some form of plasticity theory; simple elastic-plastic, models based on multi-yield surfaces or bounding plasticity theory. Then there are the choices of associative and non-associative plasticity with isotropic or kinematic hardening, radial or projective mapping and, for effective stress analysis, the choice of with or without Biot's equations. An interesting reverse development has occurred in recent years against this backdrop of sophisticated plasticity methods. The spur for these developments was the supposed limitations of the simpler models such as Mohr–Coulomb and Drucker-Prager. Yet today, with no evident rehabilitation, Mohr-Coulomb is the most frequently used of the plasticity options available in commercial software.

All models use basic soil properties but the more sophisticated models may also require the determination of parameters and functions that have no direct link to the basic properties. These are determined by calibrating the response of the model to a variety of test data. Evaluation studies have clearly shown that the model response is dependent on the loading paths used in the calibration tests. When required to predict response for a different loading path, the results have not been impressive. The lesson is that model calibration should be done at least for the dominant loading mechanism in the problem under consideration.. For example, for analysis of rocking mat foundations and footings, cyclic compression triaxial tests would seem to be more appropriate; for analysis of horizontal shearing by shear waves propagating vertically simple shear tests seem best. Calibration for the dominant loading path will improve the performance of any model.

Should a better model be sought? A study of model development over the last 40 years suggests that, in the near future, the probability of some radically different super model emerging is very low. But improvements are possible and necessary in existing programs. Practice needs above all else, user friendly and transparent models. A simple but telling example of user friendly innovation is the PROSHAKE version of the most enduring program of all, SHAKE. More efficient commercial programs are also necessary. In dynamic analyses, to facilitate parametric studies to bracket performance for potential variations in soil properties, reasonably fast execution is essential.

A crucial element in model performance is how it is used. Every model, even the most general, has its limitations and the user should be familiar enough with the underlying theory to be able to recognize them. This a very important requirement for conducting site response studies for the evaluation of computational models. To what shall the differences between recorded and measured motions be traced? Shall the program be modified or the properties re-examined? Before either is done, the possibility that factors outside the scope of the model may be responsible for the discrepancies should be investigated. Otherwise a model may be improperly calibrated. These points are illustrated by the example below.

Case History Analysis

Consider a simple example of site response as illustrated by the site UM10 on Treasure Island. This site liquefied during the 1989 Loma Prieta earthquake. It was analyzed by Hryciw et al (1) using the total stress analysis program SHAKE. Typical results are shown in Fig. 1. The calculated response spectra under-estimate the response spectrum of the recorded motions considerably. Even significant variations in soil properties did little to close the gap, as shown by the range of calculated spectra. One reason for the poor match is that the site liquefied and therefore developed high pore water pressures during shaking. The effects of those pressures are not reflected in the total stress analysis. An effective stress analysis of the same site by Finn et al (2) gave the results in Fig. 2. The effective stress results are a substantial improvement but there are still clear differences between the spectra for the calculated and recorded motions, especially around 0.3s.

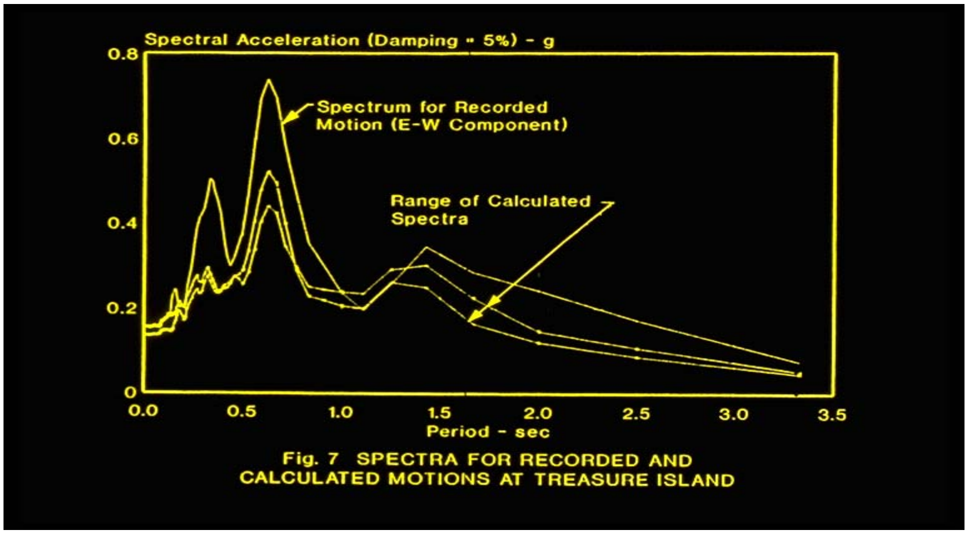

Fig. 1. Spectra of recorded and calculated motions at Treasure Island site (1)

Another factor influencing response is the degree of coherence between the recorded input and output motions. The lack of coherence between recordings with significant, spatial separation is well known and taken into account for very long span structures. However it is usually ignored in studies of case histories to determine the capability of computer programs for simulating site

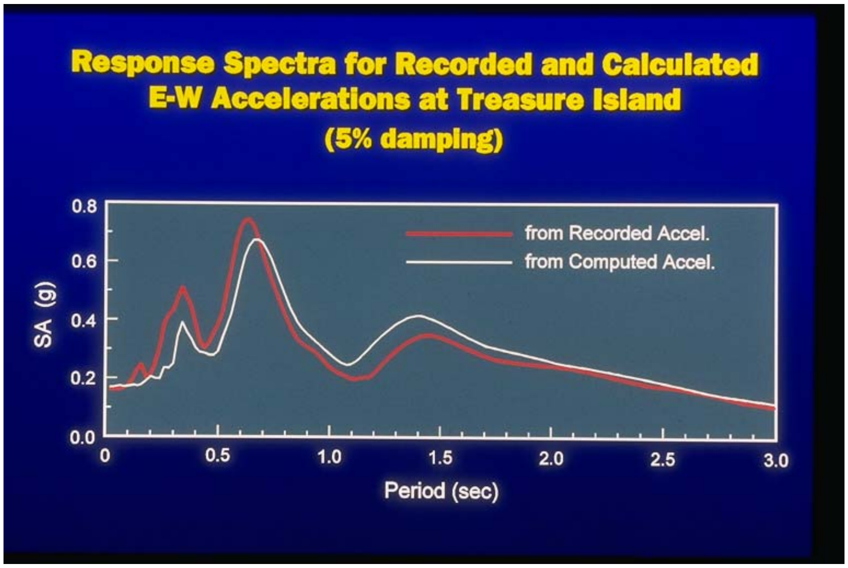

Fig.2. Response spectra of recorded motions at Site UM10 and of site motions calculated by effective stress analysis (2).

response. In these studies, rock motions from relatively distant sites are often used as input and the recorded site motions are considered to be output from input motions only.

The coherence between the E-W components of the motions recorded at Treasure Island and Yerba Buena are given in Fig.3. These locations are about 2km apart, so some lack of coherence is to be expected. The major lack of coherence is in the short period range 0.2s-0.3s. This is the period sector in which the greatest difference was noted between spectra of the measured and recorded motions in Fig. 2. There is lack of coherence also around 0.5s and in the long period range from about 1s and up. The lack of coherence appears to be reflected in the calculated spectra in Fig.2. A qualitative view of the changes in the characteristics of the motions between the two sites may be obtained from the 3-D plots in Fig. 4.

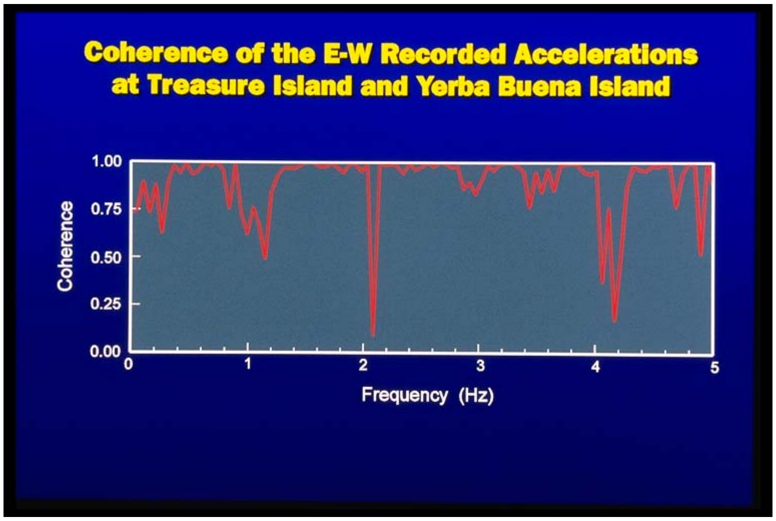

Fig.3. Coherence of E-W recorded accelerations at Treasure Island and Yerba Buena (2).

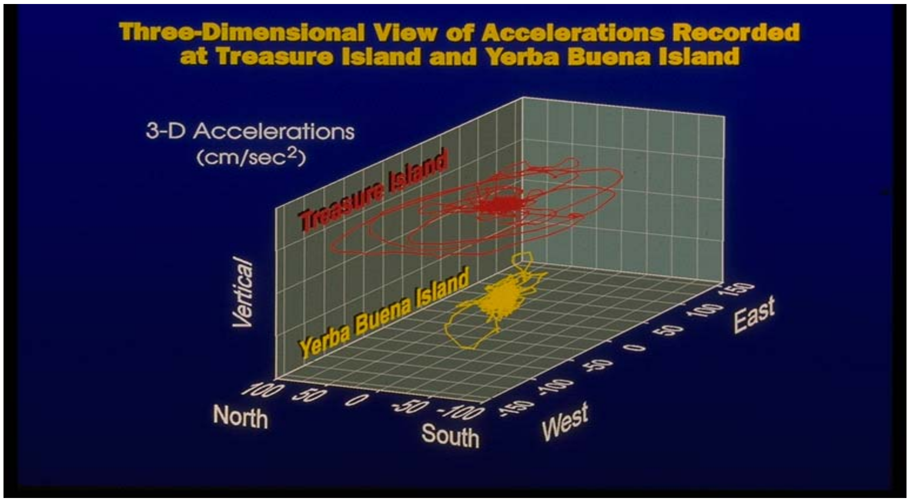

Fig. 4 3-D plot of the motions at Yerba Buena and Treasure Island (2)

Another factor that can result in differences between the recorded and calculated spectra is the presence of surface waves. Such waves are not reflected in I-D response analysis. A site response study by Ohta et al (3) of an instrumented site in Japan showed that surface waves accounted for 30% of the recorded intensity at the surface. The 1-D site response analysis, of course, missed this component. All three of these factors were outside the scope of the total stress analysis and two were outside the scope of the effective stress analysis.

Evaluation of Nonlinear Soil Properties

Reconstituted Samples

An early example of concern about how samples are reconstituted for testing is the development and use of the kneading compactor by the State of California in the 50's to ensure that the fabric of test samples approximated that imparted by compaction equipment.

One of the first quantitative studies was conducted by Mullilis on the effects of sample preparation method on liquefaction resistance. This study made clear that the manner in which a sample is reconstituted may have a significant effect on the sample properties. This finding was largely ignored because of the convenience of preparing sand samples by moist compaction. In recent years other studies have again stressed the importance of matching sample preparation to the fabric of the deposit under study. During the multi-year CANLEX Liquefaction Experiment in Canada, this issue received attention and it was shown that the liquefaction resistance and stress-strain response of Holocene sands deposited under water in the Fraser Delta of British Columbia could be closely simulated by samples formed by pluviation under water. The effects of sample preparation method are still frequently ignored. It would seem that this issue of sample preparation is one that should receive attention during the workshop. It would be a significant advance if a consensus could be reached on a recommendation regarding the more appropriate method of sample preparation for different types of deposit formation – deposit under water, hydraulic fill, wind blown sands and compacted fill.

The fabric is not the only issue in forming representative reconstituted samples. It is also important to get the density and the fines content right and to recreate the stress history in the ground as well as possible. One new technique that has been suggested for assessing how representative a reconstituted sample may be is measure the shear wave velocity in the test sample in the laboratory, using bender elements, and compare with the *insitu* velocity.

Testing of all samples, reconstituted or retrieved from the field, should be done using the dominant type of loading expected in the field, as discussed earlier. An early example of this is the practice in offshore geotechnical engineering of matching the stress conditions at different locations along potential sliding surfaces under gravity platforms by the stress conditions in the laboratory tests. Usually the sliding surface is divided in 3 different dominant stress regions that are assigned properties obtained by compression, simple shear and extension tests.

Retrieved Samples

The fundamental requirement of a retrieved sample is that it should be “Undisturbed.” The extreme effort to get an undisturbed sample is to freeze the ground first. Ground freezing was a major component of the CANLEX Experiment and many tests were run on thawed samples. There were many discussions about the proper way of thawing samples to maintain the undisturbed nature of the sample. Unanimity was not achieced. This is an important issue that would benefit from some consideration during the workshop.

For other samples, it is important to have clear criteria for deciding whether a sample is “undisturbed” in the sense of being suitable for the test under consideration. The major problem materials are sands and sensitive clays.

The equivalent linear methods and the nonlinear methods that are not based on plasticity theory can rely substantially on *insitu* tests for material properties The distribution of shear moduli in the field, for example, can be derived from shear wave velocities measured by any one of a variety of standard testing procedures and sufficiently adequate estimates of friction angle and undrained strengths can be obtained from CPT and SPT tests. The advanced plasticity methods make the greatest demand on laboratory tests for calibration because not only conventional soil properties need to be established but functional relationships also as well as “floating parameters not directly related to soil properties. Hence the quality of the sample and the “correct” mode of loading for testing are very important. This is especially true for models based on the coupled Biot’s equations for the 2-phase soil-water medium. In these models, it is vital to get the plastic volumetric strains and elastic rebounds right if the pore water pressures are to be adequately predicted.

References

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