An Opinion Paper
For
The International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response

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The California Department of Transportation (Caltrans) has long recognized the importance of and incorporated the site-effects in seismic hazard analysis for bridge structures and other highway facilities. Current practice is to evaluate the subsurface conditions for each project site and recommend for design one of the following: a standard 5% damped Acceleration Response Spectrum (ARS) curve from the Seismic Design Criteria (SDC, 2001), a modified SDC ARS curve or a site-specific ARS curve developed based on dynamic ground response analysis. At this time, the modifications to standard SDC ARS curves are generally introduced to include near-fault effects and/or structure damping other than 5%. For ordinary bridges, a site-specific dynamic ground response analysis is usually required when the bridge is:

- Located within the near-fault region and/or
- Underlain by soft or liquefiable soils

The SDC (2001) includes standard ARS curves up to a Peak Bedrock Acceleration (PBA) of 0.7g (in increments of 0.1g) for NEHRP Type A through Type D soils profiles, and 0.5g for Type E soil profiles. Since no standard SDC ARS curves are available, a site-specific dynamic ground response analysis is needed to evaluate the design ARS curve for the bridge sites with the following conditions:

- The design PBA is >0.7g for Type C and D soil profiles, and >0.5g for Type E soil profiles.
- Type F soil profiles irrespective of the design PBA.

In addition, site-specific dynamic ground response analysis is usually required for tall, long and important bridge sites, and also considered appropriate for developing design ARS curves for vertical ground motion, in particular for near-fault locations. The issues of non-linear soil properties, the associated uncertainties and the methods of analysis (e.g. equivalent linear vs. truly linear, total stress vs. effective stress), although factors for all site response analysis, are significantly more important for these site conditions. Due to high ground motion and/or soft or loose saturated soil conditions, these sites are likely to experience high shear strain and permanent deformation. The equivalent non-linear method with the associated soil constitutive model has gained wide acceptance due to it simplicity and capability to predict dynamic ground response reasonably well, but still suffers from a number of important limitations with regard to the response analysis for the above site conditions. These limitations are associated with the uncertainties involved in the pertinent non-linear soil parameters for different soil types and *state* conditions; the total stress and 1-D method of analysis; assumption of vertically propagating shear wave, in particular for near-fault sites; lack in the capability to include modulus degradation, to predict permanent deformation; lack of convergence of the solution, filtering of high frequency motion and sensitivity to model parameters, in particular damping ratio, for soft and/or moderate to deep soil sites subjected to strong ground motion; and applicability and/or lack of constitutive models and associated equivalent non-linear parameters extending to large shear strain levels.

For sites underlain by predominantly saturated granular soils, especially liquefiable soils, a truly non-linear effective stress analysis method is needed for the response analysis. A validated generalized and truly non-linear code that can perform both vertically propagating shear wave as well as compression wave analysis by incorporating both total stress and effective stress methods with constitutive models based on a limited number of parameters which can be determined by following a well defined procedure and using routine tests, preferably field tests, is needed for wide acceptance and use by the profession. Due to the many clear advantages of Cone Penetration Tests (CPT) over other current field testing methods, constitutive models with parameters developed and published with associated uncertainties quantified for different "Soil Behavior Type (SBT) or Index" as proposed by Robertson (1990) will be highly useful to the practicing engineers. Since extensive and accurate laboratory testing on site-specific soils is not feasible for most projects due to difficulties involved with undisturbed sampling and high cost, ready to use model parameters developed through research testing or back calculated by analyzing actual earthquake ground response are needed for each of the SBT. Model parameters that would require extensive or costly field-testing are not likely to gain wide acceptance either. Furthermore, many bridge structures are placed on high approach embankments, traverse waterways, valleys, canyons or other topographic features, or long and linear structures. A two or a three-dimensional analysis code to handle these topographic features plus ground improvements and the effects of soil-structure interaction will be a valuable tool.

Regarding uncertainties associated with the non-linear soil parameters, Caltrans currently utilizes a suspension-type logging system for high-quality measurements of both compression wave and shear wave velocity to evaluate site-specific small strain modulus necessary for dynamic ground response analysis. The quality of the maximum compression or shear modulus profile obtained is generally excellent with minimum measurement variability and well-defined inherent variability that can be easily quantified and incorporated in the ground response analysis. Many of the other non-linear soils parameters associated with the widely used equivalent non-linear code SHAKE (Schnabel et al, 1972) or the currently available truly non-linear total or effective stress methods, in particular, the modulus reduction and damping vs. shear strain relationships are determined by means of laboratory tests. As stated above, the necessary laboratory testing required for determining these parameters on a site-specific basis are seldom affordable. Most routine analyses are performed using published model parameters. There are many limitations and uncertainties associated with the use of these published non-linear parameters. Little, if any, quantitative information is available about the uncertainties associated with the published parameters in order to perform a sensitivity analysis.

It is known that the uncertainties associated with the equivalent damping parameter, in particular at higher strain level, are much more significant than those associated with modulus reduction curve even for well-defined and simple soil types such as clean sand and clay soils. Many real soil profiles include silts and mixed soils (e.g. silty/clayey sand or gravel, clayey/sandy silts, silty/sandy clay etc.), yet little information is available on the non-linear properties specific to each of these soil types, and only limited information is available for gravelly soils. The published sand or clay parameters are generally used to represent the non-linear behavior of these mixed soils introducing more uncertainties in the conducted ground response analysis. One of the major sources of uncertainty is the disturbance of soil samples, which destroys the important influences of soil fabric, aging or cementation and stress history, especially on the non-linear soil properties at small strain range and the cyclically induced excess pore pressure generation in saturated granular soils. Although significant field and laboratory testing has been conducted in the past, much is needed to be done to clarify and quantify the effects of and reduce the uncertainties associated with many of the factors that influences the small to large strain non-linear soil parameters and dynamic ground response analysis including not only clean sand and clay soils but also other common natural soil types and chemically stabilized or improved ground (e.g. soil-cement stabilized ground improvements).

In summary, since it is rarely feasible to perform high quality sampling and testing on a site-specific basis, detailed characterization and quantification of relevant non-linear soil parameters and the associated uncertainties due to the major factors (e.g. void ratio, effective confining stress, static shear stress, plasticity, fabric or mode of deposition, gradation, loading cycles or degradation, method of testing etc.) for various soil types and shear or compression strain levels will be highly useful to the practicing engineer. This will help not only to reduce the uncertainties associated with dynamic ground response analysis but also allow the engineer to easily perform sensitivity analysis when necessary. As stated above, model parameters developed to correspond to each of the CPT based soil types will be very useful since the "SBT" provides a more complete description of the *states of in-situ soils*, and are conveniently and, by now, widely used for classification of field soil layers.

References Cited

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