White Paper

Testing of Dynamic Soil Properties for Nuclear Power Plant COL Applications

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EXECUTIVE SUMMARY

Several companies have notified the NRC of their intention to file COL applications. An important element of the COL application is the characterization of the dynamic properties of soils that will surround, underlie and support the Seismic Category I structures, systems and components (SSC) of the power plant. These dynamic properties are important inputs to SAR sections 2.5 on geology, seismology, and geotechnical and 3.7 seismic analysis and design.

Not all sites are equal with respect to the need for laboratory testing of the dynamic properties of soils. Hard rock sites, where all Category I and II structures are founded directly on competent rock (or material of similar dynamic characteristics), may not require any dynamic laboratory testing at all. On the other hand, a deep soil site with particularly heterogeneous soils may require twice as many dynamic tests as a more homogeneous soil site. The geological characteristics of the site should dictate the number of dynamic soil samples required to adequately profile the dynamic properties of soils as they might impact the safety aspects of the site.

This paper proposes a protocol for the testing of the dynamic properties of soils that will accommodate multiple COL projects in view of the limited available testing capacity, while providing sufficient dynamic property information for each site to enable the COL application to be accepted for review by the NRC. The remaining set of Resonant Column/Torsional Shear (RCTS) testing would be identified in the COL submittal and this remaining test information will be provided as supplemental information to the COL application.

WHITE PAPER

TESTING OF DYNAMIC SOIL PROPERTIES FOR NUCLEAR POWER PLANT COL APPLICATIONS

1.0 PURPOSE

This document provides a review of the requirements regulatory guidance regarding the determination of dynamic properties of soils at the COL site. It then evaluates field, laboratory and comparative methods to determine these key properties for use in dynamic analysis. Finally, it proposes a means to prioritize among sites so that laboratory testing is performed on those samples that are of the greatest importance in characterizing the impact of dynamic activity upon nuclear safety-related structures, systems and components (SSC) at the sites.

2.0 INTRODUCTION AND BACKGROUND

Currently the Nuclear Regulatory Commission (NRC) has received notice intent from several companies to file combined license applications for new nuclear power units. Field investigation and laboratory testing activities are currently underway for at least 13 of these sites. Approximately seven of these applications are slated to be filed with the NRC in the 4^{th} Quarter of 2007. This unprecedented level of activity has resulted in a strain upon the utility, consulting, testing, quality assurance and regulatory resources involved in the new nuclear power plant planning process.

Although most of the tests required for the COL site characterization process can be performed by a significant number of commercial laboratories, certain tests are available from a very limited number of laboratory facilities. In particular, testing of soils for dynamic properties by the preferred Resonant Column/Torsional Shear testing methodology can currently be performed for COL projects by only two laboratories nationwide. This constraint has required applicants and their consultants to carefully evaluate the number of samples required for testing as well as to consider other methods to supplement the results from the laboratory tests to fully characterize the impact of dynamic soil characteristics on nuclear safety-related structures, systems and components (SSCs).

3.0 COL APPLICATION REQUIREMENTS

The NRC provides regulatory guidance to assist applicants in the development of COL applications to provide adequate information from which NRC staff can accurately assess the safety of the specified reactor design at the proposed site. Direction is given in Regulatory Guide (RG) 1.206 and RG 1.138 regarding the dynamic soil properties information to be presented as a part of the COL application.

- Chapter 2.5.4.7 of the Safety Analysis Report (SAR) (USNRC, 2007a) requires the applicant to:

Describe the response of soil and rock to dynamic loading, including the following information:
(1) any investigations to determine the effects of prior earthquakes on the soils and rocks in the vicinity of the site, including evidence of liquefaction and sand cone formation
(2) compressional and shear (P and S) wave velocity profiles, as determined from field seismic surveys (surface refraction and reflection and in-hole and cross-hole seismic explorations), including data and interpretation of the data
(3) **results of dynamic tests in the laboratory on samples of the soil and rock** (emphasis added)

- Chapter 3.7.1.3 of the SAR requires the applicant to:
  For each Seismic Category I structure, provide a description of the supporting media, including foundation embedment depth, depth of soil over bedrock, soil layering characteristics, dimensions of the structural foundation, total structural height, and **soil properties of each soil layer, such as shear wave velocity, shear modulus, soil material damping,** and density.

- Regulatory Guide 1.138 (USNRC, 2003) specifies that:
  The dynamic testing program should include tests to determine the soil parameters **needed as input for reference analyses and soil structure interaction studies** as well as testing **to determine the dynamic strength characteristics** and liquefaction potential of soils.

- Regulatory Guide 1.138 further describes the required dynamic testing program as follows:

  The basic parameters required as input for dynamic response analyses of soils include total mass density, relative density, Poisson's ratio, static soil strength, initial stress conditions, shear and compressional wave velocities, and the dynamic shear modulus and damping ratio. **The variation of strength, moduli, and damping with strain is also needed for such analyses**.

The context within which these data and these analyses are required specifically relates to the integrity of nuclear safety-related structures, systems and components (Seismic Category I and II), not the proposed plant in general.

4.0 DETERMINATION OF DYNAMIC PROPERTIES

Specific dynamic properties of soils, such as the shear modulus and damping ratio can be obtained directly through laboratory testing or indirectly through analysis of the results from field tests or from published Generic Curves. Multiple sources and methods can serve as an independent check to ensure that proper conclusions have been reached regarding these parameters.

4.1 Laboratory Methods

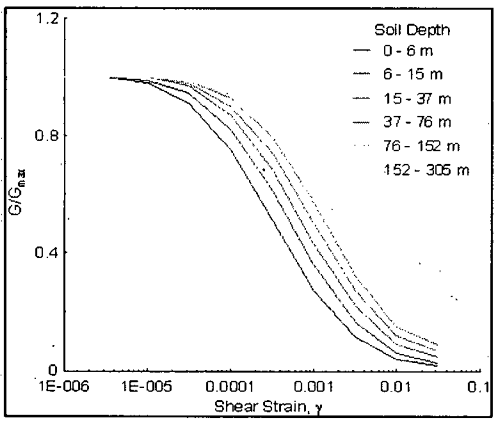
4.1.1 Resonant Column and Cyclic Triaxial Tests

RG 1.138 (USNRC, 2003) discusses the use of Cyclic Triaxial (CT) testing (ASTM D 3999) in combination with Resonant Column (RC) testing (ASTM D 4015) to determine the change in both Shear Modulus and the Damping Ratio with change in Strain. This is consistent with the recommendations made in the earlier (1978) version of this guide.

One disadvantage of the separate RC and CT test methodology is that the shear modulus and damping curves are developed from independent tests on two separate samples, rather than from the results of testing a single sample. When using two separate test systems and two discrete samples it may be difficult to achieve overlap between the results from the low-strain RC tests and the higher strain CT tests.

4.1.2 Resonant Column/Torsional Shear Test

Although not mentioned directly in RG 1.138, the combined Resonant Column / Torsional Shear (RCTS) test*, developed by the University of Texas at Austin is considered by many experts to be superior to the separate use of resonant column and cyclic triaxial tests to synthesize shear modulus reduction curves. This is the test methodology utilized in the 1993 study commissioned by EPRI to investigate methods for determining design basis ground motions (EPRI, 1993). The advantage of the RCTS methodology is that it can perform a sequential series of tests on the same specimen over a cyclic shearing range from about 10^{-4} % through 10^{-1} %. Examples of the results of this test are shown in Figure 1.



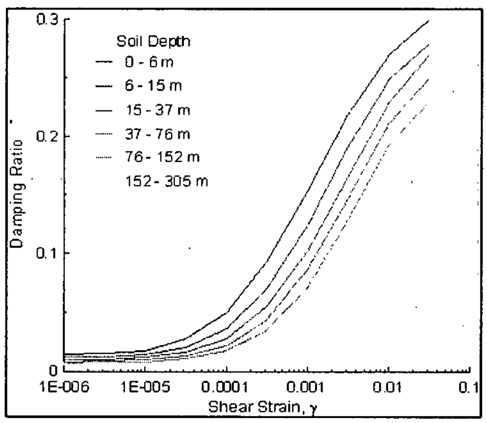


Figure 1 Example Graphs of Shear Modulus and Damping Ratio versus Strain (from EPRI, 1993)

The Standard Review Plan (USNRC 2007b) specifies that test procedures will be found adequate where:

* Where the word "test" or "tests" associated with the RCTS protocol is used in this paper, it is meant to designate the full complement of tests that are conducted on a particular sample, not a single test result.

> In meeting the requirements of 10 CFR Parts 50 and 100, the description of properties of underlying materials is considered acceptable if **state-of-the-art methods** are used to determine the static and dynamic engineering properties of all foundation soils and rocks in the site area.

The RCTS test is being used by most of the COL applicants because it represents the current state-of-the-art and is assumed to provide more representative results for the critical shear modulus and damping ratio parameters.

The one drawback experienced with RCTS testing is the current lack of adequate testing capacity. Prior to 2007, this test apparatus could only be found at a few academic institutions, which generally had only a single apparatus each. The University of Texas at Austin had committed one of its three operational cells to COL testing, but the other two cells were already required to accommodate DOE programs and academic research. No commercial soils laboratory offered the combined RCTS test until late March 2007, when Fugro brought into production the first of four RCTS units it committed to the COL program. A second commercial lab has placed an order for three RCTS cells that are slated to be online by late June 2007. One utility has taken the initiative to commission the fabrication of two new RCTS cells to facilitate the required testing for its COL project. In addition to the limited number of test cells available, the complexity of this test protocol requires the expertise of specially trained technicians, which are also in limited availability.

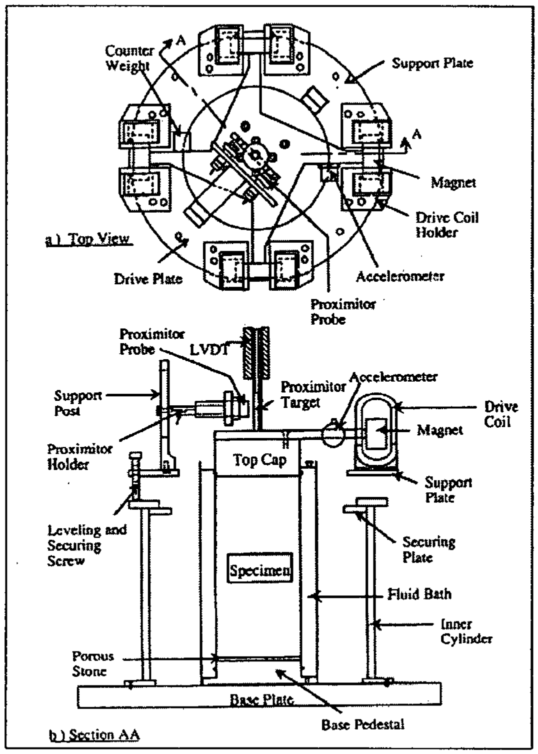


Figure 2 Schematic Drawing of Resonant Column/ Torsional Shear Apparatus (from Ni, 1987)

The University of Texas has licensed its design to a single test cell manufacturer in Houston, TX which can produce additional RCTS test cells in a minimum of six weeks, with an additional two weeks to calibrate and certify comparability of results with the UT cells. The complexity of the test apparatus (see Figure 2) is a major factor in both the cost of a new unit (approximately $50,000) as well as the difficulty in achieving a Quality Assurance certification that is acceptable for nuclear safety-related testing (10 CFR 50 Appendix B).

A second factor, in addition to capacity, that is affecting the time schedule to obtain RCTS test results is the time it takes to complete a round of RCTS testing in order to produce the required Modulus Reduction and Damping Ratio curves. Experience to date has been approximately one week per each granular sample and up to two weeks for cohesive samples (not including the time for analysis of test results and QA review). The combination of the long test duration with the limited number of available test cells has resulted in a potential inability to obtain results from all of the proposed RCTS tests prior to the planned filing dates for the first seven COL applications.

4.2 Field Methods

In situ measurement of shear wave velocity (Vs) can be accomplished by a variety of geophysical methods in prevalent use today. These include the results of crosshole testing, downhole, logging, suspension logging, seismic cone penetrometer (SCPT), and spectral analyses of surface waves (SASW). The low strain shear modulus can be calculated from Vs by the formula:

$$G_{max} = V_s^2 * \rho$$

$\rho = \gamma/g$ where γ is the soil unit weight and g is acceleration due to gravity

Shear wave velocity data from these field geophysical tests are presented as they vary with depth. The values for Vs can be averaged over an appropriate interval (~5 feet) and utilized to calculate the G_{max} for each soil interval.

4.3 Published Generic Curves

The technical literature includes studies dating back to the early 1970's (e.g. Seed and Idriss, 1970; Hardin and Drnevich, 1972) that present curves depicting the variance of Shear Modulus and Damping Ratio with shear strain for various types of soils. The pioneering work of Professor Seed and his colleagues (Seed et al, 1984) focuses on granular soils and the effect of confining pressure, while a later study (Sun, Golesorkhi and Seed, 1988) focuses on cohesive soils and the effect of plasticity index. Each of these studies provide the results of laboratory testing for a large variety of soil samples, along with classification of soil properties to enable the correlation of other soils to those tested.

Perhaps the best known of these studies is the five-volume study "Guidelines for Determining Design Basis Ground Motions" funded by EPRI (EPRI, 1993). This study provides well-developed documentation of both the field and laboratory methodology utilized to gather data and contains generic shear modulus reduction and damping ratio curves for dry sands, saturated sands and clays.

Professor Stewart of UCLA (Stewart et al, 2001) provides a table (Table 5.5) in which he cites criteria used by himself (Stewart and Baturay, 2001) and by Dr. Silva (Silva et al, 1999) to select modulus reduction and damping curves from among various published sources. Stewart indicates that, for most applications, the use of such published generic curves is the acceptable practice. The validity of this approach can be enhanced by the use of "bounding curves" as recommended by Constantino (Silva et al, 1996).

5.0 SITE CHARACTERISTICS

The geologic conditions underlying the site are a major factor in determining the extent of dynamic soils testing required to fully analyze the susceptibility of a nuclear power plant at a particular site to ground motion that could compromise the functionality of structures, systems or components that are designated Seismic Category I.

5.1 Rock Sites

For the purpose of this paper, a "hard or firm rock site" is defined as a site where the underlying rock is shallow (less than 70 feet of overburden) and the dynamic properties do not vary with strain. In such cases the category I structures are generally founded directly upon competent rock or similar foundation material. Structures other than Seismic Category I or Category II (those structures whose failure might compromise the integrity of a Category I SSC) might be founded directly upon native material (if determined to be acceptable) or engineered backfill or other types of foundations (piles or drilled shafts) might be employed.

Where fill material is required for side soil for Category I structures or subfoundation material for Category II structures this fill will be an engineered backfill, with specifications regarding gradation, lift thickness and in-place density of this material. In such cases, no real value would be gained from conducting dynamic tests on weathered rock or soils that will be excavated and not be utilized onsite. Dynamic soil properties taken from published generic curves such as those in EPRI, 1993 will suffice for this purpose.

5.2 Soil Sites

Although more than half of the sites for which COL applications are slated to be filed in late 2007 are hard or firm rock sites, the majority of sites for which applications are planned in 2008 are deep soil sites. In these cases, the nuclear island and other Seismic Category I and II structures will be founded upon soil that may extend for several hundred feet or more before reaching competent bedrock. Adequate characterization of the dynamic properties of the underlying soil is essential to SSI and modeling of ground motion effects.

For a deep soil site, the number of dynamic testing samples required to adequately characterize the site is dependent upon both the horizontal and vertical homogeneity of the underlying soils. In general, more samples will be required along the vertical dimension to accurately profile the soil column than samples along the horizontal dimension. Some sites may have buried channels or other features that will require a greater number of samples along the horizontal dimension.

Because of the large number of soil sites and the limited RCTS testing capacity, it may be impossible to conduct tests of all of the representative samples for all of the soil sites prior to filing dates for these applications. Consequently, a representative sample of tests may need to be conducted for each site, correlating the data gained from this testing with the results of field in situ testing and published generic curves. The remaining samples designated for dynamic soil testing can then be completed and these data filed as a supplement to the COL application. In the event that the follow-up testing raises issues that cannot be resolved with the information filed in the application, these issues will be thoroughly analyzed and the results presented to NRC staff.

6.0 CONCLUSIONS

Based upon the requirements of the NRC for dynamic soil testing, the limited availability of RCTS test capacity and experienced technicians and the number of sites for which COLAs are proposed, Industry recommends that the following protocol be utilized:

For Hard or Firm Rock Sites:

- No laboratory testing of dynamic soil properties is required as part of the COLA submission since nuclear safety-related structures (Seismic Category I) will be founded upon rock.
- Published generic curves such as from EPRI, 1993 will be utilized to characterize engineered backfill and native soil around any Seismic Category I or around/under any Seismic Category II structures. The basis for selection of these curves will be documented in the COLA submission.

For Other than Hard or Firm Rock Sites:

- Test results of dynamic soil properties of an appropriate number of representative samples, based upon variability of the underlying soils, should be included as part of the COLA submittal.
- These test results will be correlated with other dynamic indicators (e.g. shear wave velocity) from field testing results.
- The appropriate published generic curves, such as from EPRI, 1993, will be selected based upon the results of both laboratory and field results. The basis for selection of these curves will be documented in the COLA submission.
- Additional samples, as required to fully characterize the site, will be tested using RCTS to confirm the results obtained in the test results submitted in the COLA. These samples will be identified in the COLA. The results of these additional RCTS tests will be submitted to the NRC after the COL application is filed, but prior to the completion of the COLA review.

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