Assessment of dynamic and static characteristics of igneous bedrock by means of suspension P-S logging and uniaxial compressive strength tests

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ABSTRACT
This paper provides correlations between the values of P-wave velocity and dynamic elastic modulus through in-situ dynamic testing (suspension P-S logging) and the values of uniaxial compressive strength (UCS) and static elastic modulus through laboratory static testing (uniaxial compressive) of sound rock from two sites located in South Carolina and Virginia. For both sites, the bedrock, which classified as good to excellent, is hard fresh to slightly discolored metamorphic rock, or igneous rock with numerous metamorphic inclusions. Suspension P-S logging tests were performed in 12 uncased fluid-filled boreholes, to rock depths of over 120 m. The investigation further included the results of unconfined compression tests on rock cores and assessment of the variation of static elastic modulus with UCS from these compression tests. The comparisons show that the low strain elastic moduli values of sound rock agree well with the higher strain values obtained from the unconfined compression tests.

RÉSUMÉ
Ce document fournit des corrélations entre les valeurs de vélocité d' ondes-P et module dynamique d'élasticité par le biais de terrain des essais dynamiques (suspension P-S logging), et les valeurs de résistance uniaxiale à la compression et module statique d'élasticité des essais laboratoires statiques (uniaxial compression) de rocher solide de deux sites aux États-Unis, situés dans la Caroline du Sud et en Virginie. Pour les deux sites, le substrat rocheux) , classé comme bon jusqu'à excellent, est entre dur fraîche du roc igné légèrement décoloré avec de nombreuses inclusions métamorphiques. Des essais “suspension P-S logging” ont été effectués en 12 trous de fourage sans revêtement remplis de liquide, dans des profondeurs de roc dépassant les 120 m. L'enquête a inclus les résultats des essais de compression non-restreinte des carottes rocheux, et l'évaluation de la variation de statique du module élastique statique avec résistance uniaxiale de ces tests de compression. Les comparaisons montrent que les valeurs des modules elastiques d’une faible souche de roc solide conviennent bien aux valeurs obtenues des tests de compression non-restreinte.

1 INTRODUCTION

For licensing new generation nuclear power plants, nuclear regulatory guidelines provide guidance on conducting various subsurface investigations to determine the site characteristics (USNRC 2003). The dynamic and static rock properties most critical to the licensing applications are the compression and shear wave velocities, static and dynamic moduli, uniaxial compressive strength (UCS), and density.

Since suspension P-S logging provides a specific measure of compression (primary or P) and shear (secondary or S) wave velocity (V_P and V_S) at any chosen depth in a borehole (rather than interpretation from surface methods by integration through the soil column), it has been used as the main source of obtaining these velocities in new nuclear generation work (Biringen and Davie 2010). Like all geophysical methods, this technique offers an approach to obtain dynamic parameters without changing the internal structure of the sample.

The most commonly used method for determining rock strength is the UCS test, standardized by ASTM D 7012-04. Although the method is relatively simple, it is time consuming and requires well-prepared rock cores.

The objective of this study was to determine the rock elastic properties through in-situ dynamic testing (suspension P-S logging) and compare them with the results from laboratory static testing (uniaxial compression). The investigation also included an assessment of the relationships between UCS, V_P, and dynamic and static elastic moduli. The results are presented graphically to evaluate the applicability of various published correlations between the aforementioned properties.

The bedrock tested was hard fresh to slightly discolored metamorphic rock or igneous rock with numerous metamorphic inclusions. The data presented include samples from South Carolina (Site A), consisting of mostly granodiorite, quartz diorite, biotite gneiss, amphibole gneiss, and migmatite, and samples from Virginia (Site B), consisting of mostly quartz gneiss, biotite gneiss, and biotite-quartz gneiss.

2 TESTING PROCEDURE AND ROCK PROPERTIES

2.1 Suspension P-S Velocity Logging

Suspension P-S velocity logging (also known as suspension logging) is a method for determining V_P and V_S profiles as a function of depth in addition to supplementing stratigraphic information obtained in soil and rock formations by conventional drilling. Measurements are made in a single, uncased, fluid-filled borehole. This system determines the average velocity of a 1-m high segment of the rock column surrounding the borehole of interest by measuring the elapsed time between arrivals of a wave propagating upward through the soil column. A typical suspension P-S logging system consists of a borehole probe, cable, winch, and control/recording instrument, as shown in Figure 1 for the OYO PS 170 system. The probe consists of a source (S) and two biaxial geophones (R1 and R2), separated by flexible isolation sections (GEOVision, Biringen & Davie 2010).

The probe on which the source and the geophones (receivers) are installed is moved as a unit in the borehole, producing relatively constant amplitude signals at all depths. The suspension system probe consists of a combined reversible polarity solenoid horizontal shear-wave (S_H) and compressional-wave (P) source, joined to two biaxial receivers by a flexible isolation cylinder, as shown in Figure 1. The separation of the two receivers (R1 and R2) is 1 m, allowing average wave velocity in the area to be determined by inversion of wave travel time between the two receivers. The total length of the probe used in these surveys is 5.8 m, with the center point of the receiver pair 3.7 m above the bottom end of the probe. The probe receives control signals from, and sends the amplified receiver signals to, instrumentation on the surface via an armoured conductor cable. The cable is wound onto the drum of a winch and is used to support the probe. Cable travel is measured to provide probe depth data (GEOVision, Biringen & Davie 2010).

To determine the dynamic (low strain) elastic modulus (E_D) values of the rock formation, suspension P-S logging tests were performed in 12 uncased, fluid-filled boreholes (8 from Site A and 4 from Site B), to rock depths of over 120 m. The corresponding E_D values were obtained at 0.5-m spacing using the following relationship expressed in Eq. 1 and 2 (Bowles 1997), where ν_D is the dynamic Poisson's ratio, γ is the unit weight of rock, and g is acceleration due to gravity.

$$\nu_D = \{(V_P/V_S)^2-2\}/\{2((V_P/V_S)^2-1)\} \quad [1]$$

$$E_D = 2(1+\nu_D)(\gamma/g)V_S^2 \quad [2]$$

The elevations of sound rock at Sites A and B were interpreted both from rock quality designation (RQD) ranges of rock samples cored and from V_S measurements. RQD denotes the percentage of intact and sound rock retrieved from a borehole of any orientation (ASTM D 6032-02).

Sound rock at both sites is defined as generally hard, slightly discolored to fresh (bright mineral surfaces) rock with slight alteration or localized staining on joints and shears in the rock mass. Both Sites A and B exhibit very slight weathered joints with an average RQD in the range of 80 to 100 percent. Based on ASTM D 6032-02, the quality of sound rock at both sites classifies as *good to excellent*. The average shear wave velocity of sound rock at both sites exceeds 2,800 m/s.

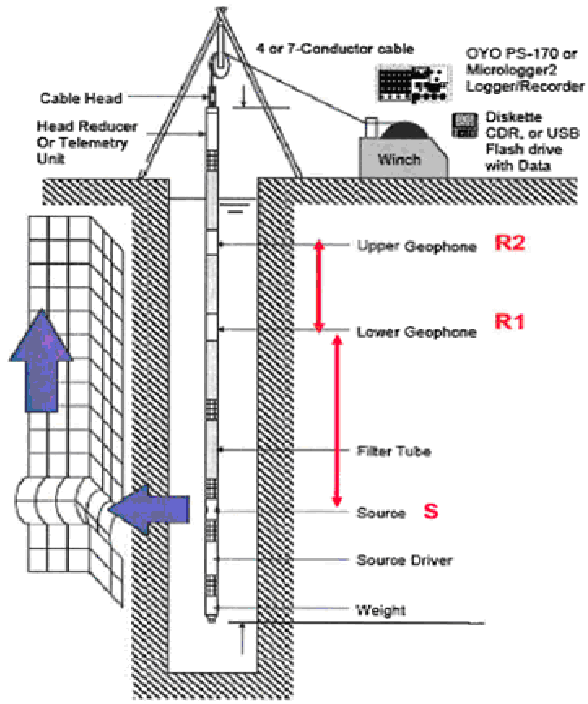

Figure 1. Illustration of P-S logging system (GEOVision)

2.2 Unconfined Compressive Test

To determine unconfined (uniaxial) compressive strength and the static (higher strain) elastic modulus values of the rock cores, samples were tested in the laboratory in accordance with ASTM D 7012-04. The prepared specimens were placed in a loading frame, and axial load was increased continuously on the specimen until peak load or failure of the specimen was obtained.

To determine the static (higher strain) elastic moduli (E_S) and static Poisson's ratio (ν_S), the specimens were instrumented with four strain gages (two mounted axially, two mounted laterally). Axial strain gages were 50 mm in length, and lateral strain gages were 25 mm in length. Axial load and deformation (axial and lateral) readings were obtained during testing. The values of E_S and ν_S were calculated using strain gage data at generally between 40 and 60 percent of maximum strain. The specific data range for each core was individually selected based on visual review of the data. The selection utilized the average slope method over a range where both the axial and lateral stress-strain curves appeared most linear. The deviations to the test standard included exception to the minimum axial strain gage length of 10 mineral grain diameters. Axial strain gages of 50 mm were used on all cores.

UCS is determined based on the cross-sectional area and the maximum recorded load applied, and a correction for length-to-diameter ratio is applied.

The samples tested in this study were cylindrical sound (parent) rock cores obtained from drilled exploratory boreholes in addition to the ones where suspension P-S logging was performed. The data include 32 samples from Site A, consisting of mostly granodiorite, quartz diorite, biotite gneiss, amphibole gneiss, and migmatite, and 24 samples from Site B, consisting of mostly quartz gneiss, biotite gneiss, and biotite-quartz gneiss. The length-to-diameter ratios for the samples vary between 2.1 and 2.2.

3 EVALUATION OF THE TEST RESULTS

Figure 2 summarizes all of the 56 test data points with respect to the measured UCS and E_S in a logarithmic plot. The well-known Deere (1968) chart determined for various rock categories has been added for comparison. The large majority of rock samples from Sites A and B lies within the area corresponding to the gneiss rock type.

Sonic logging has been used routinely in Australia to obtain estimates of coal mine roof rock strength through measurements of P-wave travel time (McNally 1987). The proposed relationship between UCS and V_P by McNally (1987) is expressed by the following equation, where UCS is in psi and V_P is in ft/microsec.

$$UCS = 143{,}000\ e^{-0.035/V_p} \qquad [3]$$

A study by Kahraman (2001) shows a non-linear relationship between P-wave velocity and UCS based on the measured values of 27 rock blocks from various locations in Turkey. The samples tested consist of mostly dolomite, sandstone, limestone, and marl, and have P-wave velocities varying from 1,000 m/s for marl to 6,300 m/s for dolomite. Based on the test results, the relationship between UCS and V_P is expressed by the following equation, with UCS in MPa and V_P in km/s.

$$UCS = 9.95\ V_P^{1.21} \qquad [4]$$

Figure 3 shows the data set collected from Sites A and B, along with of the relationships given by Eq. 3 and

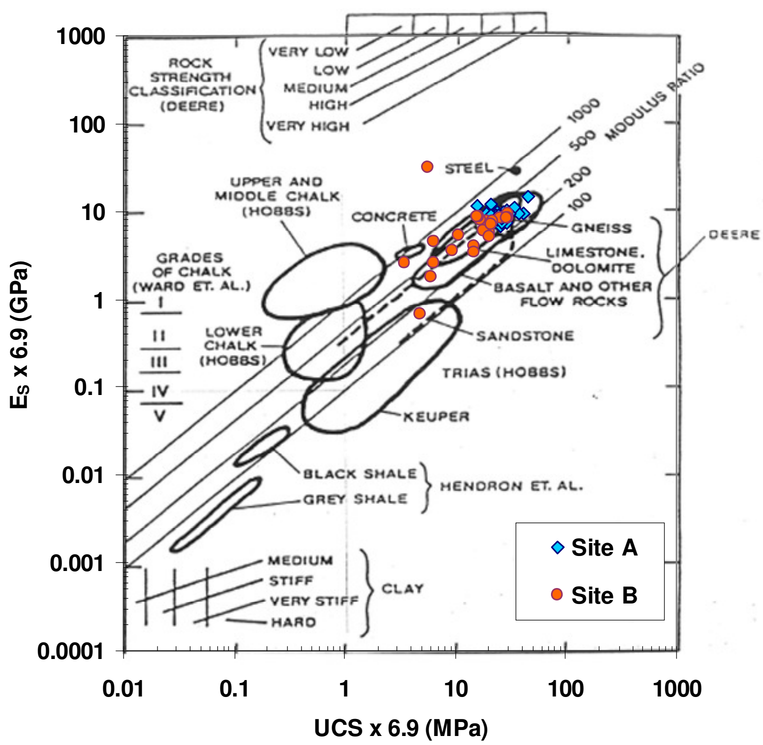

Figure 2. Relationship between static elastic modulus and UCS for intact rock (after Deere 1968)

4. The P-wave velocity values presented here correspond to the depths where the core samples from Sites A and B were obtained. The results indicate more scattered data points with increasing strength (as was pointed out by Kahraman 2001).

In a study by Moradian and Behnia (2009), uniaxial compressive and ultrasonic tests were conducted on 64 sedimentary rock core samples from Iran, consisting of 44 limestone, 12 sandstone, and 6 marlstone samples. During sampling, rock types with no bedding planes were selected to eliminate any anisotropic effects on the measurements. Based on the test results, the relationship between static elastic modulus and P-wave velocity is expressed by the following equation, where E_S is in GPa and V_P is in m/sec.

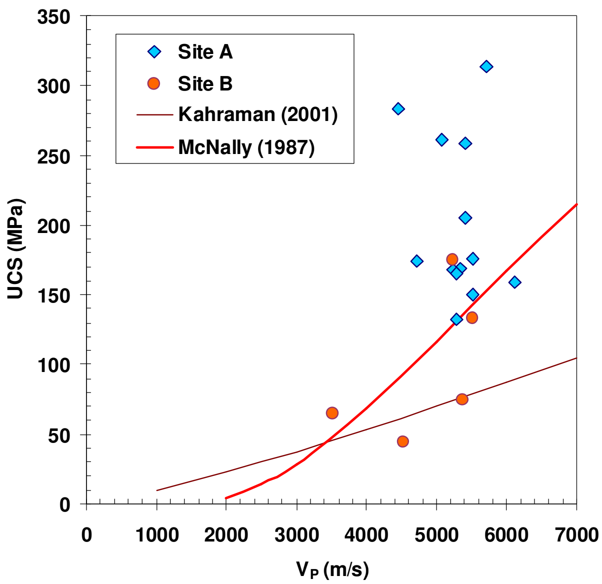

Figure 3. P-wave velocity vs. uniaxial compressive strength

$$E_S = 2.06E\text{-}9\ \ V_P^{2.78} \qquad [5]$$

The proposed non-linear relationship between the static and dynamic elastic moduli is as follows, where E_S and E_D are in GPa.

$$E_S = 0.25\ E_D^{1.29} \qquad [6]$$

Figure 4 shows the data set collected from Sites A and B, along with of the relationships given by Eq. 5. The P-wave velocity values presented here correspond to the

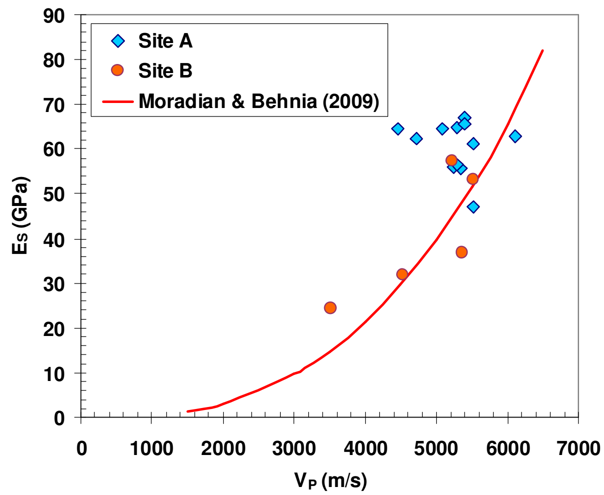

Figure 4. P-wave velocity vs. static elastic modulus depths where the core samples from Sites A and B were obtained.

A study by Starzec (1999) presents rock elastic properties of 300 crystalline rocks, including igneous and metamorphic rocks from southwest Sweden. The samples tested in an ultrasonic laboratory investigation represent five rock groups, consisting of gneissic granite, gneissic granodiorite, amphibolite, quartzite, and diabase. Note that Starzec (1999) indicates that the values of density and E_S were obtained from another study by Högström (1994). The proposed relationship between the dynamic and static elastic moduli is as follows, where E_S and E_D are in GPa.

$$E_S = 0.48\ E_D - 3.26 \qquad [7]$$

The data obtained from suspension P-S logging were used in Eq. 1 and Eq. 2 to calculate the respective dynamic elastic modulus values of the rock cores. This data set includes a total of 18 rock samples, 13 from Site A and 5 from Site B. These were samples taken from the same holes in which the suspension logging was performed, and thus E_D derived from V_P at the sample depth could be compared directly with E_S from the tested sample. The values of E_D are plotted against the laboratory measured values of E_S in Figure 5. In addition, the relationships given by Eq. 6 for sedimentary rocks and Eq. 7 for igneous and metamorphic rocks are shown on the plot. In the same graph, the divergence in the values is represented by the distance from the 1:1 diagonal line. The dynamic and static moduli from Sites A and B showed reasonable agreement in terms of the absolute values. It should also be noted that the dynamic elasticity modulus varied between 19 and 94 GPa based on the depths of the samples taken while the static modulus was between 24 and 103 GPa.

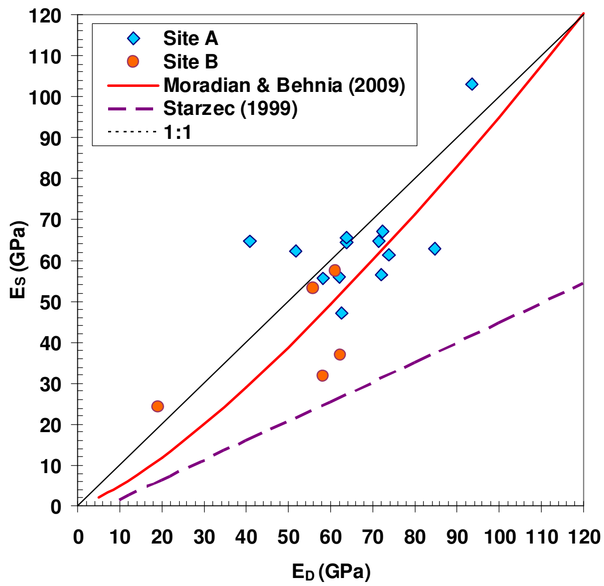

Figure 5. Dynamic elastic modulus vs. static elastic modulus

Starzec (1999) draws attention to the expectation of an invariably higher dynamic modulus than the static value. To examine the validity of this expectation, the values presented in Figure 5 are realigned in Figure 6 to illustrate the E_D/E_S ratio versus E_S. The plot shows that the values from Sites A and B exhibit a relatively large amount of scatter, as might be expected given the very different approaches used to estimate E_D and E_S. However, this scatter is distributed fairly evenly about the relationship proposed by Moradian and Behnia (2009) for sedimentary rocks. Note that according to Siggins (1993), a difference on the order of 30 percent is commonly reported. The relationship proposed by Starzec (1999) for igneous and metamorphic rocks apparently provides a conservative lower bound value of E_S with respect to the results from the Sites A and B (Figure 5).

Starzec attributes the strain levels where moduli are determined as the main reason for the discrepancy between E_D and E_S, considering the fact that the peak strains generated in dynamic tests are on the order of 10^{-6}, compared with static values of 10^{-2}. There is no doubt that this is true for soils where soil modulus degradation against increasing strain is very well documented. However, as the material gets harder and more cemented, the degradation of the modulus with strain becomes less until it essentially disappears (e.g., concrete and steel). This appears to be well illustrated in the Moradian and Behnia relationship.

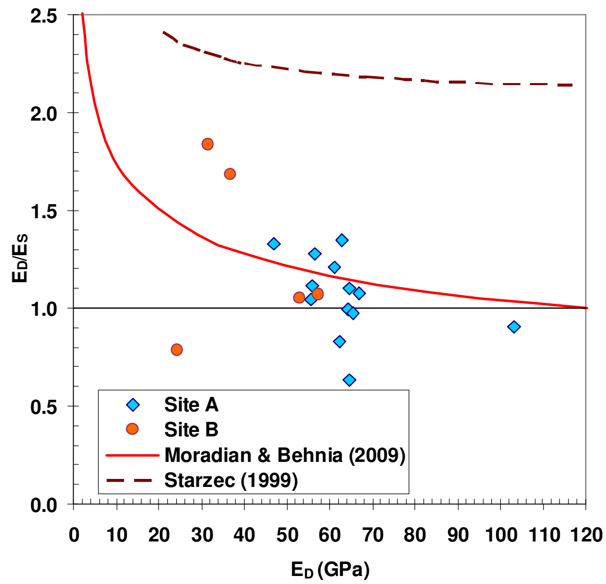

Figure 6. Static elastic modulus vs. ratio of dynamic to static elastic moduli.

4 CONCLUSIONS

The modulus ratios derived from high-quality laboratory testing on mainly gneiss samples from two sites (A and B) agree well with the range found for gneiss by Deere (1968) (Figure 2). The elastic modulus values from these static tests (E_S) were then compared with low strain modulus values derived from P-wave values (E_D) from suspension logging tests at the same depths as the tested samples. These modulus values were also compared with theoretical relationships between high and low strain modulus of rock found in the literature. As shown in Figure 6, the ratio of low-to-higher strain modulus values derived from Sites A and B showed considerable scatter, with E_D/E_S usually greater than 1, but not always so. The results appear to support the relationship proposed by Moradian and Behnia (2009), and are bounded by the relationship proposed by Starzec (1999).

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