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# IN SITU VS MEASUREMENTS IN SOIL AND ROCK USING THE BOREHOLE SASW TOOL

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## SUMMARY

A new method has been developed for measuring the in situ relationship between shear wave velocity ( $V_s$ ) and state of stress in soil and rock. This method involves conducting Spectral-Analysis-of-Surface-Waves (SASW) measurements inside an uncased, pressurized borehole with a specially design tool. The measurements involve monitoring axially propagating surface waves along the borehole wall. The borehole tool consists of SASW instrumentation housed inside a membrane that can be inflated in a manner similar to a pressuremeter. At different inflation pressures, the soil or rock is placed under different radial states of stress. At each pressure, SASW measurements are performed to evaluate the variation in surface wave velocity with frequency from which the variation in $V_s$ as a function of radial distance behind the borehole wall is determined. In this manner, the extent of the disturbed material behind the borehole wall can be characterized. In addition, variations in $V_s$ measured at different tool inflation pressures can be used to determine the in situ relationship between $V_s$ and state of stress for intact material behind the disturbed zone. Field tests are presented to demonstrate the validity and applicability of this type of borehole measurement.

## INTRODUCTION

Much research has been conducted to investigate the effect of state of stress on the small-strain shear modulus, $G_{max}$, of soil through the measurement of shear wave velocity, $V_s$ [for instance, Richart et. al., 1970; Hardin and Drnevich, 1972; Drnevich et. al, 1978]. $G_{max}$ and $V_s$ are both indicators of small-strain shear stiffness and are related through mass density, ρ, by:

$$G_{\max} = \rho V_s^2 \qquad (1)$$

Research in the small-strain range (strain less than 0.001%) has led to development of the torsional resonant column for use in the laboratory with small-scale specimens. Large-scale calibration chambers have also been employed in the laboratory to evaluate the effect of stress state on $V_s$ and $G_{max}$ with larger specimens [for instance, Stokoe et al., 1985; Belloti et al., 1996]. However, prior to development of the method presented herein, no method has existed where the relationship between $G_{max}$ and state of stress could be evaluated in situ. Traditional in situ methods for determining $G_{max}$ include crosshole and downhole seismic testing, seismic cone penetrometer testing [Robertson et. al, 1986], Spectral-Analysis-of-Surface-Waves (SASW) testing [Stokoe et. al, 1994] and suspension logging [Kitsunizaki, 1980]. All of these in situ methods are limited to evaluating $G_{max}$ under existing field conditions, with no attempt made to vary the in situ state of stress during testing.

A new field seismic technique has been developed at the University of Texas at Austin for the in situ evaluation of the relationship between $G_{max}$ and state of stress in soil. This technique involves the use of a borehole SASW tool. With this tool, a known radial stress is applied to the inside of an uncased borehole after which surface wave measurements are performed along the pressurized borehole wall. Dispersion curves (surface wave

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velocity versus wavelength) are determined at each applied radial stress level. The dispersion curves are then interpreted to evaluate how $G_{max}$ varies with distance behind the borehole wall at each applied stress level.

In this paper, the borehole SASW tool is described, and the basic principles behind its operation are discussed. Results obtained with the tool at a field site composed of silty sand are presented. The field results are compared with the $\log(G_{max}) - \log(\sigma')$ relationship determined in the laboratory with an intact specimen. This comparison, as well as other comparisons under field and laboratory settings, support the validity of the method [Kalinski, 1998]. Although all of the results presented herein were obtained at a soil site, the borehole SASW tool could also be used at rock sites to determine in situ values of $V_s$ and $G_{max}$.

## THEORETICAL DEVELOPMENT

The borehole SASW tool represents a specialized application of the generalized SASW method that was originally developed for surface wave measurements along exposed, flat surfaces at geotechnical and pavement sites [Stokoe et. al, 1994]. In the borehole application, velocities of axially propagating surface waves are measured in an uncased borehole which is pressurized using an inflatable tool (Fig. 1). The principles of operation are based upon three concepts: 1) the dispersive nature of axially propagating surface waves in a cylindrical borehole, 2) the effect of borehole pressure on the radial stress in the soil surrounding the borehole, and 3) the effect of state of stress on $V_s$ and $G_{max}$. Each of these concepts is briefly discussed below.

For axially propagating surface waves in an empty borehole, dispersion is induced by the cylindrical geometry as well as by changes in $G_{max}$ with radial distance behind the borehole wall [Kalinski, 1998]. For a uniform material, velocities of axially propagating surface waves increase slightly with increasing wavelength to a value equal to $V_s$. However, if the stiffness of the material varies with radial distance behind the borehole wall, then dispersion will be induced by both the cylindrical geometry and the change in $G_{max}$. Both dispersive mechanisms are taken into account in the analysis of the borehole SASW tests using a finite-element numerical formulation so that variations in $G_{max}$ with distance behind the borehole wall can be accurately determined [Cheng, 1997; Kalinski, 1998; Young, 1998].

To understand the effect of borehole pressure on the radial normal stress in the surrounding material, consider the case of a dry soil mass at a level site. In this soil, a uniform horizontal in situ stress field, $\sigma_h$, is assumed. When a vertical borehole with radius $r_o$ is drilled into the soil and pressurized with an internal normal pressure of $\sigma_i$, the radial normal stress, $\sigma_r$, in the vicinity of the borehole is given as a function of distance from the center of the borehole, r, as [Timoshenko and Goodier, 1970]:

$$\sigma_r = -\frac{r_o^2(\sigma_h - \sigma_i)}{r^2} + \sigma_h . \tag{2}$$

In Eq. 2, it is assumed that the material is homogeneous and elastic and drilling does not alter the initial state of stress, $\sigma_h$. Although nonlinear finite element analyses produce more exact estimates of $\sigma_r$ [Holland, 1997; Young, 1998], Eq. 2 is a reasonable first approximation for $\sigma_r$. For this study, finite element analyses [Young, 1998] were used to determine variations in $\sigma_r$ with distance behind the borehole wall. Other potential effects, such as nonlinear soil behavior, stress relief and disturbance upon drilling, and stress concentrations at the ends of the tool are topics for future investigations.

Previous research has demonstrated that an increase in the effective confining stress on soil causes an increase in $G_{max}$. For shear wave propagation in cohesionless material, values of $G_{max}$ corresponding to observed values of $V_s$ can be written as a function of the effective normal stress parallel to the direction of propagation, $\sigma'_x$, and the effective normal stress parallel to the direction of wave particle motion, $\sigma'_y$ [Stokoe et. al, 1985; Belloti, et. al, 1996]:

$$G_{max} = \rho C^2 (\sigma'_x \sigma'_y)^{2n} , \tag{3}$$

where ρ is mass density, C is a constant related to void ratio and soil structure and n typically varies between 0.10 and 0.14 for uncemented, natural sands.

A rationale for applying the borehole SASW tool in determining in situ relationships between state of stress and $V_s$ and $G_{max}$ can then be developed. By measuring surface waves propagating in the axial direction in an internally pressurized borehole using the SASW method, experimental dispersion curves are determined. These dispersion curves are then inverted to determine the in situ variation in $G_{max}$ with radial distance behind the borehole wall at each internal pressure applied by the tool. Using a relationship between radial stress and radial distance behind the borehole wall (such as Eq. 2), the in situ radial stress is estimated. By combining this information with values of $G_{max}$ obtained by modeling the SASW data, $G_{max}$ is determined as a function of radial stress. In this case, $G_{max}$ corresponds to shear waves that are propagating vertically and are radially polarized. Thus, Eq. 3 is used to describe the relationship between $G_{max}$ and state of stress in the soil near the borehole by substituting the in situ vertical effective stress, $\sigma'_v$, for $\sigma'_x$ and the in situ radial stress, $\sigma'_r$, for $\sigma'_y$.

## DESIGN OF THE BOREHOLE SASW TOOL

The borehole SASW tool is a cylindrical tool with a length of approximately 0.91 m and a nominal inflated diameter of 15 cm. It is designed to operate in an uncased borehole with a diameter of 15 cm. As illustrated in Fig. 2, the overall design consists a support frame, flexible membrane, accelerometer receivers, impact sources and internal-diameter caliper system. Each of these components is described in detail in Kalinski, 1998. One of the key components is the flexible membrane which is made of polyurethane sheeting approximately 0.79 mm in thickness. Polyurethane with a Shore durometer hardness of A70 was selected due to its flexibility, rugged nature, and similarity in stiffness to soft soil with a shear wave velocity of about 100 m/s. The low stiffness combined with the thin-sheet design make the membrane virtually invisible to surface wave energy propagating inside the borehole.

The impact sources represent another key component. Three small solenoids are used for this purpose. The solenoids are pulsed with a short burst so that the plunger of the solenoid taps the inside of the membrane and generates the required surface wave energy. This type of tapping can generate energy with frequencies as high as 20 kHz, but in most cases the energy does not exceed 5 to 10 kHz. Six miniature accelerometers attached to the inside of the membrane at pre-selected locations are used to monitor the passage of the surface waves.

To determine the radial stress induced in the soil when the tool is inflated, the pressure delivered to the tool must be separated into pressure resisted by the membrane as it stretches and pressure applied to the soil. To quantify the pressure resisted by the membrane, the diameter of the borehole must be known at all times. The diameter can then be related to the amount of pressure resisted by the membrane by measuring the diameter of the tool as it is pressurized without confinement. A caliper system (not shown in Fig. 2) is used inside the tool to measure the borehole diameter during testing.

## FIELD TESTS WITH THE BOREHOLE SASW TOOL

Over the past three years, the functionality of the borehole SASW tool has been evaluated in several laboratory tests [Kalinski, 1998]. During this period, the design of the tool has evolved into the current design described herein. In 1998, several field studies were successfully performed using this most recent design. The results from one of these field studies are presented in the following paragraphs. Results from other field studies are presented in other publications [Kalinski, 1998; Kalinski et al., 1999].

The test results presented herein were measured at a site in Austin, Texas consisting of a poorly graded silty sand (SM) overlain by a 0.76-m thick layer of stiff clay. Borehole SASW testing was performed in the sand at a depth of 2.33 m. Based on intact sampling near this depth, the soil has a total unit weight of 2,070 $kg/m^3$, a water content of 14%, a degree of saturation of 80% and a void ratio of approximately 0.46. The coefficient of earth pressure at rest, $K_o$, was estimated at 0.5 based on a measured friction angle of 31 degrees and the relationship $K_o = 1 - \sin\Phi'$. The depth of the groundwater table was 3.6 m at the time of testing, so a negligible pore water pressure was assumed at the test depth. Based on the unit weight of the soil, the estimated $K_o$ and a pore pressure of zero, the vertical and horizontal effective stresses at the test depth were estimated at 36.0 and 18.2 kPa, respectively.

To prepare the borehole for testing, a pilot hole was initially drilled using an 11-cm solid stem auger. A hand auger was then used to ream the borehole to its final test diameter of 16.2 cm. SASW measurements were performed using a number of different source and receiver combinations. Measurements were successfully performed at six tool pressures: 27.6, 41.4, 62.1, 82,7, 103.4 and 124.1 kPa. Based on measurements with the caliper system, these tool pressures corresponded to radial stresses applied to the soil at the borehole wall of 20.1, 33.7, 54.3, 74.7, 95.2 and 115.8 kPa, respectively.

Individual dispersion curves from each source-receiver combination in the borehole tool were combined to generate a composite dispersion curve at each tool pressure. These composite curves are shown in Fig. 3 by the different symbols. The composite curves indicate that the soil surrounding the borehole became stiffer with increasing tool pressure as indicated by the upward movement of the curves. To model the dispersion curves, the soil surrounding the borehole was divided into 1.52 –cm thick layers (annuli). The shear wave velocity of each annulus was varied until the theoretical dispersion curve matched the measured dispersion curve. The resulting theoretical (model) dispersion curves are shown by the solid lines in Fig. 3. The $V_s$ profiles determined by this forward modeling process are shown in Fig. 4. The changes in stiffness with radial distance and tool pressure are clearly seen in these $V_s$ profiles. It is interesting to observe that the soil nearest the borehole wall was softer than the soil further away, even when the borehole pressure was significantly higher than the estimated in situ horizontal stress. This difference in stiffness is an indication of soil disturbance near the borehole wall due to borehole installation. It is important to note that, as shown in Fig. 4, $V_s$ values evaluated for annuli F and G agree well with shear wave velocities that were independently evaluated by crosshole testing at a comparable depth.

To determine the state of stress around the pressurized borehole, a vertical stress of 36.0 kPa was used and radial stresses were determined using a finite-element formulation which accounts for the concentric variations in soil stiffness around the borehole (Young, 1998). Average radial stresses were determined for each annulus of soil at each tool pressure. Values of $G_{max}$ were determined using the results in Fig. 4 combined with Eq. 1. These $G_{max}$ values represent the average stiffness of the soil in each annulus ("A" through "G" in Figs. 4 and 5) over the instrumented length of the pressurized borehole, which was centered at a depth of 2.33 m. The radial stresses equal the tool pressure at the borehole wall and approach the in situ horizontal stress of 18.2 kPa at distances behind the borehole wall which increase with increasing tool pressure. For the tool pressures in this set of tests, the zone over which changes in radial stress would likely cause measurable changes in $V_s$ ranged from less than 0.1d at the first pressure to about 2d at the highest pressure (with d equal to the borehole diameter).

To evaluate the relationship between $G_{max}$ and state of stress derived with the borehole tool, $G_{max}$ was plotted as a function of $\sigma'_r\ \sigma'_v$ on a log-log scale. The resulting seven relationships (for annuli A-G) are shown in Fig. 5. Each relationship exhibits a somewhat different intercept and slope. However, the relationships are converging towards one curve as distance behind the borehole wall increases. To help understand this trend and assess the validity of the results, resonant column testing was performed in the laboratory on an intact specimen of silty sand. The specimen was recovered with a thin-walled Shelby tube at a site approximately 30 m north of the borehole test location. The specimen was recovered from an elevation approximately 0.80 m higher than the elevation of the center of the borehole SASW test. For the resonant column test, values of $G_{max}$ were determined over a range of cell pressures so that laboratory values could be directly compared with field values of $G_{max}$ at the same effective stress. As shown in Fig. 5, annuli less than 6.1 cm behind the borehole wall appear to be more disturbed than the soil used in the resonant column test. However, annuli at distances greater than 6.1 cm behind the borehole wall appear to be "undisturbed" relative to the intact soil specimen.

In addition to comparison with the resonant column data, the borehole SASW data are compared to crosshole seismic data in Fig. 5. The crosshole data were derived by converting measured values of shear wave velocity at a depth of 2.44 m to $G_{max}$ and estimating the in situ $\sigma'_r\ \sigma'_v$ using an assumed $K_o$ of 0.5. The crosshole data shown in Fig. 5 correspond to a shear wave velocity range of 189-198 m/s, a $G_{max}$ range of 73.7-81.0 MPa, a vertical effective stress ($\sigma'_v$) of 38.1 kPa, and a horizontal effective stress (equated to $\sigma'_r$) of 19.0 kPa. As shown in Fig. 5, the crosshole data, which are representative of free-field shear wave velocities, compare well with annuli F and G, which are greater than 7.6 cm behind the borehole wall. At this distance, which is about equal to the borehole radius, the soil seems to be "undisturbed." This undisturbed material shows a slightly stiffer log $G_{max}$ – log $\sigma'_r\ \sigma'_v$ relationship (higher $G_{max}$ values and flatter slope) than found in the laboratory with the intact specimen.

## SUMMARY AND CONCLUSIONS

A new technique for the in situ measurement of $V_s$ and $G_{max}$ is presented herein. The technique involves the measurement of axially propagating surface waves inside an uncased borehole. An inflatable tool is placed in the borehole and is used to apply radial stresses to the borehole wall. Surface wave measurements are performed with the borehole tool at each applied pressure. With these measurements, it is possible to determine variations in $V_s$ and $G_{max}$ with distance behind the borehole wall and with changes in applied radial stress. This testing technique offers, for the first time, the opportunity to perform an in situ parametric study to determine the relationship between soil stiffness and state of stress. Although all results presented herein were obtained at a soil site, the borehole tool could also be used at rock sites to determine in situ values of $V_s$ and $G_{max}$.

The results demonstrate the functionality of the borehole SASW tool. One set of tests was conducted in which the in situ relationship between $G_{max}$ and state of stress was determined for a silty sand. The soil behind the borehole wall was divided into seven annuli, each 1.52-cm thick. A log $G_{max}$ - log $\sigma'_v$ $\sigma'_r$ relationship was found for each annulus. The results show that soil disturbance near the borehole wall adversely affected this relationship. In the “disturbed” zone, this relationship exhibited lower moduli and more influence of effective stress than in the “undisturbed” zone. At a distance of about one borehole radius behind the borehole wall, the soil appeared to be undisturbed and a close comparison was found with crosshole seismic measurements at the estimated free-field stress state. In this undisturbed region, the in situ relationship between $G_{max}$ and stress state was similar to, but slight stiffer than, the same relationship determined in the laboratory with an intact specimen. One interpretation of this comparison is that the silty sand is responding in situ as a lightly cemented and/or mechanically overconsolidated soil and that this response is not captured in the laboratory with the intact specimen. It is also interesting to find that the in situ soil structure, which has been altered near the borehole wall due to drilling and stress relief, cannot be restored to its original undisturbed state simply by increasing the state of stress. Future efforts should be directed towards minimizing soil disturbance, possibly via the development of a self-boring SASW tool.

The methods used to analyze the data presented herein are based on the assumption that the soil surrounding the borehole behaves in a linear elastic manner. This assumption simplifies the analysis, but is not the case at the higher radial stresses, where passive pressures in both horizontal and vertical planes are exceeded. Future analyses of the nonlinear deformations around the borehole (Holland, 1997) will be more computationally rigorous and will more accurately determine the state of stress around the borehole by accounting for nonlinear deformation and any associated stress redistributions and changes in void ratio.

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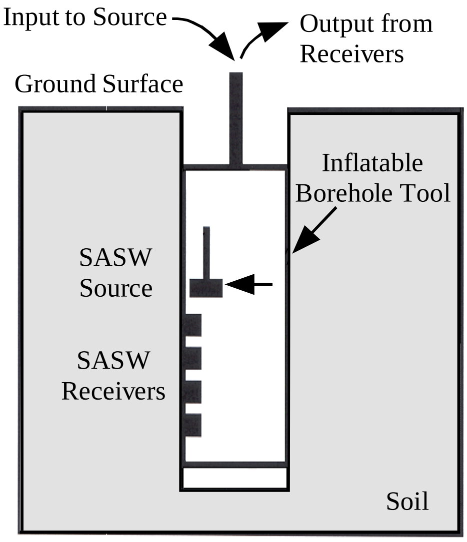

**Figure 1. Schematic illustration of the borehole SASW tool in an uncased borehole**

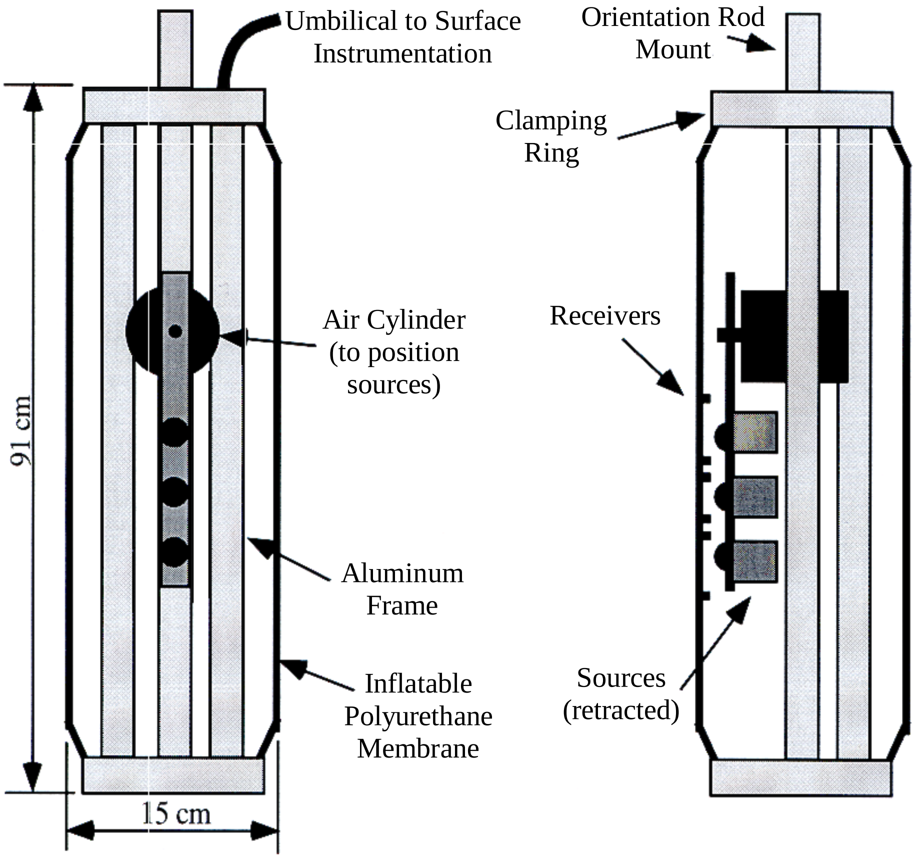

**Figure 2. The borehole SASW tool (internal caliper system not shown)**

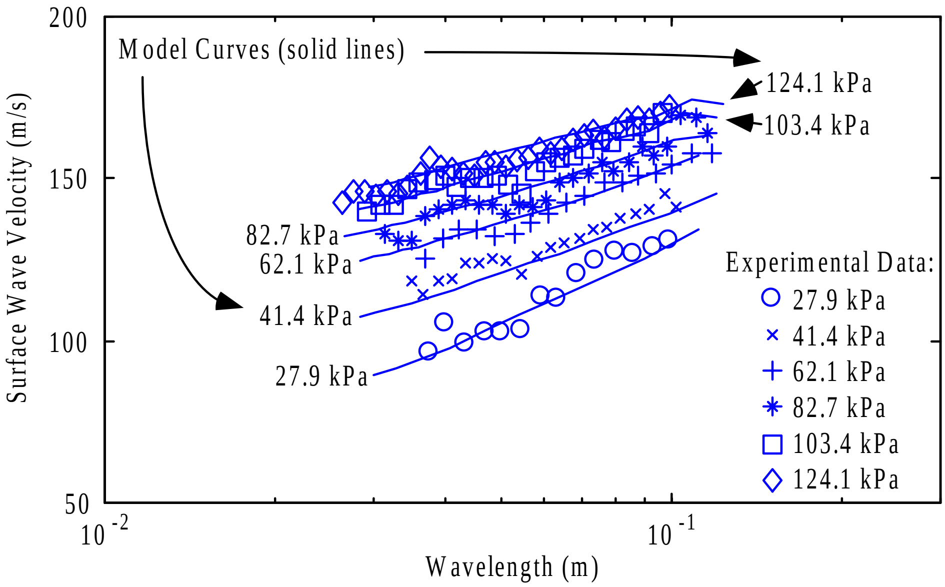

**Figure 3. Composite dispersion curves generated from borehole SASW testing**

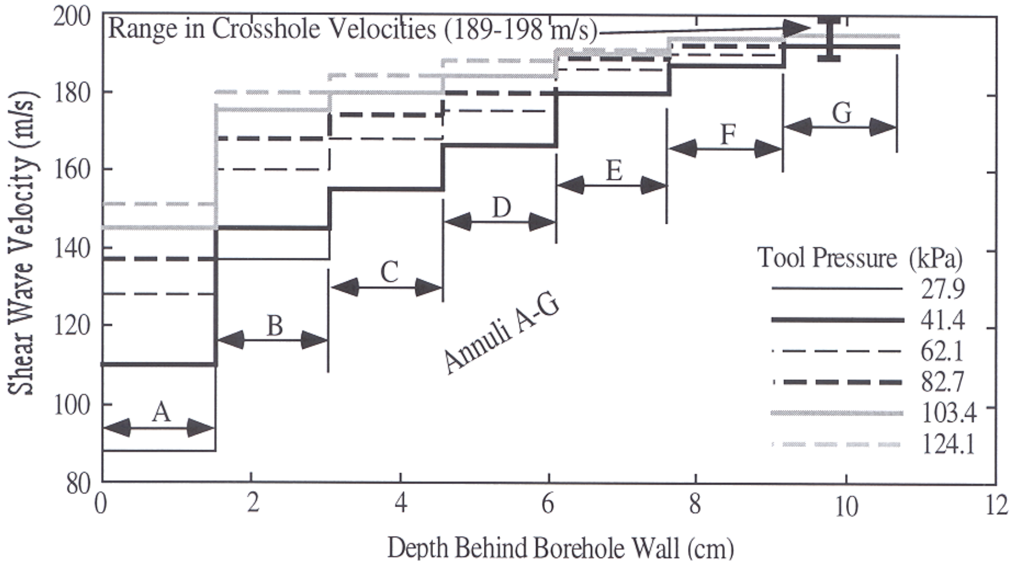

**Figure 4. Variation in $V_s$ with distance behind the borehole wall evaluated from borehole SASW testing**

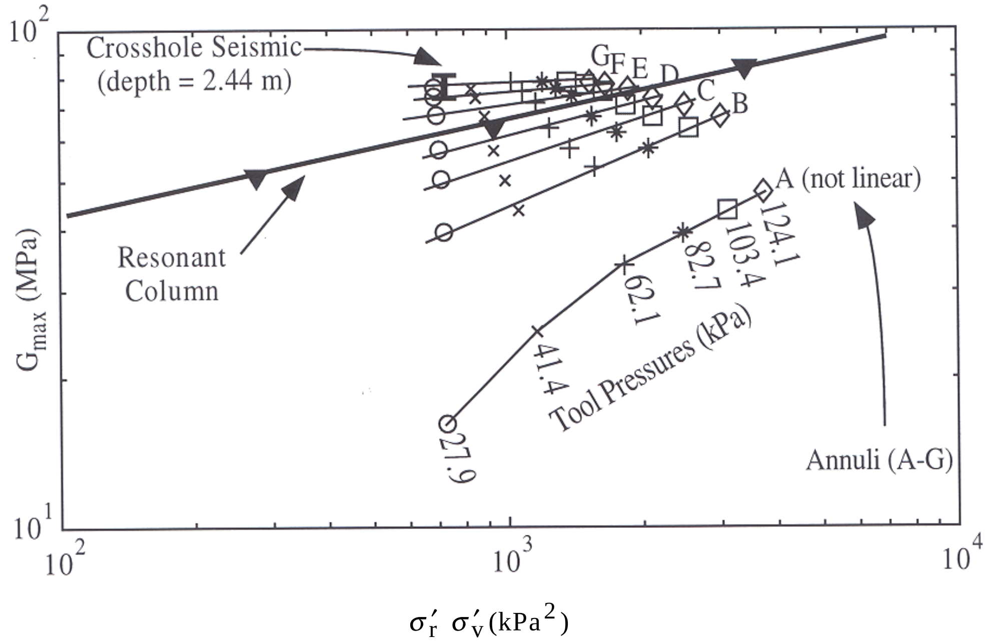

**Figure 5. Log ( $G_{max}$ ) – log( $\sigma'_r \; \sigma'_v$ ) relationships measured in situ with the borehole SASW tool and in the laboratory with resonant column testing of an intact specimen**