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Evaluation of bender transmitter response inside soil using novel laser measurements

M. Irfan, G. Cascante & D. Basu
University of Waterloo, Waterloo, ON, Canada

ABSTRACT: Seismic design of foundations requires an estimate of the shear wave velocity of soils (V_s). Bender elements (BE) test is one of the two laboratory methods used to measure V_s. BE is more popular because the method is simple and less expensive. Although BE test was developed more than three decades ago, there's still no standard testing procedure mainly because of lack of understanding of the frequency response of BE inside the soil. Many studies have performed investigations to address this lack of understanding; however, there is still a significant lack of understanding mainly because the actual behavior of the transmitter inside a soil specimen is not understood well. This study uses a state-of-the-art laser vibrometer with a transparent soil specimen to measure, for the first time, the actual vibrations of a BE transmitter inside the transparent soil specimen. Preliminary results show that the BE transmitter response is significantly different from the input excitation.

1 INTRODUCTION

Shear wave velocity of soil (V_s) is an important parameter for seismic characterization of sites and dynamic analysis of structures and foundations. The bender element (BE) method is widely used to measure V_s in laboratory specimens (Shirley & Hampton, 1978). In this method, two piezo-ceramic transducers (the bender elements) are inserted at the opposite ends of a soil specimen and an input voltage signal is applied to one of the transducers (the transmitter). This signal generates a disturbance in the soil sample, and the mechanical energy from the shear wave propagating through the soil sample is converted to an output voltage signal upon reaching the other transducer (receiver). The distance between the transmitter (T_x) and receiver (R_x), and the time of travel t_s of the shear waves from T_x to R_x are used to estimate V_s (Dyvik & Madshus, 1985). Despite its popularity, no standardized procedure is available for the BE method mainly because the response of the BEs inside the soil specimen has not been characterized experimentally.

A few experimental studies have been performed to hypothesize the actual behaviour of BEs inside the soil specimens. Rio (2006) measured, using a laser velocimeter, the response of transmitters in air and under embedded conditions inside a synthetic rubber specimen. Rio (2006) showed that, when bender elements are embedded in synthetic rubber specimens, the natural frequency and damping ratio of transmitter vibration are greater and the amplitude of vibration is less than the corresponding quantities measured when the bender elements are in air. The first mode resonance frequency in air of one of the benders studied by Rio (2006) is 3.4 kHz (dimensions 1.5 mm x 6 mm x 8 mm). Rio (2006) estimated that the maximum shear strain from the peak BE displacements was of the order of 10^{-3} % which is inconsistent with the maximum shear strain in BE testing given by previous researchers (Leong et al., 2005, Camacho-Tauta et al., 2015). Pallara et al. (2008) used a laser vibrometer to study the response of transmitters in air and showed that the shape of transmitter response is different from the shape of input signal. These studies provide a preliminary insight into the response of BEs under embedded conditions; however, because of the use of synthetic rubber specimens in these studies, the response of BEs embedded inside soil specimens is still not understood.

A novel experimental program is described in this paper in which the actual transmitter vibrations inside a transparent soil specimen are measured for the first time by using a state-of-the-art laser vibrometer. The transparent soil used in this study has mechanical properties similar to those of granular soils with angular particles (Ezzein & Bathurst, 2011). The first mode resonance frequency of the transmitter in air is determined by performing a sinusoidal sweep and calculating the transfer function. Then, the effect of input voltage amplitude applied on the transmitter response in air and in liquid is measured by exciting the transmitter with increasing voltage of input pulses and measuring the displacement response using the laser. The effects of mass density on the transmitter response are evaluated by measuring the transmitter response in water, sucrose, and mineral oil mixture (liquid used for making the transparent soil). Thereafter, the transmitter response is measured in the transparent soil and compared with the input excitation. Finally, the effects of applied vertical stress in the transparent soil on transmitter response is evaluated. The effects on the transmitter responses are characterized using changes in peak displacement amplitude and natural frequencies, which are obtained from the frequency spectra of the displacement responses of the transmitter inside the soil under vertical stress.

2 BACKGROUND

2.1 *Mineral oil and transparent soil*

The mineral oil mixture used in this study comprises of two mineral oils, namely, Krystol-40 and Puretol-7 (Weast et al.,1981, Ezzein & Bathurst, 2011). The mixture is colourless, odourless, and chemically stable. The viscosity and density of this oil mixture are μ = 10 cSt and ρ = 0.8 g/mL respectively which means that this oil mixture is 10 times more viscous and 20 % lighter than water.

In this study, the transparent soil developed by Ezzein & Bathurst (2011) is used and is made up of fused quartz and the mineral oil mixture described above. Fused quartz is a non-crystalline form of quartz sand (with silicon dioxide [SiO_2] as the main mineral present), which is widely used in semiconductors, solar cells, and telescopes. The transparency in the soil specimen occurs because of similar refractive indices of fused quartz and the mineral oil mixture. The mechanical properties (such as the shear strength) of this transparent soil are comparable to cohesionless soils of angular shaped particles (Ezzein & Bathurst, 2011).

2.2 *Vibration of a BE system*

The vibration behavior of a BE is assumed to be similar to the response of a cantilever beam with fixed-free boundary conditions. The resonant frequency of the *nth* mode of a cantilever beam can be used to estimate the resonant frequency of the BE by using Equation 1 below (Clough & Penzien 1993):

$$f_n = \frac{k_{L,n}^2}{2\pi(\alpha L_b)^2}\sqrt{\frac{E_b I_b}{\rho_b A_b}} \tag{1}$$

where k_L is a characteristic number which depends on n and the boundary conditions; L_b, I_b and ρ_b are the length, area moment of inertia ($I_b = bh^3/12$), and mass density of BE respectively; b, h, and A_b are the width, thickness, and cross-sectional area ($A_b = bh$) of the BE respectively; E_b is the Young's modulus of the piezoceramic element; α is the effective length factor where α = 1 for perfectly fixed conditions and α > 1 for flexible conditions. On the other hand, the resonant frequency of the first mode of vibration of a BE under embedded conditions can be estimated using Equation 2 below (Lee & Santamarina, 2005):

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{1.875^4 \frac{E_b I_b}{(\alpha L_b)^3} + \eta E_s L_b}{\rho_b A_b \alpha L_b + (\rho_s b^2 L_b)\beta}} \tag{2}$$

where ρ_s and υ are the mass density and Poisson's ratio of the soil respectively; β is the experimental factor related with the volume of soil affecting the vibration of BE; and $\eta \approx 2$ is the mean displacement influence factor at the soil-BE interface.

3 EXPERIMENTAL SETUP

A novel experimental setup consisting of a BE transmitter (T_x), peripheral electronics, a laser vibrometer, liquids, and a transparent soil specimen is used in this study. The T_x used in this study has dimensions of 13 mm x 5 mm x 0.5 mm, and is attached to a steel base platen. A schematic of the transmitter cross-section and experimental setups in air, in liquids/soil without confinement, and in soil under confinement are shown in Figure 1.

A function generator (FG) (model HP33120A) is used to generate an input voltage signal to the T_x through the steel base; this input signal is amplified using a piezo-driver. The amplified signal is monitored on an oscilloscope (HP-54645A) and stored in a computer. The T_x response to the input voltage is measured by the laser head (LSH) (OFV-5000), which is fixed to an aluminium plate; the laser head measurements are decoded by the vibration controller and the output signal from the vibration controller is monitored on the oscilloscope and stored in the computer. The steel base is fixed to a positioning stage which allows controlled movements of the steel base along the horizontal plane (moving left/right and in/out of the plane of the paper in Figure 1). The stage allows T_x vibrations to be measured at different points on the T_x surface; this stage can also be moved in the vertical direction manually. The positioning stage and the aluminium plate are fixed on an isolation table (manufactured by NewPort) to prevent the ambient vibrations from affecting the laser measurements.

The equipment setup for measurements in liquids and transparent soil is similar to that of measurements in air. A plexiglass square tube is used to hold the liquids and transparent soil in place. The base of the plexi-glass tube is sealed to the steel platen with silicon sealant to prevent leakage. The plexiglass tube is polished with a polishing liquid to ensure maximum transparency for

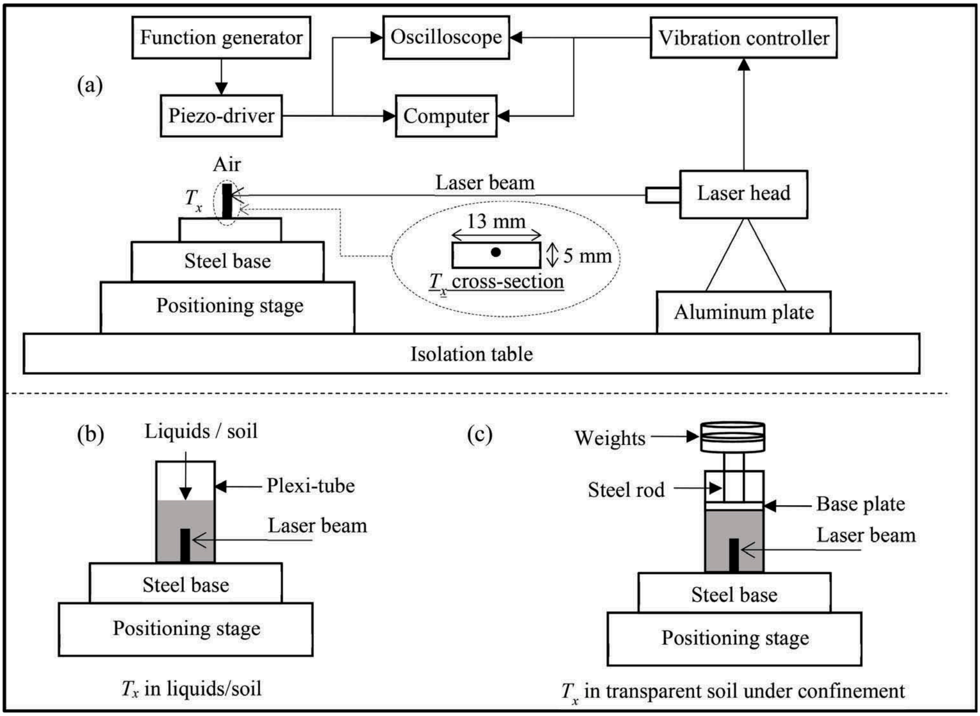

Figure 1. Schematic of the experimental setup.

penetration of laser beam. The liquid is poured in the box gently until the T_x gets completely submerged. For preparing the transparent soil specimen, the mineral oil mixture is first poured in the tube; then, the fused quartz are air pluviated. Dead weights, with the help of a steel cylinder with a square base, are used to induce vertical stress in the soil around the T_x (Figure 1).

A reflecting paper is glued on the T_x surface to enhance the signal quality of the laser vibrometer. This reflective tape is typically used with surveying equipment and is commercially available (SOKKIA^{TM}). The length of the laser beam is fixed at 0.5 m for all tests (Polytec, 2013). All time signals are recorded for a total time of 5 ms with a time interval of 3.2×10^{-5} ms.

3.1 *Laser vibrometer*

The laser vibrometer used in this study is a single point vibrometer developed by Polytec Inc. (Polytec, 2013). This device operates on the principle of heterodyne interferometer to obtain the characteristics of the mechanical vibrations (Polytec, 2013). The laser beam emanating from the laser head is pointed at the target (transmitter in this case) which reflects back the laser beam. A frequency or phase modulation of the laser light is generated by the displacement and velocity amplitudes of the target because of Doppler effect. Then, the vibration decoder recovers this modulation and converts it into signals that can be displayed on a computer screen. Phase modulation of the Doppler effect is used for displacement information while the frequency modulation is used for velocity information. The laser vibrometer is capable of measuring displacements with frequencies up to 24 MHz (Polytec, 2013).

4 EXPERIMENTAL METHODOLOGY

4.1 *Measurements in air*

First, the resonance frequency of the first mode (f_1) of the transmitter (T_x) is determining by performing a sinusoidal sweep of the T_x. This sinusoidal sweep is performed using a spectrum analyzer (HP-35670A) which calculates the transfer function between two signals in real time. Then, f_1 is used as the central frequency (f_c) of a sine pulse which is used as input to measure the T_x response in air; a sine-pulse is used because it does not excite higher modes in the T_x response (Irfan et al. 2016). The effects of input voltage amplitude (V_{inp}) on the peak displacement (x_p) of the T_x response are evaluated by measuring the T_x responses to sine pulses of increasing V_{inp}.

4.2 *Measurements in liquids*

After the measurements in air, the plexi-glass square-tube is placed around the T_x and sealed with the silicon sealant; then, three hours of silicon sealant curing time is allowed before gently pouring the liquids in the square tube up to a level of 1-inch (25.4 mm) (Figure 1b). Between measurements of different liquids, the silicon sealant is broken and the square tube and T_x with the base platen are thoroughly washed. T_x response with the square tube alone is measured before pouring the new liquid to ensure repeatability.

A sine-pulse of 10 Volts peak-to-peak (VPP) is used to evaluate the T_x response in liquids of different mass densities (ρ). First mode resonance frequencies of the T_x inside the liquids, estimated from the sinusoidal sweep of the T_x in these liquids, are selected as the f_c of this input sine-pulse. The liquids used are mineral oil mixture (ρ = 0.8 g/mL), water (ρ = 1.0 g/mL), sucrose of 20 % concentration (ρ = 1.1 g/mL) and sucrose of 40 % concentration (ρ = 1.19 g/mL).

The displacement time signal in each liquid is measured and saved for estimating their frequency spectra; then, resonance frequencies and damping ratios of the T_x in different liquids are estimated from these frequency spectra. These frequencies and damping ratios are analyzed with the mass densities of the liquids to understand the effects of the mass density.

4.3 *Measurements in transparent soil*

Fused quartz are pluviated into the square tube after completing the measurements with the mineral oil mixture. A sine-pulse input excitation is used to measure the T_x response in the transparent soil. Due to the lack of energy in T_x response in the transparent soil with 10 VPP, a piezo-driver is used to amplify the input voltage amplitude to 30 VPP. The first mode resonance frequencies of the T_x responses to a sinusoidal sweep in the transparent soil under vertical stress are not identifiable because of mode coupling; hence, a fixed f_c of 10 kHz is used because this f_c is the closest to the first mode frequency of the T_x in the transparent soil.

Displacement responses of the T_x to the sine-pulse excitation in transparent soil under different levels of vertical stress are measured at the point represented by the solid circle on the T_x surface shown in Figure 1a. The vertical stress in the transparent soil is induced by placing dead weights on a steel rod which is placed on the transparent soil to transfer the weight from the weights to the soil (Figure 1c). A rectangular base plate with dimensions equal to the internal area of the square tube (1.25 mm x 1.25 mm) is glued to the base of the steel rod to ensure uniform distribution of the weight on the transparent soil. Then, the Boussinesq's solution for vertical stress under a rectangularly loaded area is used estimate the induced vertical stress at the top of the T_x

5 RESULTS AND DISCUSSION

All results presented are for the measurements at location on the T_x indicated by the solid circle in Figure 1a.

5.1 *Transfer function in air*

Figure 2 shows the transfer function of the T_x in air in which two resonance modes of the T_x are identifiable. The energy in the first mode of vibration is about 50 % more than that of the second mode of vibration. The resonance frequency of the second mode (f_2) is more than double the first mode resonance frequency (f_1); however, the damping ratio of the first mode (ξ_1) is almost equal to the damping ratio of the second mode (ξ_2). f_1 = 15.3 kHz is used as the f_c of the sine-pulse excitation for the subsequent results in air.

5.2 *Effects of applied voltage*

The novel experimental setup of this study allows measurements of the actual displacements of the T_x. This feature is utilized to evaluate, for the first time, the effects of the input voltage amplitude (V_{inp}) on the peak displacement (x_p) of the T_x response in air and in liquid (mineral oil). Figure 3 shows (a) a typical T_x response in air to a sine-pulse with the x_p labelled; and (b) the variation of x_p with V_{inp}. x_p in air of the T_x can be estimated using Equation 3 (Leong et al. 2005).

$$x_p = \frac{3L_b^2 V_{inp} d_{31}}{2h^2} \tag{3}$$

where V_{inp} is the input voltage amplitude applied to the transmitter, d_{31} is the piezoelectric strain constant, and h is the transmitter thickness. Using d_{31} = 390 x 10^{-12} m/V (Piezo 2005), L_b = 0.006 m, h = 0.0015 m, and V_{ino} = 10 V. This equation is also compared to the experimental results in Figure 3b.

Linear curve-fit of the experimental data shows an excellent correlation coefficient for both, air and oil. The results in both, air and oil, agree with Equation 3 in terms of the variation i.e. x_p varies linearly with V_{inp} in the range of 0 – 35 V. However, the slope of Equation 3 is larger than those of air and oil; the slope of the measurements in air is about 50 % smaller than that of Equation 3 and the slope in liquid is about 60 % smaller. The reason for difference in slopes in liquid and Equation 3 is that Equation 3 is developed for x_p in air. The difference in slopes in air and of Equation 3 is because of the geometry and the boundary conditions of the T_x used in this study; the T_x geometry is usually affected by material imperfection and manufacturing faults (Vazquez et al., 2009); moreover, the fixed end of the T_x is usually not perfectly rigid. Nonetheless, the results of this study are much closer to Equation 3 than those of Rio (2006).

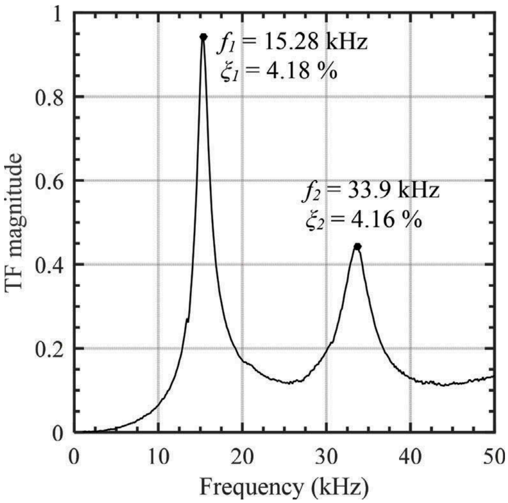

Figure 2. Transfer function of the transmitter (T_x) in air computed from T_x response to a sinusoidal sweep.

5.3 *Effects of mass density of liquids*

The effects of mass density (ρ) of different liquids on the first mode resonance frequency (f_1) and damping ratio (ξ_1) of the T_x is evaluated here. f_1 is obtained from the peak magnitude of the frequency spectrum and ξ_1 is estimated using half-power bandwidth method with the frequency spectra. Figure 4a shows the frequency spectra of the T_x responses in oil, water, sucrose with 20 % and sucrose with 40 % concentration. The peak magnitude of the frequency spectra reduces with increase in mass density (from oil to sucrose 2). Figure 4b shows the variation of f_1 and ξ_1 with ρ of different liquids; Clearly, the presence of liquids has a significant effect on f_1 and ξ_1 of the T_x. Addition of water alone reduced f_1 by 30% and enhanced ξ_1 by about 120% from their corresponding values in air. Both f_1 and ξ_1 more or less vary linearly with the ρ; with a 50% increase in ρ, f_1 decreases by about 12% at the rate of 1.8 kHz-mL/g and ξ_1 increases by about 95% at the rate of 10.7%-mL/g. This decrease in f_1 and peak magnitude and increase in ξ_1 is the result of added liquid mass around the T_x.

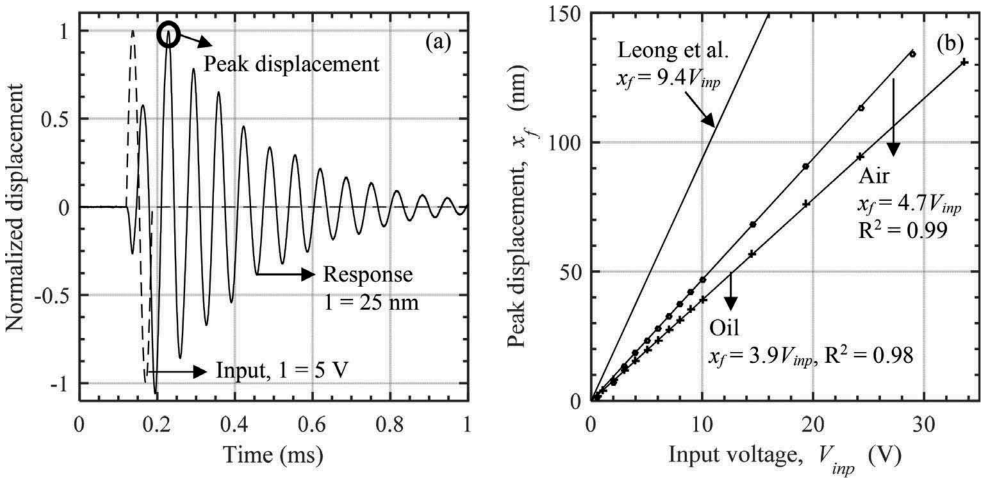

Figure 3. (a) A typical T_x response in air to a sine pulse; (b) peak T_x response displacement vs input voltage.

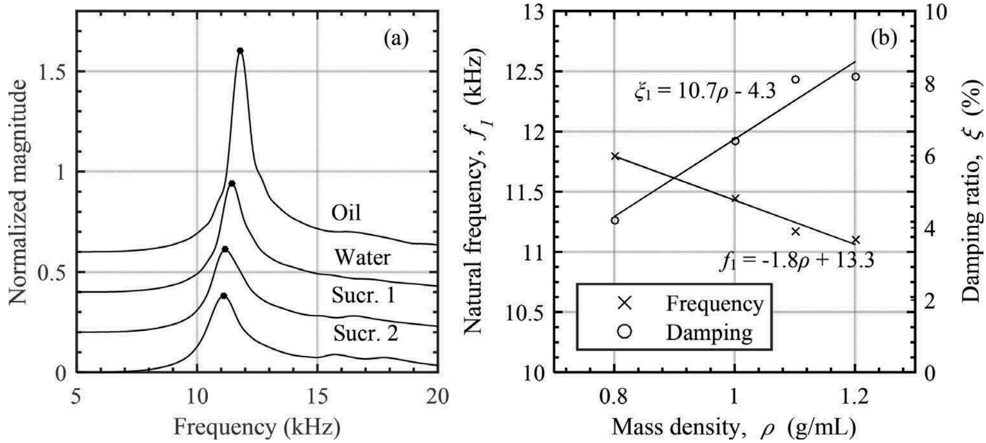

Figure 4. (a) Frequency spectra of the T_x responses in liquids (b) f_1 and ξ_1 of the T_x against ρ of the liquids.

5.4 *Measurements in transparent soil*

Figure 5a shows the displacement response of the T_x, subjected to a 10 kHz sine pulse, embedded in transparent soil (no applied stress). As expected, the presence of transparent soil has significantly reduced the displacement of the T_x vibration; the peak displacement reduced by ≈ 55% from its value in air. The addition of fused quartz results in an increase in mass around the T_x because of which f_1 and ξ_1 of the T_x response in transparent soil are respectively about 9% less and 300% more than the corresponding quantities for the T_x in air. These results confirm that the T_x response in transparent soil is completely different from the sine pulse input excitation. The reliability of conventional BE test results now becomes highly questionable because the predominant assumption in BE test is that the T_x response in soil has the same shape as the shape of the input excitation (Lee & Santamarina, 2005).

Figure 5a also shows the normalized displacement signal of the T_x response for vertical stress (σ_v) = 35 kPa. The increase in σ_v from 0 to 35 kPa reduces the peak displacement by about 68%. Figure 5b shows the variation of the peak magnitude (m) of the frequency spectra of the T_x responses in transparent soil subjected to vertical stress with the vertical stress; Figure 5b also shows the variation of the first mode resonance frequency (f_1) of the T_x inside the soil with the vertical stress. The peak magnitude from the spectra and f_1 show approximately linear relationships with logarithm of the applied vertical stress. The peak magnitude reduces at a rate of 0.21 unit/kPa and f_1 increases at a rate of 0.06 kHz/kPa.

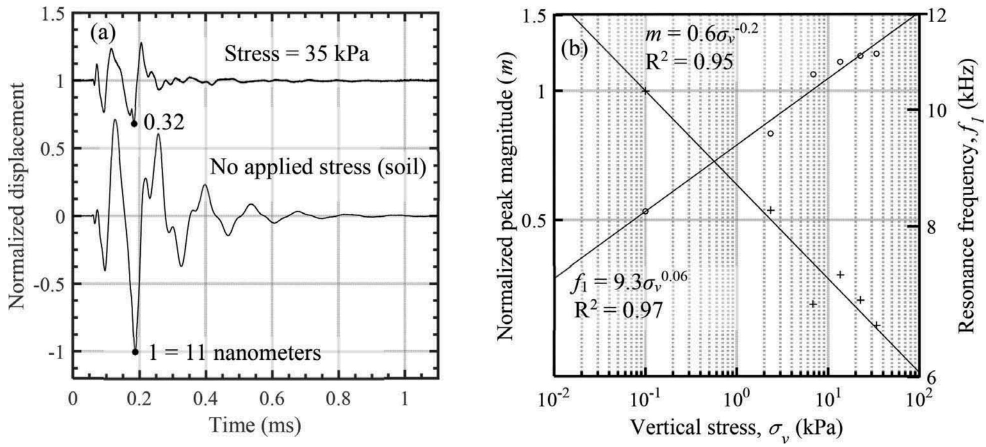

Figure 5. (a) T_x responses in transparent soil with and without stress; (b) m and f_1 vs σ_v in the soil

6 CONCLUSIONS

Bender elements (BE) test is widely used to estimate the shear velocity of soils (V_s); V_s is an important parameter in earthquake design of foundations and structures; unreliable results from BE test can lead to significant consequences. There is high probability of unreliable results from the conventional BE test because there is no standardized BE test procedure. This limitation is mainly because of a lack of understanding of the actual behaviour of BEs inside the soil specimen. This study presents the results of a novel experimental program in which the actual behaviour of a transmitter bender element placed inside a transparent soil is studied for the first time using a state-of-the-art laser vibrometer. Actual BE vibrations are measured in air, in liquids with different mass densities, and in transparent soil specimens under different vertical stresses. This study shows from actual measurements of transmitter vibrations inside a soil that the response of transmitter embedded in soil is significantly different from the input excitation. These results raise serious questions on the reliability of the analysis of BE tests which use frequency domain methods because they assume that the BE response has the same shape as the input excitation. The study of the effects of input voltage amplitude on transmitter response clearly shows a linear relationship between the input voltage amplitude and the peak transmitter displacement in air and liquids confirming the trend predicted by the theoretical equation. Transmitter responses measured in liquids show that a 50% increase in density causes a decrease in f_1 by about 12% and an increase in ξ_1 by about 95% for the range of liquid density (0.8-1.2 g/mL) considered in this study. The results of transmitter response in transparent soil show that f_1 of the transmitter varies linearly with log of vertical stress.

Results presented in this study are the preliminary results of this experimental program; future studies will present the actual behaviour of the transmitter and receiver simultaneously inside the transparent soil specimen which will greatly advance the understanding of the frequency response of BEs inside the soil. Consequently, the process of standardization of the BE test will be tremendously expedited.

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