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Piezo Film Technology and Applications in Geotechnical Testing

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ABSTRACT: Piezo films are thin, piezoelectric membranes that can be used both as source or as receiver. They may be adapted to a variety of in situ and laboratory geotechnical testing needs. This paper summarizes fundamental concepts in piezo film technology and the physical properties of this material. The principles behind common utilizations are reviewed, and three geotechnical applications are described: a low-cost field sensor and modified triaxial and oedometer cells to measure low-strain moduli in resonant and pulse mode.

KEY WORDS: piezoelectric effects, piezofilm, resonance, wave velocity, geophysical, laboratory testing, field testing

Piezoelectric materials deform when excited with an electric potential and generate a voltage output when deformed. Jacques and Pierre Curie discovered the piezoelectric effect in 1880 at the University of Paris. It was not until 1947 that it was discovered that ceramic substances could be made piezoelectric by poling. Soon afterwards, a marked piezoelectric effect was observed in lead zirconate titanate (PZT) and it became the piezoelectric ceramic of choice.

Early work in piezopolymers took place in Japan during the 1950s and 1960s. In 1969, the high piezoelectricity of polyvinylidene fluoride (PVDF) was discovered, and in the mid-1970s the first commercial transducers based on PVDF were developed (Sessler 1981; Eliasson 1984).

Naturally occurring piezoelectric materials include quartz, tourmaline, Rochelle salt, and even human skin. The cause of inherent piezoelectricity is the lack of centered crystal symmetry or the electrically polar nature of crystals. Voltage output is proportional to the stress applied and is inversely proportional to the crystal symmetry; i.e., the more symmetrical the crystal, the more stress is required to generate a voltage.

There are two types of thin piezoelectric polymers: piezo sheets (200 μm to 2 mm) and piezo films (less than 200 μm). This paper centers on piezo film technology and applications.

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Piezo Films: Manufacture and Properties

Polyvinylidene difluoride PVDF is a semicrystalline, long-chain polymer unit of molecular weight 10^5. It resembles "Saran-wrap" plastic (polyvinylidene dichloride), but chlorine atoms are replaced by fluorine (Amato 1989). The repetitive unit of PVDF is CF_2CH_2. Although the crystals are polar, the chains align to form a noncentrosymmetric unit cell where dipoles point in the same direction.

Manufacture

PVDF is manufactured as thin films or sheets with thickness ranging from 5 μm to 2mm. The polymer is stretched uniaxially or biaxially to many times its length at temperatures ranging from 60 to 80°C; this process forces the alignment of the carbon chain, i.e., a change in crystalline phase. Thermal polarization follows: electrodes are deposited on the film by evaporation in vacuum (e.g., Al, Al-Ni, Ag, Au, or Cr), and an electric field 500 to 800 kV/cm is subsequently applied to align the dipoles at a temperature of about 100°C. The polymer is then cooled while maintaining the electric field, "freezing" the polar alignment.

Physical Properties (Publications by Solvay and Pennwalt)

Some of the most relevant properties documented in the literature indicate that piezo films are mechanically durable, very flexible, rugged, light weight, highly resistant to stress fatigue, chemically inert, and have an acoustic impedance similar to water (this favors some underwater applications). PVDF absorbs electromagnetic waves in the near infrared range (5 to 15 μm), making an excellent detector of human IR radiation. On the other hand, it is not affected by UV radiation.

PVDF has a unit weight of 17.5 kN/m³. It melts at about 170°C, and glass transition happens in the vicinity of −40°C. The operating temperature is between −40 to 80°C; it deactivates at higher temperatures. Aging is not a problem for operating temperatures less than 60°C.

Drawing processes during manufacturing give PVDF orthotropic mechanical properties. Elastic moduli range between 1500 and 2500 MPa; low values correspond to low draw ratios and/or high operating temperatures. The tensile strength is between 60 and 200 MPa, with elongations of 50 to 150% at failure. The wave propagation velocity is between 1000 and 2000 m/s. The ratio of electrical (or mechanical) energy output to the mechanical (or electrical) energy input is k^2, where k is the electromechanical coupling coefficient. Typical values of k are between 0.1 to 0.2 (for PZT, k varies between 0.3 and 0.6).

Electrical-Mechanical Relations

The electrical output generated by a mechanical input is referred to as "direct" piezoelectricity. This effect is primarily relevant in the design of sensors. In piezo films, where the electrodes are across the thickness—Direction 3, the relationship between input and output is

$$E_3 = -g_{3m}\,\sigma_m \tag{1}$$

where

E = the output field, V/m,
g_{im} = the piezoelectric stress constant, V·m/N, and
σ = the applied normal stress, N/m²

The subindex m refers to the direction of the mechanical action: "1" parallel to the machine drawn direction; "2" in the plane of the piezo film but perpendicular to the machine direction; and "3" perpendicular to the plane of the piezo film.

The change in strain due to an applied electric field is referred to as the "converse" piezoelectric effect. This effect is of primary importance in the design of sources. The expression relating an applied field E_3 between the electrodes and the resulting strains is

$$\varepsilon_m = d_{3m}\,E_3 \tag{2}$$

where ε_1 and ε_2 are along the plane of the piezo film ("transverse effect"), and ε_3 is in the direction of the thickness ("longitudinal effect"). The d_{3i}'s are the piezoelectric strain constants, C/N. The constant d is related to the piezoelectric stress constant g by the dielectric constant e': $d = ge'$.

The response of piezo films is most linear in the draw direction (Hahn 1985). Mechanical boundary conditions may affect the value of d. For example, d_{33} in free conditions may be different than d_{33} when $\varepsilon_2 = \varepsilon_2 = 0$ is enforced (Furukawa et al. 1984). The restrained condition may develop in applications where the piezo film is sandwiched between two plates or materials.

The piezoelectric stress and strain constants depend on formation characteristics, including crystal form, stretch rate and ratio, poling method, and process temperature (De Mattei and Feigelson 1984). For the material used in this research, the piezoelectric strain constants are $d_{31} = d_{32} = 7$ to 8 pC/N and $d_{33} = 14$ to 16 pC/N.

While the piezoelectric constant of PZT is three to ten times higher than PVDF, much higher electrical fields may be applied to piezo films. Therefore, PVDF transducers may generate strain levels ten times higher than ceramic transducers (strain levels greater than 20 to 40% are possible).

Practical Considerations

A permanent short circuit may result from improperly cutting piezo films. In this study, following manufacturers recommendations, cutting was successfully done by placing the film on a glass surface and cutting with a sharp blade.

The connection of piezo films can be achieved by means of commercially available copper or aluminum strips which have a conductive adhesive on one side, or with a silver-filled, conductive epoxy glue. The authors have also used mechanical connections, e.g., clamps.

Cost

Initially, piezo films were commercially produced in Japan; however, two other manufacturers currently produce PVDF in Belgium and in Pennsylvania. The cost of piezo films is \$35 to \$45 for the first square foot, and less than \$10/ft² for large quantities. For most applications, hundreds of transducers can be made from a square foot.

Applications

The increased use of PVDF in many fields is mainly due to its flexibility, ruggedness, low acoustic impedance, low mass, and very broad band (millihertz to gigahertz). A 10-μm-thick film experiences the first resonant mode in the No. 3 direction near 100 MHz, but with high internal damping the gain is low (i.e., low mechanical Q, where Q equals the quality factor ($Q \simeq W_0/B$, where B is the bandwidth). In addition to PVDF's piezoelectric properties, PVDF is often used in pyroelectric devices. A number of applications appear in both the general literature and publications provided by manufacturers (Lerch 1979; Sessler 1981; Carlisle 1986; Gerliczy and Betz 1987; Garner and Holden 1988; publications by Pennwalt and by Solvay): medicine (e.g., flow detectors, ultrasonic echography, monitors to prevent sudden infant death syndrome), acoustics (e.g., microphones, hydrophones, speakers, headphones), robotics (e.g., tactile sensors for gripper), and security (e.g., fire detectors, alarms based on the detection of IR radiation from a human body up to 30 m away). These applications involve a variety of geometrics and underlying concepts which are summarized next.

Common Concepts in Design

Sources in the audible range, e.g., headphones, are often based on the transverse piezoelectric effect, where the displacements in the plane of the film are converted into pulsating motion by curving the film in the form of a dome and fixing its ends (Fig. 1*a*). Most sources in the upper ultrasonic range are based on the longitudinal effect (up to 500 MHz at room temperature—Fig. 1*b*). The close matching of mechanical impedance of PVDF and water favors the use of piezo film-based hydrophones. The schematic of a miniature hydrophone is shown in Fig. 1*c*.

When two layers of piezo film are glued in between and reverse connected, the small relative strains in each element translate into large flexural motion. This bimorph, bender configuration can be used when large deformations are needed (Fig. 1*d*). Numerous applications are based on two films in which one is an exciter and the other is a receiver (Fig. 1*e*). These systems are characterized by a very wide dynamic range. The resonant column described later in this paper is an example of such a system. Using two films to detect resonance of a mechanical system allows for very careful monitoring of slowly changing conditions.

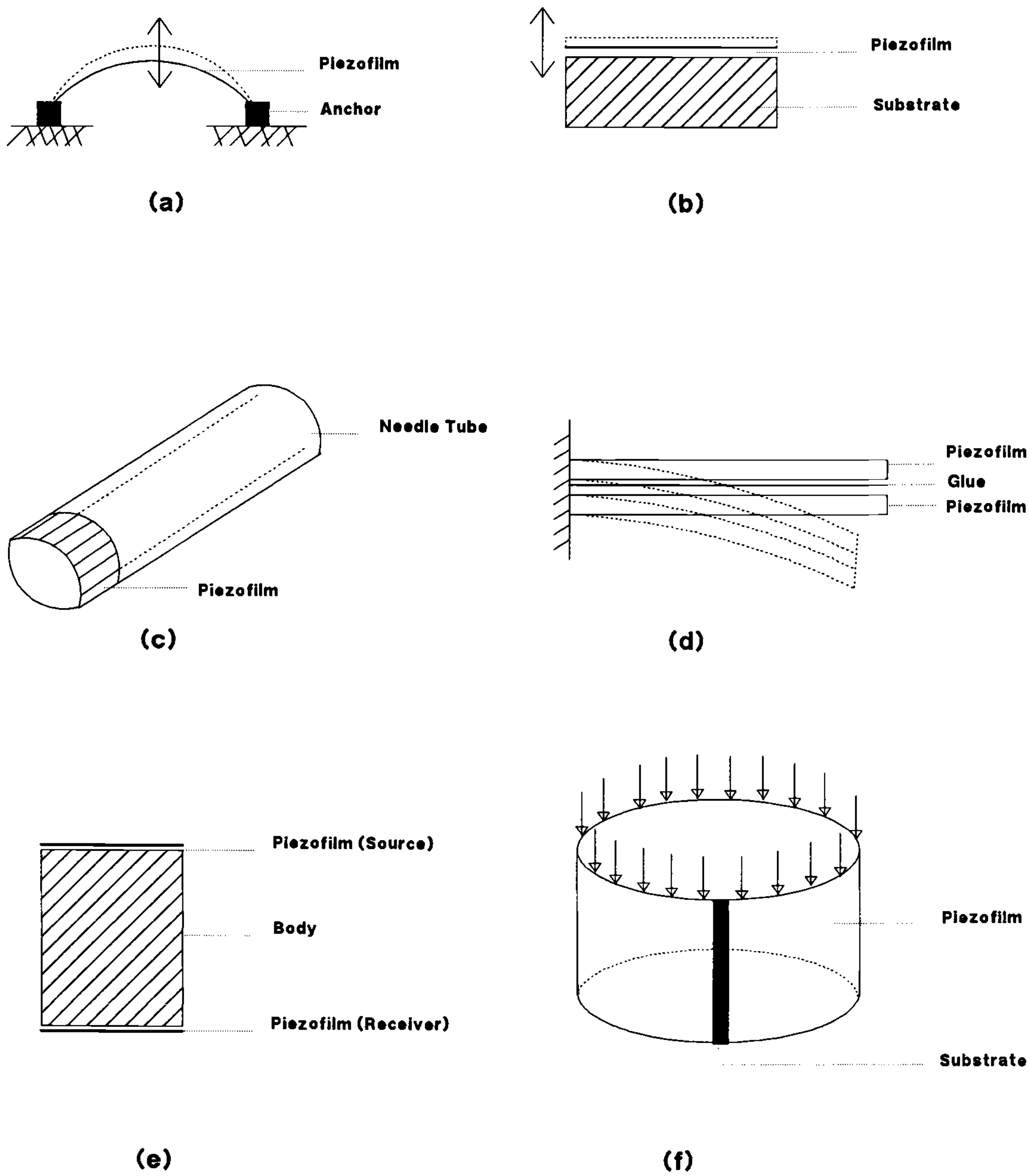

FIG. 1—*Common configurations.*

The simplest use of piezo film as receiver is as a strain gage. A piezo film as a receiver does not require an external power source and has a very wide frequency response (for example, it can be used as a sensor for acoustic emission). Due to the very low mass of the film, it does not resonate with the mounting surface. Because of its low Q, received signals have a limited amount of the high frequency ringing which is characteristic in other transducers. Because films are thin, forces along the plane of the film (Directions 1 or 2) produce high stresses and therefore high output voltage. Figure 1*f* shows a device based on this observation: a thin strip of piezo film in the form of a cylinder is very sensitive to forces on the platens. Curving the film also increases the sensitivity of a transducer to a plane stress wave acting against the plane of the film; as the curvature increases, the resonant frequency decreases and the sensitivity increases.

Design Precautions

The high pyrosensitivity of piezo films may affect the performance of devices based on the piezoelectric effect. In the two-film resonant configuration, proper shielding and grounding are required to avoid electromagnetic interference and "cross-talk" between the driving film and the receiving one. Finally, if there are problems with external vibrations and temperature changes, a "second" film can be placed close to the film acting as receiver: only one film is exposed to the input but the two are subjected to the environmental noise; the output of the two films is either in a series or is fed to a differential amplifier so that environmental effects are canceled.

Geotechnical Applications

Stress-Dependent Response

In view of geotechnical applications, it is important to assess the piezo film response under stress. It is generally believed that piezoelectric properties are nearly insensitive to the level of static stress. Meeks and Ting (1983) tested different types of PVDF under hydrostatic pressure changing between 0 to 70 MPa (10 300 psi); the piezoelectric stress and strain constants decreased linearly with the pressure, showing a maximum loss of 17% for *d* and 11% for *g*; *d* and *g* were not affected by cycling the hydrostatic pressure. The interaction of piezo films with soils differs from the hydrostatic case due to a number of effects such as point loading, indentation, and in-plane straining.

A test was conducted to measure the response of piezo film embedded in Ottawa 20-30 sand in an oedometer cell (D_{50} = 0.72 mm, Cu = 1.25). The amplitude of the response, normalized with respect to the peak response, is shown in Fig. 2. The response during unloading was similar to the one shown but with 2 to 5% higher amplitude.

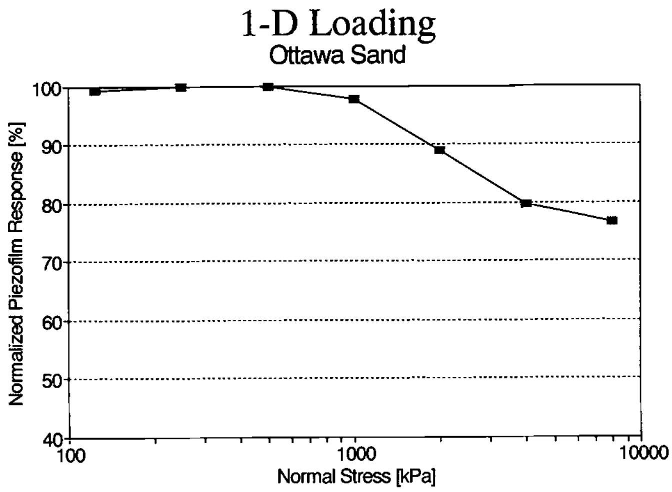

FIG. 2—*Stress-dependent response in soil.*

Field Sensors for Geophysical Studies

The development of special sensors became part of an ongoing research program on underground imaging with emphasis on geotomography. It was required that receivers should be low cost so that they could be readily deployed in a casing-less, use and lose scheme.

The receivers consist of strips of piezo film that act as strain sensors. The thin film fully couples to the surrounding soil, accommodating to the soil mass with minimum effects to the medium. When stimulated by the arrival of the mechanical wave, it generates a voltage which can be directly detected by an oscilloscope or a digitizer. This simple system may prove sufficient and was used by the authors in a tomographic study of a 27 by 27-ft, massive concrete pier under a New York bridge. Alternatively, a small end amplifier can be connected to each piezo film strip to reduce the noise to signal ratio.

For this purpose, small and low-cost amplifiers were designed and tested, using field effect transistors (FET) and operational amplifiers (Op Amp). These two electronic devices provide power gain between the input and output signal. FET is characterized by very high input impedance, thermal stability, and limited distortion of the input signal; however, it does not provide high gain. An Op Amp is a high-gain device, capable of providing accurate output by using negative feedback configuration.

The design of an amplifier depends on the electrical characteristics of the source. The piezo film source can be characterized as a strain-dependent voltage source in series with a capacitance, where the capacitance is a function of size of the piezo film strip. (This electrical model of the piezo film is applicable at low frequencies, including the 100 to 1000 Hz frequency range of interest in the current application.) Accurate amplification requires that the source voltage be independent of source impedance at the input stage of the amplifier. For this purpose, the input impedance of the amplifier is made higher than the source impedance.

The amplifier circuit shown in Fig. 3*a* uses a 2N3819 FET transistor and a 741 Op Amp. The FET-based input stage functions as an impedance "buffer," i.e., high input R_B (10 MΩ) and low output impedance. It has a small voltage gain which is determined by R_D and R_S. The bypass capacitance C_S is chosen to short R_S at midband to give maximum gain. The FET circuit is coupled by C_1 to the Op Amp circuit, which serves as the main amplifier. The voltage gain of this circuit is determined by R_f and R_i. The overall voltage gain of this amplifier is about 46 dB. Figure 3*b* presents the variation of the gain and the phase shift with frequency for this amplifier.

Low Strain Modulus: Resonant Mode

The resonant column technique was first used to test soil materials in the late 1930s in Japan. The specimen can be either excited in compression or in torsion with different boundary conditions. Increased use of this test has led to the understanding and overcoming of some of its early limitations, namely distribution of angular rotation in torsional systems with free-end, strain variation with the radius, limited-strain amplitude, coupling with end platens, and the end platens effect (Drnevich 1978; Avramidis and Saxena 1990).

The low-mass, nonresonant characteristics of piezo films are ideal for maintaining and sensing resonance of the soil column. Under this mode, the sample is excited at one extreme by attaching a signal generator to the piezo film located at the cap. An oscilloscope is connected to the piezo film on the other extreme. The frequency is gradually changed to detect resonance and cancellation.

A 40-μm-thick disk of PVDF was glued on top of the lower platen of the triaxial cell to act as source, and a second 40-μm-thick disk was attached to the upper platen to work as a sensor (Fig. 4*a*). While friction may be sufficient for compliance, gluing or clamping along the periphery may help restraint straining in the Nos. 1 and 2 directions). The lower disk was connected to the signal generator and the upper disk to an analog oscilloscope without intermediate amplification. Coaxial cable was used to minimize noise. The sample made with Ottawa 20-30 sand

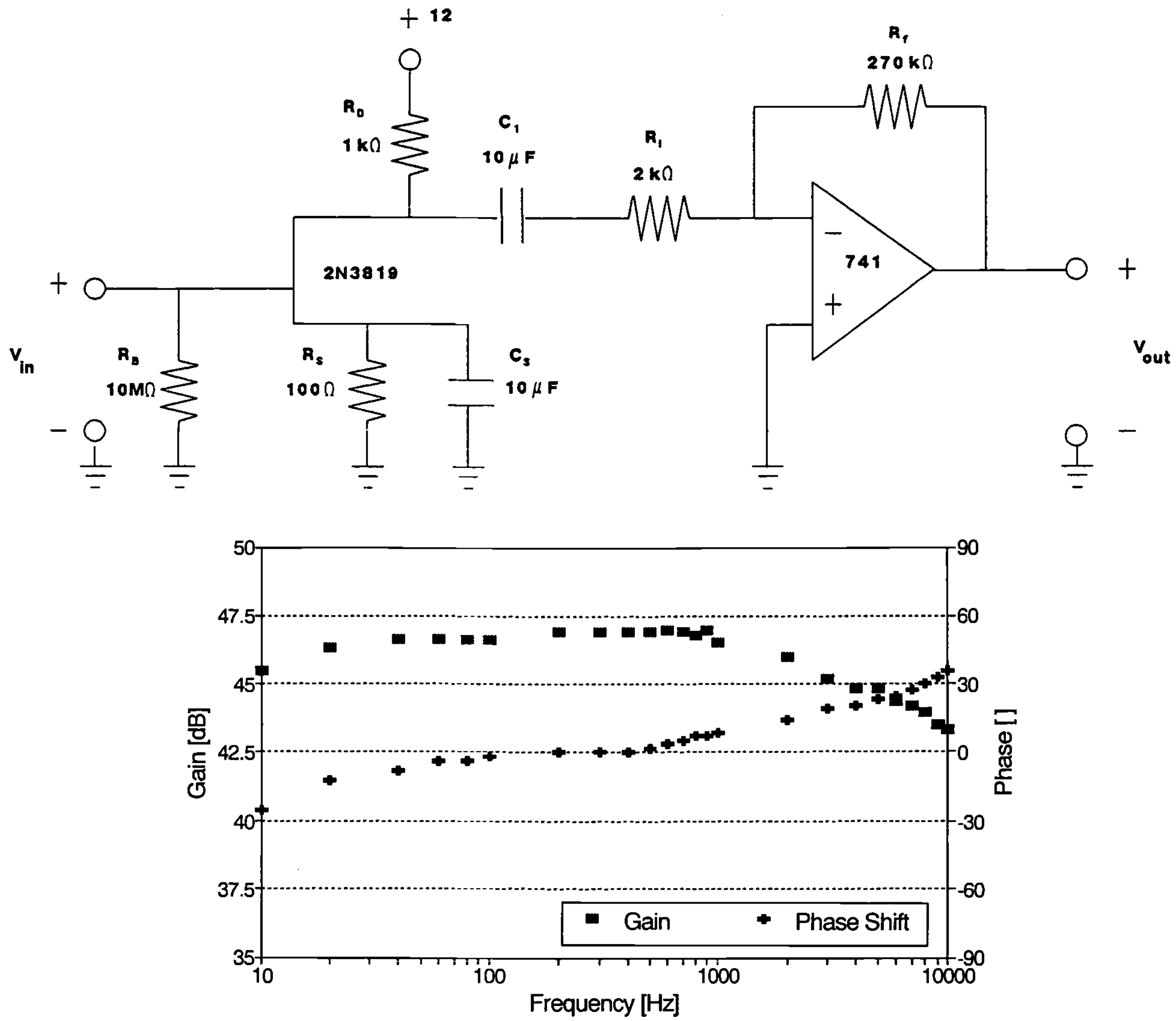

FIG. 3—*Amplifier for low-cost receivers.*

(D = 64 mm; L = 153 mm) was densified by rodding and loaded with an isotropic state stress [σ_c = 30 psi (207 kPa)]. Test results are shown in Fig. 5 as a ω-versus-q dispersion plot, where ω is the frequency, $\omega = 2\pi/T$, and q is the wave number, $q = 2\pi/\lambda$. The wave length was computed from the mode number.

Limited dispersion has been observed in this and other similar tests conducted with this device. For the results presented in Fig. 5, the phase velocity $V_p = \omega/q$ is almost constant. This indicates that the soil acts as a continuum in this frequency range. Assuming a one-dimensional monoatomic lattice, the saturation frequency is $f_{max} = V/\pi a$, where "a" is the average particle to particle distance; for this test f_{max} is about 300 kHz. The continuous line in Fig. 5 is the dispersion predicted assuming a monoatomic lattice.

A major advantage of dynamic torsional testing is the lack of geometry-dependent dispersion. In compression excitation, as the wavelength reduces with increased frequency and becomes comparable to the radius of the rod, part of the energy travels as a Raleigh wave with velocity $V_R < V_P$. This effect is minimized when the wave length to diameter ratio, λ/D, is greater than 5. In resonant mode testing of standard triaxial specimens (L/D = 2), the first resonant mode takes place at $\lambda = 2L = 4D$ and the error in the velocity is minimum (1 to 2%). The simultaneous propagation of compression waves and slower surface waves may explain the difficulty in detecting some of the higher modes and the presence of "ghost" modes. The dotted lines in Fig. 5 correspond to V_P = 345 m/s (first mode) and $V_R \simeq V_S$ = 233 m/s (calculated assuming μ = 0.1).

Low Strain Modulus: Pulse Mode

Developments in electronics permit pulse sonic testing in small specimens. This type of measurement may be preferred, for example, to determine transfer functions, and overcomes some of the difficulties involved in resonant devices, e.g., boundary conditions. In the time domain, the wave velocity is determined by measuring the travel time between source and receiver. Piezoceramic bimorph elements have been used in pulse and CW determinations of G_{max} (Dyvik and Madshus 1985; Thomann and Hryciw 1990; Baldwin et al. 1991).

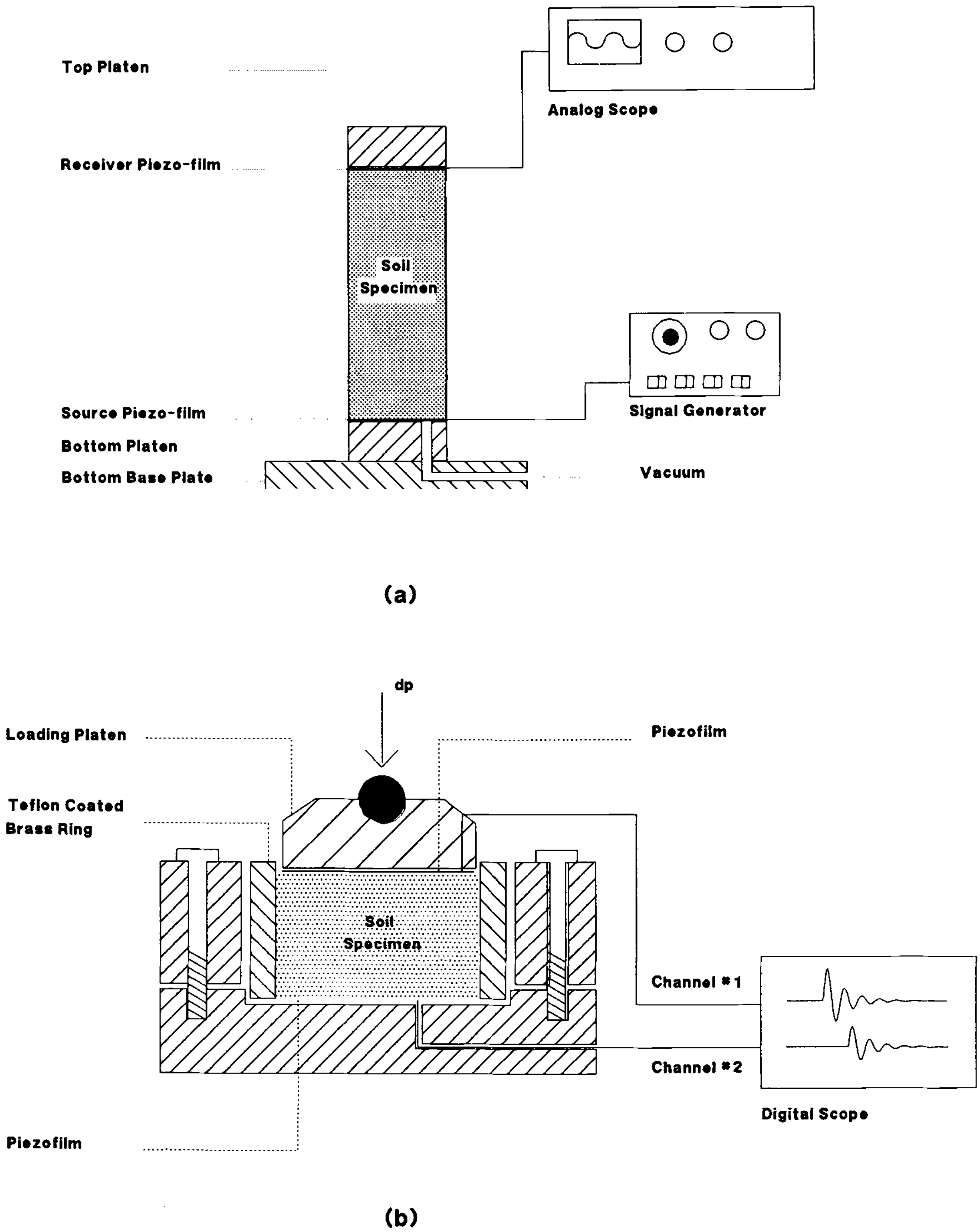

FIG. 4—*Modified triaxial and oedometer cells.*

The modified resonant triaxial cell described above can be used in this mode by connecting the upper and lower piezo film to a two-channel scope (without disturbing the specimen). Alternatively, an oedometer cell can be adapted for this purpose, and the effect of k_0 loading and unloading on V_p can be studied (Fig. 4*b*). A standard oedometer cell, ID = 63 mm, was readily modified, adding a disk of piezo film on the top and on the bottom platens. The excitation can be electronically generated using the converse piezoelectric effect on either of the two films. However, for this test a mechanical "weight-drop" source was used (0.07 N) through a perforation in the loading yoke. The frequency of the first arrival was in the order of 1 kHz. A multichannel PC-based digital scope was used for this experiment, sampling at a rate of 500 kHz per channel; the 2-μs resolution approaches the critical value when thin oedometer soil specimens are tested. The scope was triggered in digital mode using the input from the film on the upper platen.

A sample test conducted also with Ottawa 20-30 sand is shown in Fig. 6. At each load stage, the travel time was determined. Subsequently, additional static load was applied to produce a

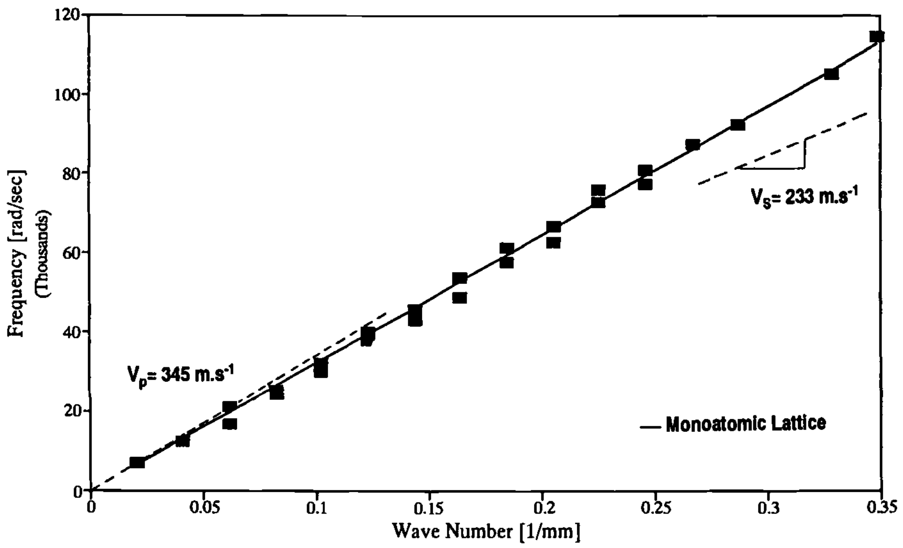

FIG. 5—*Resonant measurement in modified triaxial cell.*

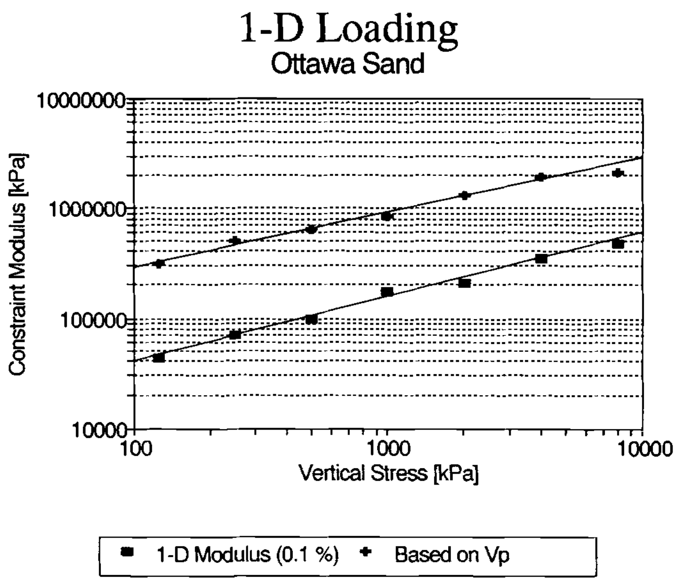

FIG. 6—*Pulse measurement in modified oedometer cell.*

normal strain of $\varepsilon = 0.1$ to 0.15% in order to evaluate a midstrain tangent constraint modulus, M. While the velocity-based constraint modulus, M_{V_p} increases exponentially with the vertical stresses with an exponent $\alpha = 0.5$, the constraint modulus at 0.1% strain, $M_{0.1\%}$, increases at a higher rate with an exponent $\alpha = 0.59$. (The monotonic constrained loading of a face-centered array of equal spheres results in a constraint modulus independent of the strain level and exponentially related to the vertical stress with $\alpha = 0.33$; see also Duffy and Mindlin's results in Richart et al. 1970.) A comparative study of pulse-based and resonant-based moduli obtained with the modified triaxial device at a similar strain level also showed that pulse-based measurements are less sensitive to confining stress than resonant-based measurements.

Conclusions

Imposing piezoelectric properties to polymers opens a large number of possible active and passive geotechnical applications. Piezo film is a versatile, low-cost, and easy-to-use technology. It is mechanically durable, very flexible, rugged, light weight, highly resistant to stress fatigue, and chemically inert. It has a low acoustic impedance similar to water and a very broad band. It is an excellent detector of IR radiation, and it is not affected by UV radiation.

Simple field sensors and laboratory geotechnical devices for dynamic measurements can be readily built using piezo films. A triaxial cell was modified to determine wave velocities. In resonant mode, the device can be reliably used, particularly when only the first resonant mode is needed. It was observed that pulse-based moduli are less sensitive to confining stress than resonant-based moduli at similar strain levels or than quasistatic moduli at large strain.

Acknowledgments

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