

## Laboratory measurements of the stiffness of normally consolidated till polluted by benzene with bender element tests

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This study examines the effect of benzene in the pore space of normally consolidated till on the initial stiffness ( $G_0$ ), the shear wave velocity being measured by the bender element method in a special designed triaxial cell. A significant reduction in  $G_0$  was connected with increasing benzene in the till. The results obtained on the till specimens showed the strong influence of benzene on the undrained shear modulus.

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### INTRODUCTION

The design of foundations and excavations requires the prediction of ground movements and hence a knowledge of the relevant stress-strain properties (Mair, 1993). It is now appreciated that under working conditions the strains in the ground surrounding foundations or excavations may be relatively small. Therefore it is important to measure stiffness at small strain levels  $< 0.1\%$ , since stress-strain relationships are non-linear (Burland, 1989; Atkinson, 2000).

Figure 1 is an idealisation of soil stiffness over a large range of strain, from very small to large, and approximately distinguishes strain ranges. At very small strains the shear modulus ( $G$ ) reaches a nearly constant limiting value  $G_0$ . This figure summarises the current understanding of the variation of soil stiffness.

The very small strain shear stiffness of soils is a useful parameter in both static and dynamic analyses of the behaviour of geotechnical structures. Non-linear models for soil behaviour may be developed using the theory of elasticity with empirical non-linear stress-strain curves obtained from laboratory stress path tests.

Values of the shear modulus at very small strain ( $G_0$ ) can be measured using dynamic techniques in field and laboratory tests, in which the deformation properties of the soil are related to elastic shear wave velocities. Laboratory testing on geomaterials have recently made remarkable progress. Advanced techniques are utilised not only for academic research but also in practice. Besides the safety factor at failure, accurate estimations of deformation, displacement and stresses in the ground and in structures have become an important topic of study in geotechnical engineering.

This paper presents some results of a series of tests performed on undisturbed specimens of normally consolidated till from the town of Płock in central Poland.

To evaluate the maximum shear moduli from laboratory tests, propagation of seismic waves by means of piezoceramic transducers has been widely adopted in the last decade, termed simply “bender elements”, housed in triaxial apparatus (Brignoli *et al.*, 1996). The bender element method, developed by Shirley and Hampton (1977) and Dyvik and Madshus (1985), is a simple and useful technique to obtain the shear modulus at small strain levels ( $G_0$ ) in soils by measuring shear wave velocity through a specimen. If the stress-strain relationship at very small strains is elastic then the elastic shear modulus ( $G_0$ ), should be independent of the method of measurement.

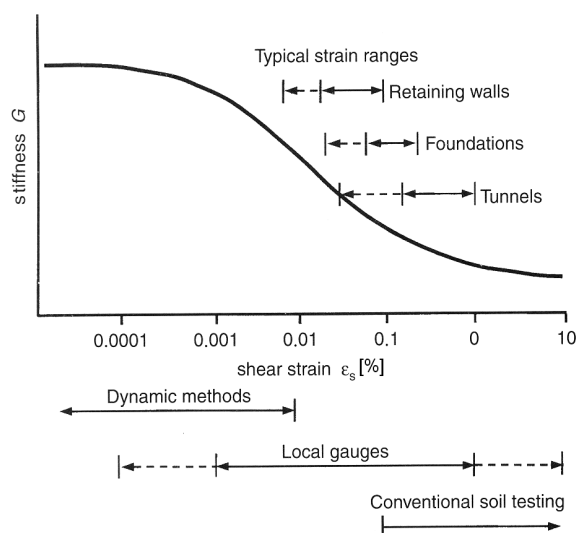


Fig. 1. Characteristic stiffness-strain behaviour of soils with typical strain ranges for laboratory tests and structures (after Atkinson and Salfors, 1991; Mair, 1993)

#### LABORATORY TEST EQUIPMENT AND PROCEDURES

A triaxial apparatus was used for this study with a special triaxial cell (Fig. 2). The apparatus has a maximum capacity of 50 kN for the vertical load and 1.7 MPa for the pressure cell. The cell structure is very stiff and consist of two platens connected by three tie rods located inside a perspex pressure cell. Dimensions of a triaxial specimen of till were 50 mm in diameter and 100 mm in height respectively.

The triaxial cell is equipped with the following sensors:

- a two pairs of piezoceramic bender element transducers,
- a pair of LVDT for local measurement of the axial strain,
- a three proximities for the local measurement of radial strain,
- a load cell located outside the pressure cell,
- a pressure transducer to measure the pore pressure at the bottom of the specimen,
- a pressure transducer to measure the cell pressure.

A multichannel conditioning system is used for data acquisition. The data are automatically transferred via multiplexer connection from the conditioning system to a PC. The Virgo version 7.2 is used to control the whole test procedure by means of a user made program.

The piezoceramic elements are devices which convert mechanical deformation into electrical energy and *vice versa*. In this method a shear wave pulse is generated by a transmitting element and the arrival time for the shear wave is estimated by comparing the transmitted and received pulses. The average sample shearing strain associated with the measurements is estimated to be from  $10^{-4}$ – $10^{-3}$ % (Shibuya and Mitachi, 1994; Viggiani and Atkinson, 1995).

The saturated specimens of till were prepared by the dry setting method with vacuuming and subsequent back pressurisation proposed by Ampadu and Tatsuoka (1993). Undisturbed till specimens were reconsolidated to the best estimate of the in situ vertical stress under ( $K_0$ ) conditions (nil radial strain).

#### TESTED SOILS

The experimental investigation was conducted on undisturbed specimens of normally consolidated till from a soil deposit located at the petroleum refinery in Płock. The specimens were retrieved from depth of about 4 m below surface by means of block samples.

The material tested for this study was clean till specimens with water in the pore space and till specimens polluted by:

- a solution of water and benzene (1.780 mg benzene/1 dm<sup>3</sup> water),
- benzene.

The polluted specimens for bender element tests were prepared by the back pressure method (Ampadu and Tatsuoka, 1993).

Basic physical and classification properties of soil before testing are listed (Table 1). Till is medium stiff, normally consolidated and of low plasticity. The preconsolidation pressure determined from the oedometer test using Casagrande, Janbu procedures is approximately 1. The overconsolidated ratio:

$$OCR = \sigma'_p / \sigma'_{v0} = 1.07 - 1.60$$

where:  $\sigma'_p$  — effective preconsolidation stress,  $\sigma'_{v0}$  — effective overburden stress.

Table 1

#### Index properties of tested specimens

Specimen with:	Moisture content $w$ [%]	Specific density $\rho_s$ [Mg/m <sup>3</sup> ]	Total mass density $\rho$ [Mg/m <sup>3</sup> ]	Clay fraction $CF$ [%]	Plastic limit $PL$ [%]	Liquid limit $LL$ [%]	Plasticity index $PI$ [%]
water	18.74	2.67	2.13	18	12.70	22.80	9.90
water + benzene	21.36	2.67	2.07	18	13.40	23.10	10.30
benzene	23.52	2.67	2.03	18	–	24.20	–

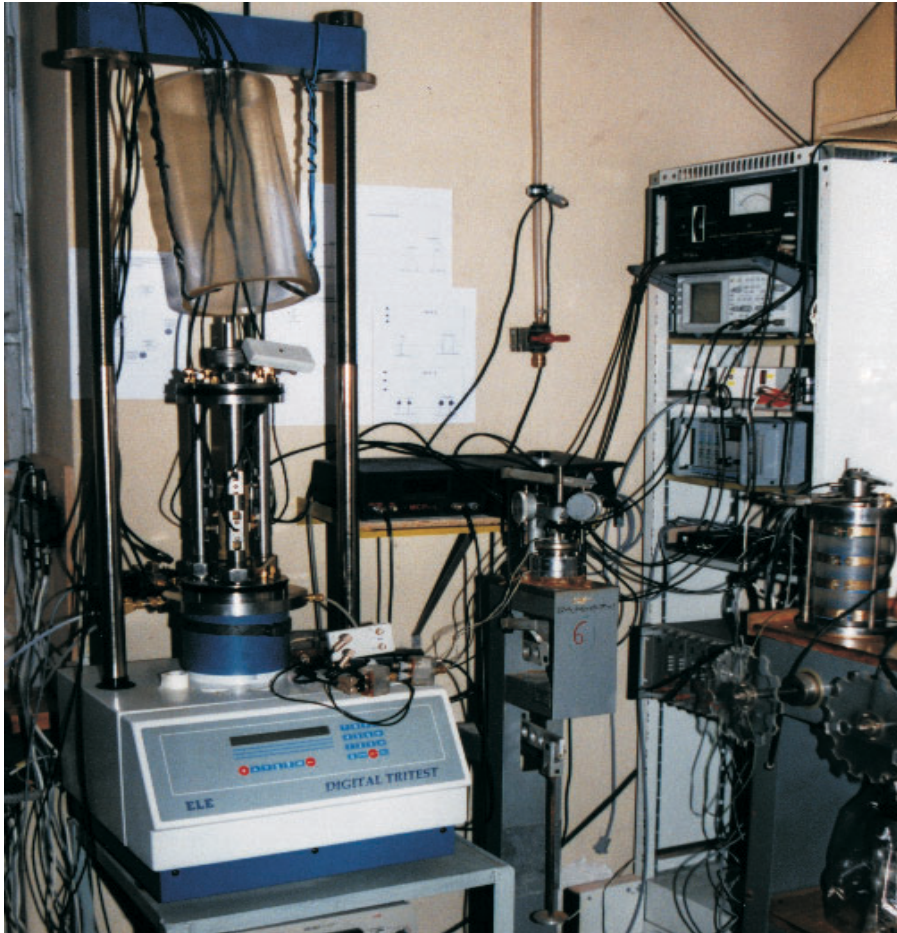


Fig. 2. General view of the triaxial apparatus with bender elements

Table 2

Shear strain  $\gamma$  versus normalized modulus  $G/G_0$  for tested specimens

Shear strain $\gamma$	Normalised shear modulus $G/G_0$ [kPa/kPa] for various specimens with:		
	water	water + benzene	benzene
$1.00 \times 10^{-6}$	1.000	1.000	1.000
$1.00 \times 10^{-5}$	0.999	0.999	0.990
$1.00 \times 10^{-4}$	0.980	0.980	0.975
$3.00 \times 10^{-4}$	0.968	0.968	0.900
$6.00 \times 10^{-4}$	0.964	0.932	0.735
$1.00 \times 10^{-3}$	0.955	0.900	0.630
$2.00 \times 10^{-3}$	0.871	0.695	0.492
$4.00 \times 10^{-3}$	0.651	0.537	0.351
$7.00 \times 10^{-3}$	0.485	0.381	0.253
$1.00 \times 10^{-2}$	0.400	0.302	0.180
$3.00 \times 10^{-2}$	0.122	0.088	0.072
$1.00 \times 10^{-1}$	0.036	0.036	0.036
$1.00 \times 10^0$	0.025	0.025	0.025

More information on the characteristics of till were given by Barański (unpubl.).

## TEST RESULTS AND INTERPRETATION OF SOIL STIFFNESS

In the bender element method, an elastic shear wave is generated by a piezoceramic transducer placed on one end of a confined specimen and is received at the other end of the specimen by another piezoceramic transducer. The distance between the two transducers ( $L$ ) and the time required by the wave to cover the distance  $t$  are used to calculate the propagation velocity ( $V_s$ ) defined by:

$$V_s = L/t$$

After determining the propagation velocity of the shear wave it is possible to calculate the maximum shear modulus ( $G_0$ ); this can be calculated from:

$$G_0 = \rho V_s^2$$

where:  $\rho$  — the total mass density of the soil.

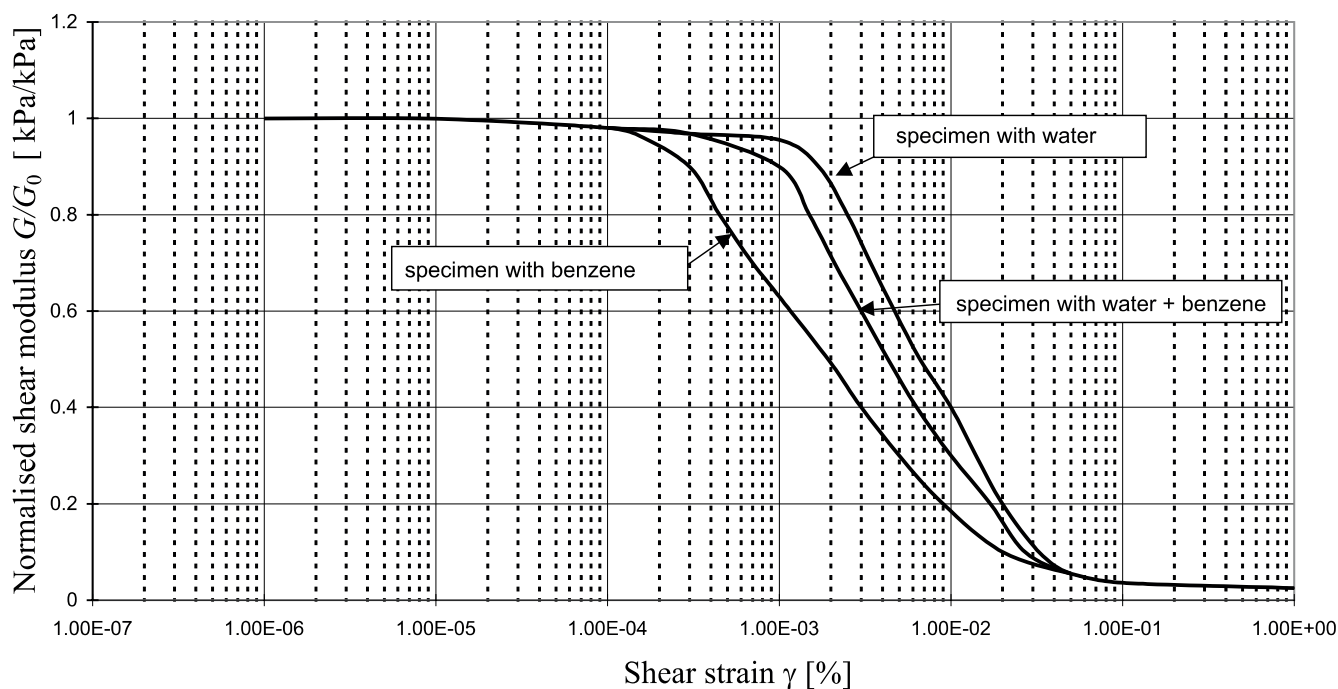


Fig. 3. Comparison of normalised shear modulus  $G/G_0$  versus shear strain  $\gamma$

A total of 15 triaxial compression undrained bender element tests were performed on undisturbed till specimens. Four tests were performed on clean till specimens, five on till specimens with water + benzene and six on specimens with benzene. The test results are summarised with shear strain  $\gamma$  and normalised modulus ( $G/G_0$ ) for all tested specimens (Table 2).

The results from bender elements tests on clean specimens and contaminated specimens with water + benzene and benzene as pore fluids are shown in Figure 3.

## CONCLUSIONS

In this paper, an experimental investigation on the mechanical behaviour of normally consolidated till is given. The following conclusions can be derived from the results of

triaxial compression bender element tests on clean and contaminated specimens of till:

- the stress-strain behaviour of till is highly non-linear;
- stiffness decays with strain;
- shear moduli ( $G_{0W}$ ) of clean specimens of till were higher than shear moduli of specimens with water + benzene ( $G_{0WB}$ ) and benzene ( $G_{0B}$ ) as pore fluids:  $G_{0W} > G_{0WB} > G_{0B}$ ;
- due to existence of physicochemical effects, the benzene as pore fluid generally has a significant influence on till behaviour at very small and small strains.

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