G_{max} measured in oedometer and DSS tests using bender elements

G_{max} mesuré par essais oedométriques et DSS utilisant des éléments pliés

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SYNOPSIS: Parallel G_{max} tests on Drammen clay with piezoceramic bender elements mounted in the oedometer, DSS and triaxial devices were performed. The G_{max} values obtained at various consolidation stress levels by the different tests are compared. The results show that G_{max} can be easily and accurately determined in the oedometer and DSS devices, G_{max} values at comparable times are similar (i.e., end of primary consolidation) and that assuming a travel length for the shear waves as the bender element tip to tip distance is correct.

1 INTRODUCTION

Previous investigations have shown that piezoceramic bender elements can be used to measure the initial shear modulus (G_{max}) in triaxial sized specimens (Dyvik and Madshus, 1985). In these studies, bender elements were mounted in a resonant column device. Parallel determinations of G_{max} by the conventional method (resonant column) and the new technique (bender elements) showed that the results were very similar, if not identical.

Some of the many advantages of using the bender element method for determining G_{max} in standard triaxial tests are: bender elements can be installed in many devices such that the need for parallel resonant column tests may be eliminated, measurement and calculation of G_{max} is much faster and easier than in the resonant column device, and shear modulus at small and large strains can be compared directly on the same specimen. The purpose of this investigation was to see if the bender element technique could also be used in the oedometer and direct simple shear devices. The primary difference is that the specimen height (and therefore travel distance for shear waves) in the oedometer and direct simple shear devices is typically one-fifth to one-tenth that of a triaxial specimen height.

2 TEST SERIES 1 AND 2

This investigation consisted of two parallel test series (hereafter referred to as Series 1 and Series 2). Piezoceramic bender elements were installed in the oedometer, direct simple shear (DSS) and triaxial devices.

Test Series 1 consisted of parallel tests on Drammen clay in the oedometer, direct simple shear and triaxial devices. Identical consolidation procedures were used in the three devices (stress increment magnitudes and durations) and G_{max} was determined throughout.

Test Series 2 consisted of three different oedometer tests on Drammen clay, including 2 constant rate of strain (CRSC) oedometer tests and one standard incremental oedometer test. G_{max} was determined throughout consolidation in each of the tests.

3 TEST EQUIPMENT

The procedure used for producing and installing a set of bender elements into a triaxial testing device is described in detail in Dyvik and Madshus (1985). The same procedure is used regardless of the testing device (oedometer, direct simple shear or triaxial).

Figures 1 and 2 show simplified cross-sections

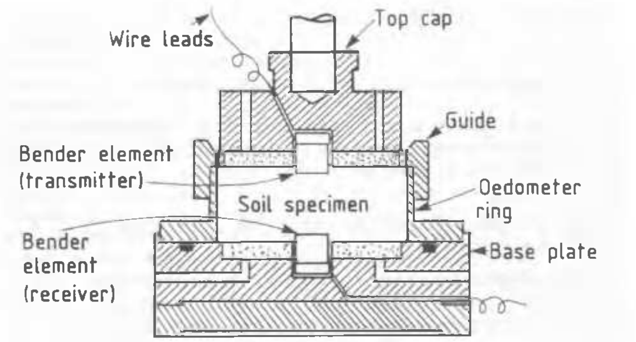

Figure 1. Simplified cross section of an oedometer device with piezoceramic bender elements.

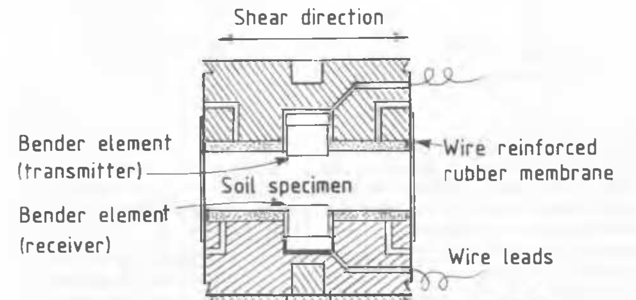

Figure 2. Simplified cross section of a direct simple shear device with piezoceramic bender elements.

of the oedometer and direct simple shear equipment, respectively, after the bender elements had been installed for this study. The bender elements each protruded about 1 to 2 mm into the specimen (2 to 3 mm protrusion for triaxial).

Two digital oscilloscopes with storage were used in this study (Nicolet 4094 and 4094A). The excitation signal to the transmitter bender element was a step function (square wave) with a ±10 volt amplitude.

4 CLAY TESTED

Plastic clay from Drammen was used for all the tests in Series 1 and 2. The corresponding in situ depth from which the test speciemns were taken was about 6.5 m for Series 1 and 7.7 m for Series 2. The typical water content for all the specimens ranged from 54 to 56%.

The Drammen clay samples were taken with a 200 mm diameter sampler. Sections of the sample were quartered (vertically) to provide four adjacent samples at equal in situ depth and therefore similar properties. The test specimens in Series 1 and 2 were trimmed from such quarter samples at the above in situ depths.

The specimen dimensions for the triaxial test was 10.8 cm in height and 5.4 cm in diameter (≈ 23 cm² area). The specimen dimensions for the oedometer tests (incremental and CRSC) were 2.0 cm in height and 6.67 cm in diameter (≈ 35 cm² area). The specimen dimensions for the direct simple shear test were about 1.6 cm in height and 6.67 cm in diameter (≈ 35 cm² area).

5 TEST PROCEDURES

5.1 Consolidation program - Series 1

The consolidation program for the oedometer, direct simple shear and triaxial tests in Series 1 is presented in Table 1.

Table 1. Consolidation program - Series 1

Consolidation step	σ'_{ac} (kPa)	OCR	K_o	σ'_{oct} (kPa)
1	32	2.8	0.64	24.3
2	64	1.4	0.50	42.7
3	100	1.0	0.50	66.7
4	200	1.0	0.50	133.3
5	300	1.0	0.50	200.0
6	392	1.0	0.50	261.3
7	245	1.6	0.60	179.7

As indicated by column 1, all the tests had 7 consolidation increments. Column 2 indicates the vertical effective stresses (σ'_{ac}) used in all the tests for each of the consolidation increments. Drammen clay at a depth of 6.5 m has an in situ vertical effective stress (p'_o) of about 58 kPa. The apparent preconsolidation pressure (p'_c) at this depth is about 90 kPa. The clay specimens were therefore overconsolidated for consolidation steps 1 and 2, normally consolidated for steps 3 through 6 and again overconsolidated for step 7 (column 3). Column 4 shows the lateral stress ratio (K_o) used in the triaxial test. These values are assumed to be equal to those for the oedometer and direct simple shear tests which are typically not measured. Column 5 lists the effective octahedral stresses (σ'_{oct}) in the triaxial test.

5.2 Consolidation program - Series 2

The consolidation program for the incremental oedometer tests in Series 2 is presented in Table 2.

Table 2. Consolidation program - Series 2

Consolidation step	σ'_{ac} (kPa)	OCR
1	32.4	3.1
2	64.8	1.5
3	100	1.0
4	200	1.0
5	250	1.0
6	300	1.0
7	400	1.0
8	300	1.3
9	200	2.0
10	100	4.0

For Drammen clay at an in situ depth of 7.7 m, p'_o = 65.4 kPa and p'_c = 100 kPa. For reasons which will be discussed later, each consolidation step except number 7 (maximum σ'_{ac}) was only maintained for a few hours.

Two constant rate of strain consolidation or oedometer tests (CRSC tests) were also performed in this series. The consolidation procedure is listed below. The numbers in parentheses are for test CRSC 2 (the others are for CRSC 1).

- Load up to 32.4 (32.4) kPa in 7 (4) min.
- Maintain 32.4 (32.4) kPa for 1125 (1176) min.
- Load up to 403.9 (403.3) kPa in 1060 (1075) min.
- Maintain load for 720 (720) min.
- Unload down to 99.8 (98.6) kPa in 96 (96) min.

6 METHOD USED IN COMPARING G_{max}

Figure 3 shows typical trends for G_{max} develop-

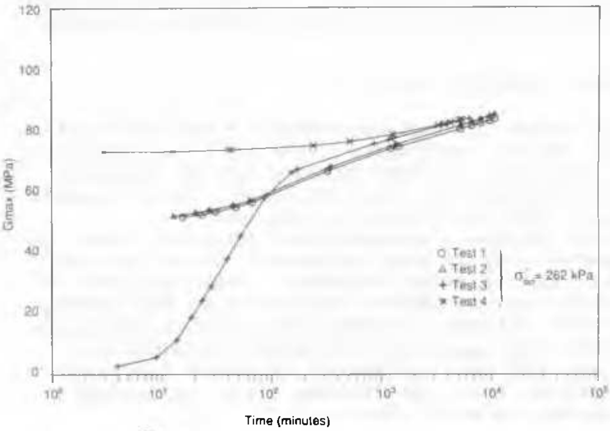

Figure 3. G_{max} versus log time for large (Test 3), medium (Test 1 and 2) and small (Test 4) consolidation increments to the same stress.

ment versus log time during consolidation of four resonant column tests on Drammen clay specimens. All curves are for the same effective stresses at the end of primary consolidation (σ'_{oct} = 262 kPa). Tests 1 and 2 were identical and had two previous (lower) consolidation increments. Test 4 had four previous increments and Test 3 none (σ'_{oct} = 262 kPa in one step). The last portions of the curves are similar and increase fairly linearly with log time. In other words, during primary consolidation the G_{max} development is primarily dependent on the changing effective stress (increasing or decreasing), and during secondary consolidation the development is independent of consolidation increment step size and is always increasing (although at a lesser rate for overconsolidated clays).

The triaxial, oedometer and direct simple shear devices all have specimens of different heights and therefore different primary consolidation times. It would therefore seem logical to compare G_{max} at the end of primary consolidation for each of the different types of tests. The coefficient of consolidation, C_v, for clay varies with overconsolidation ratio and with confining stress in the normally consolidated range. For simplicity, the following approximate values are used for Drammen clay in this study:

Overconsolidated (up to p'_c and unloading):

$$C_v = 15 \text{ m}^2/\text{year} \cong 0.3 \text{ cm}^2/\text{min}$$

Normally consolidated (after p'_c to before unloading):

$$C_v = 5 \text{ m}^2/\text{year} \cong 0.1 \text{ cm}^2/\text{min}$$

The following equation can be used to approximate the primary consolidation times, t_p, for each of the types of tests:

$$t_p = \frac{h^2\, T}{C_v} \tag{1}$$

where h = drainage distance
T = dimensionless time factor

If one assumes T = 1.0 (degree of consolidation, U, ≅ 92%), the approximate primary consolidation times will be as shown in Table 3 (note that h for each is approximately one-half the specimen heights because of double drainage).

Table 3. Approximate primary consolidation times (t_p) for normally- and overconsolidated Drammen clay in the oedometer, direct simple shear and triaxial devices

Drammen clay	C_v	Oedometer	DSS	Triaxial
	(cm²/min)	t_p(min)	t_p(min)	t_p(min)
Normally consolidated	0.1	10	6	300
Overconsolidated	0.3	3	2	100

Figure 4 shows typical curves of G_{max} versus log time for a selected consolidation increment in Series 1. Also shown in this figure is the method for selecting G_{max} at the end of primary consolidation for each of the tests.

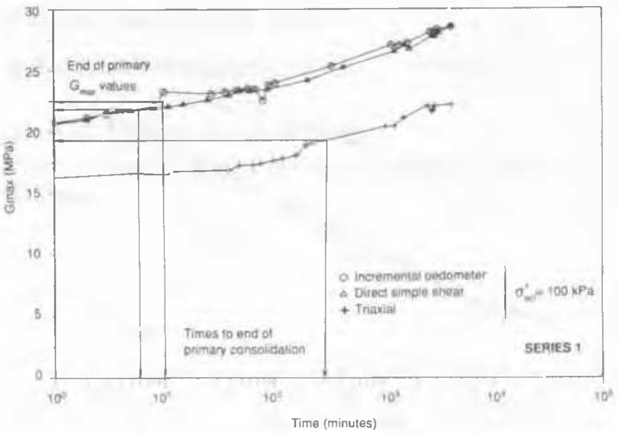

Figure 4. G_{max} versus log time for the tests in Series 1 (σ'_{ac} = 100 kPa).

Another reason for basing the comparison of G_{max} measured in the various tests to those at the end of primary consolidation, is to include the CRSC results. The CRSC oedometer tests are continuously loaded at a rate such that the specimen is always at or very near the end of primary consolidation, and the G_{max} results can therefore be compared directly.

7 RESULTS

The results of Series 1 and Series 2 are presented in Figs 5 and 6, respectively. G_{max} at the end of primary consolidation is plotted versus σ'_{ac} in each consolidation increment. The maximum stress (σ'_{ac} = 392 kPa in Fig. 5 and 400 kPa in Fig. 6) was maintained for about 5500 min. in Series 1 and about 1000 min. in Series 2. This is seen as the vertical portions of the curves labelled "rest" in the two figures. The lower points are the end of primary values and the highest points correspond to the G_{max} measured just before unloading.

The results of a resonant column test which was not a part of this study are also presented in both Figs 5 and 6. This was a standard ani-

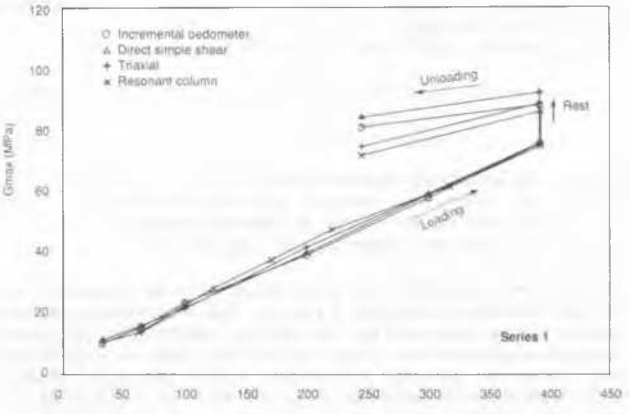

Figure 5. G_{max} at the end of primary consolidation versus consolidation stress for Series 1.

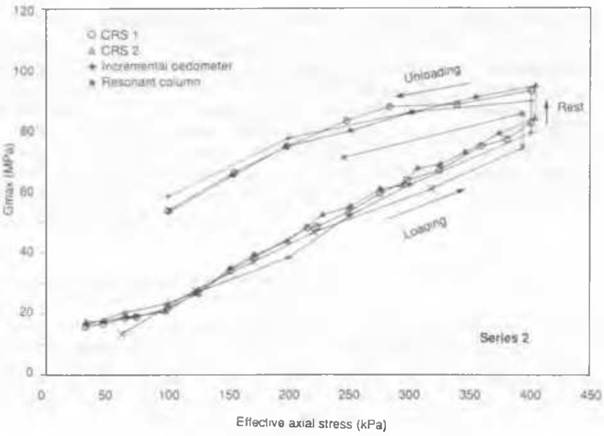

Figure 6. G_{max} at the end of primary consolidation versus consolidation stress for Series 2.

sotropically consolidated resonant column test on Drammen clay for a depth similar to those of Series 1 and 2 (6.28 m).

8 DISCUSSION

Figures 5 and 6 show the end of primary consolidation G_{max} values for all the tests in Series 1 and 2. The incremental oedometer, CRSC, DSS triaxial and earlier resonant column results agree very well with eachother in the loading portion (for comparison, use the earlier resonant column curve which is the same in both figures). The "rest" (vertical) portions of the curves at maximum stress is the stiffness increase which occurred while the maximum load was maintained after end of primary consolidation (t_p). The reason for the slightly different stiffness increase in each of the tests during this rest period could be differences in the specimens and/or different durations (time from t_p to the end of the increment). Although the maximum increments in the different tests were maintained for similar lengths of time, the tests with shorter primary consolidation times would have longer times for secondary compression. The unloading curves are similar in shape but some do not coincide with the others. The difference between these unloading curves seems largely controlled by the differences in the amount of stiffness developed at maximum stress.

The method used for calculating G_{max} is:

$$v_s = \ell/t \qquad (2)$$

$$G_{max} = v_s^2 \rho \qquad (3)$$

where v_s = shear wave velocity
ℓ = travel length of shear waves
t = travel time of shear waves
ρ = mass density of the soil

The travel length has previously been assumed to be the bender element tip to tip distance within the soil specimen for triaxial tests (total specimen height minus protrusion of the transmitter and receiver bender elements into the specimen). This assumption was also used for the oedometer and DSS tests presented herein. If one instead were to assume a travel length including part of the bender element protrusion or, in the extreme case, the total height of the specimen, the G_{max} results for a triaxial test would be relatively unchanged as the specimen height is much greater than the bender element protrusion. This would not be the case for the oedometer and DSS results, however, as the bender element protrusion is a significant percentage of the total specimen height. As an example of this, the initial specimen height in the DSS test in Series 1 was 15.98 mm and the total protrusion of the two bender elements was 3.5 mm. If, instead of using the bender element tip to tip distance, the total specimen height is used, the shear wave travel length and shear wave velocity would be 28% greater (Equation 2). This would result in a 64% increase in G_{max} (Equation 3). This would have completely changed the picture in Figs 5 and 6 as the short oedometer and DSS specimens were even shorter in the later consolidation stages (bender element protrusion always constant) and the bender element G_{max} results would have devated very significantly from the resonant column results. It therefore seems reasonable that assuming the travel length to be the bender element tip to tip distance, as was done for these results, is correct.

Compared with the triaxial measurements, the short oedometer and direct simple shear specimens have relatively short shear wave travel times (typically tens versus hundreds of microseconds) and relatively large signal amplitudes registered by the receiver bender element (typically tens versus a few millivolts). This was the reason for using two oscilloscopes in that the Nicolet 4094 has a better amplitude resolution and the Nicolet 4094A has a faster sampling rate. The sampling rate resolution for the shear wave travel times was better than 0.5% for all the tests.

9 CONCLUSIONS

The two tests series showed that G_{max} can easily and accurately be determined in the oedometer and direct simple shear (DSS) devices using piezoceramic bender elements.

In spite of some discrepancies in the results of these test series, it can be concluded that G_{max} measured at the end of primary consolidation in the incremental oedometer, CRSC, or DSS devices is comparable to G_{max} measurements at the end of primary consolidation in a triaxial test with bender elements or a resonant column test.

Based on the results of these tests, it seems correct to use the bender element tip to tip distance in the computation of the shear wave velocity in all of these test devices.

REFERENCES

Dyvik, R. and C. Madshus (1985). Lab measurements of G_{max} using bender elements. Proceedings of ASCE Annual convention. "Advances in the Art of Testing Soils under Cyclic Conditions", Detroit, Michigan, October 1985.