Pressuremeter, Penetrometer and Oedometer Tests

Pressiomètre, Pénétromètre et Essais d'Oedomètre

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SYNOPSIS. Comprehensive field tests made it possible to set up empirical relationships between the blow count of the standard penetration test (SPT), the light (LDP) and heavy dynamic probing (HDP), the cone resistance of the static penetration test and the modulus of deformation taken from the pressuremeter according to Menard and Leischner for various kinds of soil. Besides the direct comparison between the measured values of the penetrometers and the pressuremeters, multiple regression functions have been examined with the overburden pressure as a further coefficient which gave, in most of the cases, a higher correlation coefficient than in a linear form.
The moduli of deformation which have been obtained in situ for both pressuremeters were compared with the moduli of compressibility obtained from oedometer tests. The former are a function of stress; therefore the moduli of compressibility were determined for the same stress ratio and permit a comparison of the moduli.

INTRODUCTION

In the last 10 years working with the pressuremeter has got a world-wide spreading to get the deformation of the soil by in situ field testing. To prove the exactness of the results obtained from the pressuremeter there exist only small efforts. An acceptable way to get to sufficient declarations is to compare the results of the pressuremeter with different types of penetrometers in the field and with the common laboratory tests. For this purpose a comprehensive research work has been done with two types of pressuremeters, the pressuremeter according to Menard and the pressuremeter according to Leischner which is a development of the former instrument of Kögler.
Till now there exist some relationships between the different penetrometers and the pressuremeters, but only based on a very small number of data and valid for some special types of soil. Especially between the moduli of deformation obtained from pressuremeter tests and the moduli of compressibility obtained from the oedometer tests no guaranteed relationships exist up to now.

FIELD TESTING EQUIPMENT

Pressuremeters

The pressuremeter tests were performed with two different types. First of all the pressuremeter PM according to Menard (1961) was used with an apparatus of a diameter of 44 mm and a length of 59 cm for the measure cell and the two guarding cells.
The work was done with a rubber and also with a metal plate sleeve.
Furthermore tests using the pressuremeter PL according to Leischner (1966) have been performed.

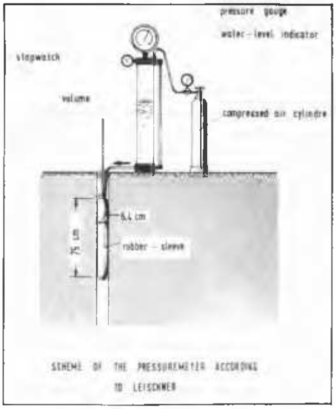

Fig. 1: Scheme of the pressuremeter according to Leischner

This pressuremeter has been developed from the pressuremeter according to Kögler (1933) The pressure cell that has been used has a diameter of 64 mm and a length of 75 cm. There exist also pressure cells with a different length from 50 cm to 100 cm. The main part is the cylindrical rubber sleeve with a thickness of 5 mm which has a thread lengthwise enclosed to guarantee the important conditions of lying close to the sides

of the bore- or sounding hole and having a true radial cylindrical extension. In difference to the pressuremeter according to Menard there are no guarding cells above and below the measuring cell at the Leischner apparatus. The whole rubber cell is a measure cell.
The two pressuremeters were not brought into the soil by sampling. They got a cone at the top of the pressuremeter with a diameter which was a little greater than the diameter of the pressuremeter, to avoid great disturbance at the sleeve. Then the apparatus was brought into the soil with pressure like a static penetrometer to the corresponding depth to make a pressuremeter test there.

Penetrometers

To compare the values of the pressuremeter tests with those of the penetrometers, a great number of tests with different dynamic (HDP, LDP, SPT) and static penetrometers (SBP) have been performed during a research work. Table I shows the dimensions of the different dynamic penetration tests according to the German Standard DIN 4094, Bl. 1 (1974).

Table I. Different types of dynamic sounding apparatus

no	type of dynamic sounding apparatus	symbol	diameter of the point	area of the point	mass of the hammer	height of fall	penetration depth	number of blows
			d	F	Q	h	t'	$N_{t'}$
			mm	cm	kg	cm	cm	1
1	heavy dynamic probing	HDP	43.7	15	50	50	20	N_{20}
2	light dynamic probing	LDP	35.6	10	10	50	20	N'_{20}
			25.2	5			10	N'_{10}
3	standard penetration test	SPT	50.8	20.3	63.5	76.2	30	N_{30}

As for LDP there are values with two different areas F of the point, with F =10 cm^2 and F = 5 cm^2 it is necessary for the use of these results in a comparison to transform the number of blows for the LDP with a point of F = 5 cm^2 into those with a point of F = 10 cm^2 , using the following working equation:

$$A = \frac{Q \cdot h \cdot N}{t' \cdot F} \qquad (1)$$

with

N = number of blows for the penetration depth t'.

For the static penetration SBP test the Begemann point with an area of F = 10 cm^2 has been used in order to get the cone resistance σ_S kp/cm^2 and skin friction separately.

ANALYSIS

The modulus of deformation E_p according to Menard has been determined from the stress-strain-curve according to Menard's (1961) formula

$$E_p = 2\,(1+\mu)\,(V_o+V_m)\,\frac{dp}{dV} \quad \ldots \ldots \quad (2)$$

with

μ = Poisson's ratio = 0.33
V_o = Volume at rest = 535 cm^3
V_m = induced volume
dp = difference of pressure } of the straight part of curve
dV = mean difference of volume } of the straight part of curve

The modulus of deformation E_L according to Leischner has also been determined from the stress-strain-curve according to Kogler's formula (1933).

$$E_L = \frac{\Delta p \cdot r}{\Delta r}\;\frac{H}{H-2r\cdot\tan\alpha}\;\ln\frac{H}{2r\cdot\tan\alpha} \quad \ldots \ldots \quad (3)$$

with

H = height of the pressuremeter
α = 45°
r = radius
Δr = difference of radius } of the straight part of curve
Δp = difference of pressure } of the straight part of curve

Leischner (1966) has improved this formula and has found that better results will be obtained, if the angle of internal friction φ of the soil instead of α is used.

COMPARISON BETWEEN THE PRESSUREMETER ACCORDING TO MENARD AND DIFFERENT TYPES OF PENETROMETERS

In order to get a broad base of the results from the pressuremeters and the dynamic and static penetrometers, results of different types of soils from France, Belgium and West Germany have been collected together with those of the research work tests, which have been performed in Rhineland silt. Furthermore, comparable values from literature have been added. This made it possible to obtain the great number of values written in Tab. II.

Table II. Relationship between modulus of deformation E_P according to Menard and different types of penetrometers

general equation: $y = a \cdot x_1 + b \cdot x_2 + K$

no.		y	x_1	x_2	a	b	K	r	n
1	HDP	$\log \frac{E_P}{p_a}$	$\log N_{20}$	$\log \frac{\sigma_{vo}}{p_a}$	0.87617	0.08048	1.03806	0.7462	468
2	LDP	$\log \frac{E_P}{p_a}$	N_{20}	$\frac{\sigma_{vo}}{p_a}$	0.00500	0.20386	1.69730	0.8165	125
3	SBP	$\log \frac{E_P}{p_a}$	$\log \frac{\sigma_s}{p_a}$	$\log \frac{\sigma_{vo}}{p_a}$	0.48147	0.59388	1.18272	0.7326	563

E_p = modulus of deformation according to Menard

σ_{vo} = overburden pressure

p_a = atmospheric pressure = 1 kp/cm^2

r = correlation coefficient

n = number of tests

Fig. 2 shows the result of a correlation between the modulus of deformation according to Menard E_P and the blow count of the standard penetration test N_{30}. The places of investigation, the literature and the types of soil are declared. A linear regression of all the values has been made, with a correlation coefficient of r=0.8045. The multiple regression with the overburden pressure σ_{vo} as a second parameter brought the following empirical equation

$$E_p/p_a = 6.12 \cdot N_{30} - 24.61 \cdot \sigma_{vo}/p_a + 39.07 \qquad (4)$$

with a correlation coefficient of r=0.8081. It is obvious that the overburden pressure has no influence in the relationship between E_P and N_{30}.
Nevertheless it can be seen that some of the values scatter widely, which seems to be due to the corresponding type of soil. Till now the only relationship between E_P and N_{30} which can be found in the literature is stated by Cassan (1969) as follows

$$E_p = 1.67 \cdot N_{30} \; .. \; .. \; .. \; .. \; .. \qquad (5)$$

This relationship is based on 7 values for a sand from "Barcarès" and is also valid for 8 values for a sand of "Dunkerque". No correlation coefficient and no range of scatter can be seen by Cassan. The values of Cassan were not brought into the correlation of Fig. 2, because they didn't fit in this relationship, and there are no further informations why they depart from the values in Fig. 2 in such a manner, but the small number of values could be an uncertainty in the equation of Cassan.

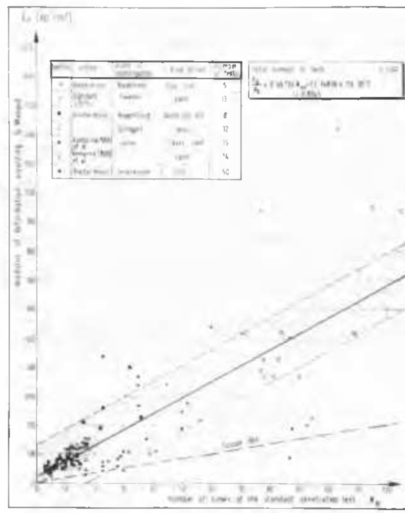

Fig. 2. Relationship between E_P and number of blows N_{30} of SPT

The relationships between the other dynamic and static penetrometers and E_P are shown in Table II. There are described these empirical functions between the three parameters E_P, N_t', resp. σ_s and σ_{vo} which gave the highest correlation coefficient r. This is the reason why in this table there are different types of functions between the parameters and it was not possible to find one type of function to be valid for all the relationships. The relationship between E_P and HDP from 468 original values for sand and silt showed a correlation coefficient of r = 0.7165 for the direct connection of the two parameters E_P and N_{30}. With the overburden pressure σ_{vo} as an additional coefficient a correlation coefficient of r = 0.7462 was reached in the regres-

sion (Tab. II, No. 1).
The direct connection between the modulus of deformation according to Menard E_P and the number of blows of the light dynamic probing (LDP) N'_{20} is shown in the following empirical equation

$$E_p/p_a = 1{,}86 \cdot N'_{20} + 8.03 \quad \ldots \ldots \ldots \ldots \quad (6)$$

with a correlation coefficient of $r = 0.7216$. With the overburden pressure σ_{vo} as a second parameter a correlation coefficient of $r = 0.8165$ was computed (Tab. II, No. 2). The 125 values are valid for sand and silt.
The relationship between E_P and the cone resistance σ_s of the static penetrometer was computed for 563 values for the different kinds of soil, for clay, silt and sand. The direct connection between E_P and σ_s is shown in the following equation

$$\log E_p/p_a = 0.68 \ \log \frac{\sigma_s}{p_a} + 0.88 \quad \ldots \ldots \quad (7)$$

with a correlation coefficient of $r = 0.6445$. When introducing the overburden pressure σ_{vo} as a second coefficient, the correlation coefficient increases to $r = 0.7326$ (Tab. II, No. 3). The influence of σ_{vo} when using the static penetrometer is obvious.
For the great number of tests and for the different kinds of soil the result of the empirical equation (Tab. II, No. 3) shows an acceptable relationship.

COMPARISON BETWEEN THE PRESSUREMETER ACCORDING TO LEISCHNER AND THE OTHER PENETROMETERS

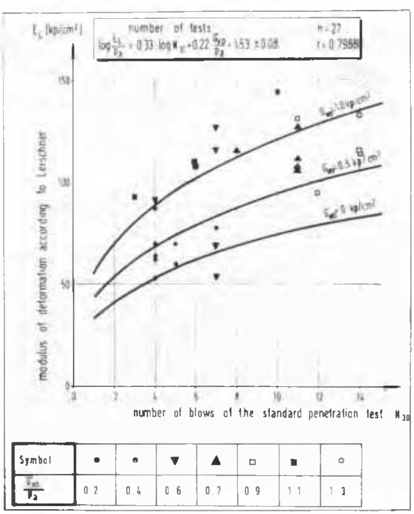

Fig. 3: Relationship between E_L and N_{30}

The comparison between the modulus of deformation according to Leischner E_L and the different types of penetrometers could only be done for Rhineland silt, as there are no other values obtainable besides those of this research work. This explains the lower number of data compared to those of the PM pressuremeter. For the determination of E_L according to equ. (3) an angle of internal friction $\varphi = 30°$, obtained from triaxial compression tests, has been used. The result between E_L and N_{30} of SPT is shown in Fig. 3. It is obvious that in this case the overburden pressure σ_{vo} has a great influence in the multple regression. The direct regression between E_L and N_{30} yielded a correlation coefficient $r = 0.6617$ which increased with the coefficient σ_{vo} to $r = 0.7988$.

Table III. Relationship between E_L and penetrometers

general equation: $y = a\,x_1 + b\,x_2 + K$

no		y	x_1	x_2	a	b	K	r	n
1	HDP	$\log \frac{E_L}{p_a}$	$\log N_{20}$	$\log \frac{\sigma_{vo}}{p_a}$	0 51304	0 32063	1.59570	0 8180	28
2	LDP	$\frac{E_L}{p_a}$	N'_{20}	$\frac{\sigma_{vo}}{p_a}$	2 01716	40 75395	1716314	0 9027	20
3	SBP	$\log \frac{E_L}{p_a}$	$\log \frac{\sigma_s}{p_a}$	$\log \frac{\sigma_{vo}}{p_a}$	0 68060	0.04001	0.90179	0 8623	21

E_L = modulus of deformation according to Leischner
σ_{vo} = overburden pressure
p_a = atmospheric pressure = 1 kp/cm²
r = correlation coefficient
n = number of tests

During the correlation between E_L and N_{20} of the HDP the correlation coefficient r increased from $r = 0.6058$ to $r = 0.8180$ with the overburden pressure σ_{vo} as a second parameter (Tab. III, No. 1). In this case σ_{vo} has also a great influence. The relationship between E_L and N'_{20} of the LDP brought the following equation

$$E_L/p_a = 3.03 \cdot N'_{20} + 16.32 \quad \ldots \ldots \ldots \quad (8)$$

with $r = 0.8569$. In the multiple regression a correlation coefficient of $r = 0.9027$ (ab. III, No. 2) was calculated. σ_{vo} has therefore less influence in this correlation than with HDP.
The comparison between E_L and the point of resistance σ_s of the static penetrometer-test (SBP) only gave an increase from $r = 0.8343$ to $r = 0.8623$ with σ_{vo} as a second parameter.

In this case (Tab. III) there were also preferred the best correlations with the highest correlation coefficients for the relationships between E_L and the different penetrometers. That is why different empirical functions are placed in Table III.

COMPARISON BETWEEN THE DIFFERENT MODULI OF DEFORMATION

Besides this the modulus of compressibility, obtained from the oedometer, has been compared with the moduli of deformation, obtained from the different pressuremeters.

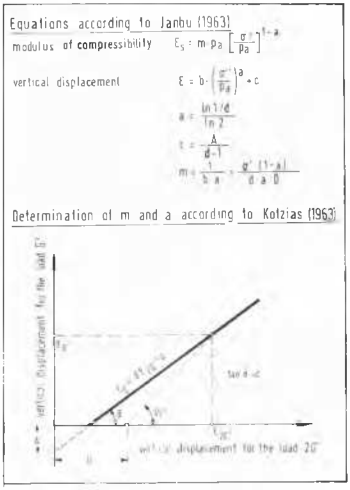

Fig. 4. Determination of the compression indices m and a according to Kotzias (1963)

The modulus of compressibility E_s was evaluated from the equation according to Janbu (1963)

$$E_s = m\, p_a \left(\frac{\sigma}{p_a}\right)^{1-a} \quad \text{.. .. ..} \qquad (9)$$

which can be seen in Fig. 4. The compression indices m and a have been determined according to the method of Kotzias (1963) which is also shown in Fig. 4. To compare the different moduli in the right manner, it is necessary to use the same range of stresses in equation (9) which has been obtained as a difference of stress from the elastic part of the stress-volume-curve of the pressuremeter. Using this way, the moduli are comparable, because they have the same state of stress.
The results of these relationships are shown in Tab. IV. It can be seen, that the comparison between E_s and E_p only a correlation coefficient of r = 0.56 (Tab. IV, No. 1) has been achieved.

Table IV. Relationship between E_s, E_p and E_L

general equation: $y = a\,x + K$

no.	y	x	a	K	r	n
1	E_s	E_p	1.38	18.31	0.56	36
2	E_s	E_L	1.68	-26.62	0.90	15
3	E_L	E_p	0.99	31.88	0.87	24

E_s = modulus of compressibility
E_p = modulus of deformation according to Menard
E_L = modulus of deformation according to Leischner
r = correlation coefficient
n = number of tests

And it is also obvious that E_s is always greater than E_L . The reason is probably that E_s is based on a vertical compression with entire lateral confinement instead of a horizontal compression for E_p and E_L .
A good relationship has been evaluated between E_s and E_L with a correlation coefficient of r = 0.90. E_s is in this case also greater than E_L . The relationship between E_L and E_p shows that E_L is also greater than E_p . The reason for this is probably that the rubber sleeve of the pressuremeter according to Leischner has a greater length than the pressuremeter according to Menard.

CONCLUSIONS

It is obvious that the empirical relationships between the results of the dynamic and static penetrometer tests and the values E_p from the pressuremeter according to Menard fit in a good manner. It can also be seen that the multiple regressions with the overburden pressure gave a higher correlation coefficient than the linear regression. Only the relationship between the number of blows of the SPT and E_p showed that in this case the overburden pressure had no influence on the correlation coefficient. It is also remarkable that these empirical relationships are valid for several kinds of soil and for a very great number of tests.
The relationships that were found between the results of the static and dynamic penetration tests and the modulus of deformation E_L according to Leischner lead in general to very high correlation coefficients especially with the overburden pressure as a second parameter. But in this case there has to be noticed that these relationships are only valid for the Rhineland silt.

The relationship between the modulus of compressibility E_s and the modulus of deformation E_p don't fit very well. One of the reasons is that the compression direction of the oedometer is vertical instead of the horizontal direction in the pressuremeter test. Therefore horizontal pressuremeter tests with vertical pressure have been made during this research work together with horizontal static penetrometer tests to compare them. In order to compare the pressuremeter tests in horizontal and vertical direction with the oedometer tests, tests in the laboratory have also been performed with samples which were turned around 90° and loaded in the common way.

All these and further results will be published in 1977, when the whole research work will be submitted (see also the references).

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