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RESEARCH ARTICLE

Estimation and Separation of Preconsolidation Stress Using Triaxial,- and Oedometer Test in Kiscelli Clay

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Abstract

The study is about the estimation of preconsolidation stress using a correlation method. Disturbance of soil samples can result in the yield point of void ratio-log vertical stress data from oedometer test being unreadable. Therefore, correlations were calculated to estimate preconsolidation stress using effective vertical stress (σ'_{v0}), oedometer modulus (E_{oed}) from oedometer tests and unloading-reloading modulus (E_{ur}) from triaxial tests. Profile of stress history: Overconsolidation ratio (OCR), overconsolidation difference (OCD) and overconsolidation gradient (OCG) were determined in Kiscelli Clay based on new equations. An additional new parameter, ratio of mechanical preloading component of overconsolidation is defined and analysed.

Keywords

Overconsolidated clay · Kiscelli Clay · preconsolidation stress · overconsolidation difference · overconsolidation gradient · overconsolidation ratio

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1 Introduction

Stress history, the overconsolidation of soil is classically determined using oedometer tests of undisturbed samples. The yield point denotes the preconsolidation stress (σ'_p). Determination of σ'_p from void ratio (e) - log σ relationship is presented in Fig. 1, where σ is the loading stress.

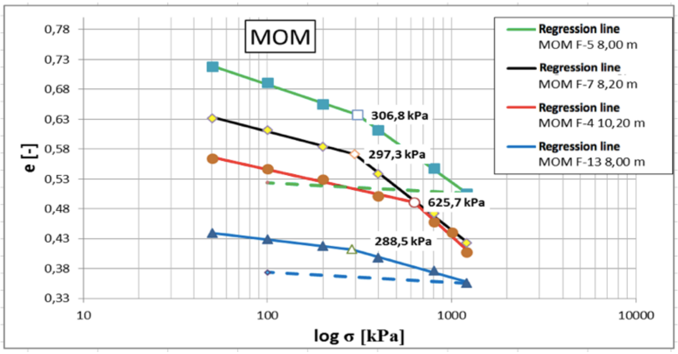

Fig. 1. Determination of Preconsolidation stress using own intersection method, Kicelli Clay, 12th District of Budapest, MOM Park

The overconsolidation difference (*OCD*) or pre-overburden pressure (in Plaxis: *POP*) is termed and suggested by Olsen et al. [1], as in

$$OCD = \sigma'_p - \sigma'_{v0} \tag{1}$$

In normalized form, the degree of preconsolidation is termed overconsolidation ratio (*OCR*), as in

$$OCR = \frac{\sigma'_p}{\sigma'_{v0}} \tag{2}$$

where σ'_{v0} is the effective vertical geostatic stress and the overconsolidation gradient (*OCG*) is defined by [2], as in

$$OCG = \frac{\Delta\sigma'_p}{\Delta\sigma'_{v0}} \ . \tag{3}$$

The preconsolidation stress can be determined based on cone penetration test (CPT) results (cone resistance), but harder soil strata cannot be penetrated (e.g. intact Kiscelli Clay) [3], CPT is more applicable to calculate pile bearing capacity with additional in-situ test (e.g. dynamic probing) [4]. In this study, the profiles of the stress history were analysed by triaxial and oedometer test results.

2 Laboratory tests

Oedometer,- and triaxial tests were investigated mainly of the oligocene clay (Kiscelli Clay) from the Buda area by the Laboratory of Department of Geotechnics (BUTE) related to Metro Line 4 in Budapest. Additional data of Tardi Clay from the Danube area and additional data (Fig. 1) of Kiscelli Clay from the 12 th District of Budapest (MOM Park) were presented and used for better correlations. Results, e.g. void ratio,- moisture content,- shear strength,- major stress at failure,- oedometer,- unloading-reloading modulus,- overconsolidation ratio as functions of depth were already analysed previously [3–6].

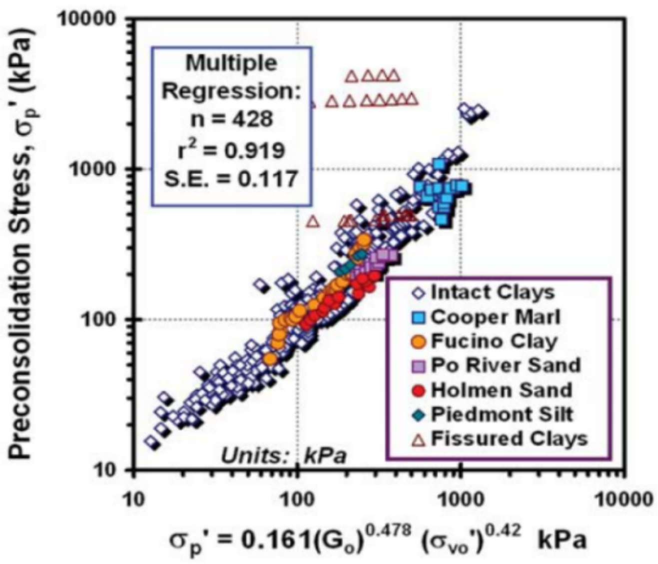

Fig. 2. Preconsolidation stress evaluation from small-strain shear modulus in soils., after Mayne, 2007

The fundamental idea for the present article was provided by the research result associated with Fig. 2, where preconsolidation stress evaluation from small-strain shear modulus was analysed by [7]. The overall relationship is shown in Fig. 2 and expressed as

$$\sigma'_p = 0.161 \cdot G_0^{0.478} \cdot \sigma'^{0.42}_{v0} \tag{4}$$

with a statistical coefficient of determination $R^2 = 0.919$ for intact soils.

In the present instance, small-strain shear modulus data were not available, so other moduli was used to study similar relationships.

Now, correlations were calculated to estimate σ'_p from effective vertical stress (σ'_{v0}), oedometer modulus (E_{oed}) and unloading-reloading modulus (E_{ur}). Oedometer modulus was obtained at various stress level based on stress history, disturbance and characteristics of soil sample. Only a small number of the laboratory tests could be used to study the correlation equations, where σ'_p was clearly readable, and acceptable to analyse

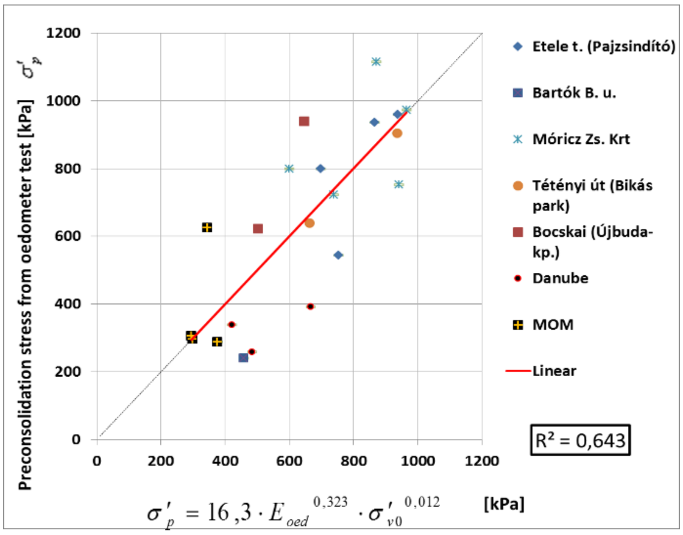

Fig. 3. Preconsolidation stress evaluation from oedometer modulus and effective vertical geostatic stress

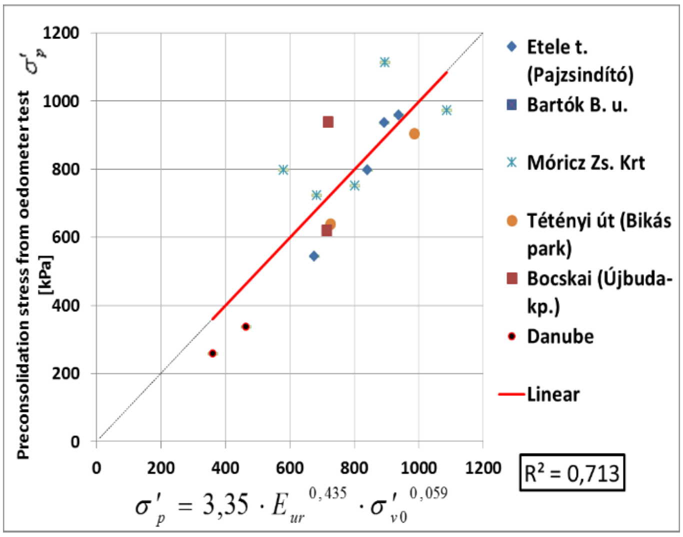

Fig. 4. Preconsolidation stress evaluation from unloading-reloading modulus (triaxial test) and effective vertical geostatic stress

the connection to the previously mentioned soil parameters. The results of the evaluation are expressed in Eq. (5); and Eq. (6):

$$\sigma'_p = 16.3 \cdot E_{oed}^{0.323} \cdot \sigma'^{0.012}_{v0} \tag{5}$$

$$\sigma'_p = 3.35 \cdot E_{ur}^{0.435} \cdot \sigma'^{0.059}_{v0} \tag{6}$$

with a statistical coefficient of determination $R^2 = 0.643$ (Fig. 3) and $R^2 = 0.713$ (Fig. 4) respectively. Regression line was determined using Excel Solver, with interception set to zero. Those two moduli were selected because they could be in some sort of relationship with preloading/stress history, their values increase with depth, as the preloading of Kiscelli Clay is easier to detect with depth, the material's "memory" increases with depth.

The secant modulus at 50% strength (E_{50}) was also determined from the triaxial tests, but that is of less utility, because it is shown in Fig. 5, that the ratio of E_{ur} and E_{50} is around 1

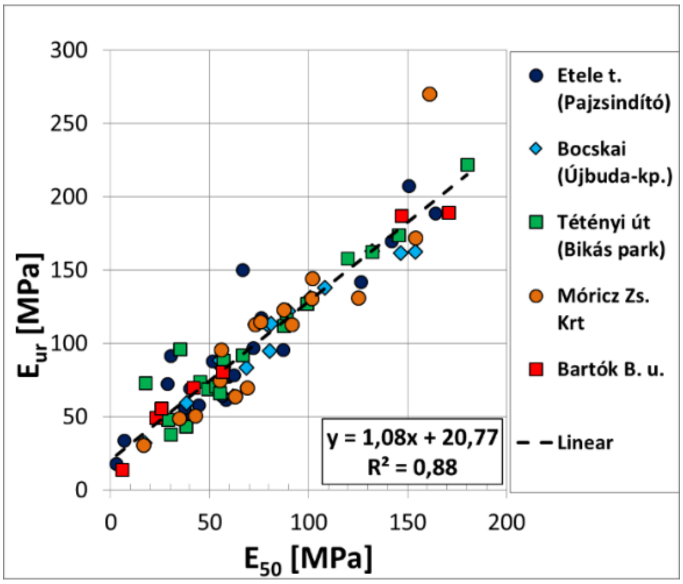

Fig. 5. Correlation between E_{ur} and E_{50} in Kiscelli Clay

rather than the factor of 2 – 3 expected. The phenomenon may be related to the overconsolidation. Correlation between E_{ur} and E_{50} in Kiscelli Clay related to the Metro Line 4 stations area is given in Eq. (7):

$$E_{ur} = 1.08 \cdot E_{50} + 20.77 \quad . \tag{7}$$

Although for the purposes of the calculations, weathered, fissured and intact rock mass zones of Kiscelli Clay were not separated, those categories do appear in the values of the soil parameters (moduli).

3 Stress history analysis

Depending on the conditions (e.g. quality of drilling, soil sampling method, the time lapsing between the taking and the testing of samples, tectonic effects, temperature, etc.) preconsolidation stress can be recognized, especially for clays. Identification of the causes of overconsolidation can be difficult, because natural soils have been formed by geological, environmental and chemical effects. However, the profiles of stress history caused by different mechanisms can be categorised as follows, based on [8]:

1 Normally consolidated (NC) deposits

2 Groundwater fluctuation

3 Aged NC deposits

4 NC deposits with crustal layer

5 Overconsolidated deposits preloaded by mechanical means (erosion, glacial action, or excavation)

6 Overconsolidated deposits caused by desiccation

7 Overconsolidated deposits caused by cementation

In this study, the profiles of the stress history were separated into two simplified main categories (groups of above mentioned

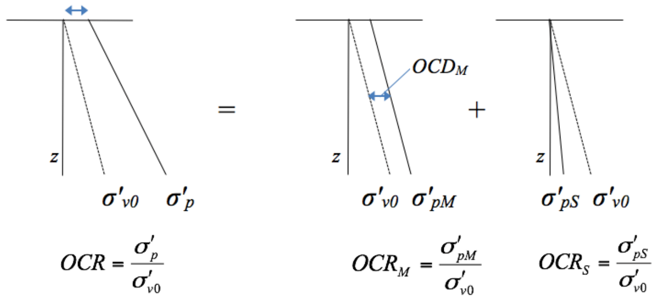

Fig. 6. Definition of simplified categorisation (separation) of *OCR* by mechanically preloading and secondary effects

stress history profiles based on the calculation results, Fig. 11 - 22, as shown in Fig. 6:

- Overconsolidation caused by mechanical preloading using subscript M, where OCD_M is constant, and $OCG = 1$. The estimated preconsolidation stress line (PSL) is parallel to the effective vertical stress.
- Overconsolidation caused by non-mechanical preloading (e.g. aging, cementation, water table changing, crusted layer), where $OCD_M = 0$ kPa and the secondary overconsolidation ratio (OCR_S) caused by secondary effect is constant. PSL starts from zero at ground level.

In this case, where the preconsolidation stress increases linearly with depth, OCG = constant. A new classification method is described in the present paper concerning overconsolidation, defined as follows. New separation method of the overconsolidation ratio is defined in Eq. (8):

$$OCR = OCR_M + OCR_S \, . \tag{8}$$

Refer to Eq. (8) and Fig. 6 the preconsolidation stress can be separated, as in

$$\sigma'_p = \sigma'_{pM} + \sigma'_{pS} \tag{9}$$

where σ'_{pM} and σ'_{pS} are related to preconsolidation stress caused by mechanical preloading and secondary effects.

The ratio of mechanical preloading of overconsolidation was defined and analysed as follows:

$$\Lambda_{MP} = \frac{\sigma'_{pM}}{\sigma'_p} = \frac{OCR_M}{OCR} \, . \tag{10}$$

When Λ_{MP} is 100%, the overconsolidation is purely the result of some sort of mechanical preloading (e.g. erosion, glacial action, or excavation), PSL is parallel to the effective vertical stress, $OCD (= OCD_M)$ has a constant value, and $OCG = 1$. When Λ_{MP} is below 100% and greater than 0%, the remainder was elicited by some form of secondary effect (non-mechanical preloading), OCG remain constant at a value greater than 1, OCD starts from OCD_M and increases linearly with depth. When Λ_{MP} is 0%, the overconsolidation caused by

Tab. 1. Ratio of mechanical preloading of overconsolidation

	Λ_{MP}			
	based on Eq. (5)		based on Eq. (6)	
	min	max	min	max
Etele t. (Pajzsindító)	92%	95%	69%	81%
Tétényi út (Bikás park)	100%*	100%*	70%	85%
Bocskai (Újbuda-kp.)	77%	85%	78%	88%
Móricz Zs. Krt	85%	92%	68%	81%
Bartók B. u.	100%	100%	51%	63%
Danube	93% *	94% *	95% *	96% *

* data are calculated with low R^2, detailed information is presented in Tab. 2 - 3.

Tab. 2. Calculation results of preconsolidation pressure estimation from oedometer modulus, based on Eq. (5)

	OCD_{min}	OCD_{max}	OCR_{min}	OCR_{max}	Slope	OCD_{lin}	R^2	OCG_{lin}	OCD_M min	OCD_M max	H_{min} ero-sion	H_{max} ero-sion
	[kPa]	[kPa]	[-]	[-]	[kPa/m]	[kPa]	[-]	[-]	[kPa]	[kPa]	[m]	[m]
Etele t. (Pajzs-indító)	379.9	570.0	2.2	4.0	12.0	461.7	0.63	1.20	330.4	506.0	17	25
Tétényi út (Bikás park)	290.0	664.8	2.1	4.0	10.0*	484.0*	0.17	1.00*	290.0*	664.8*	14*	33*
Bocskai (Újbu-da-kp.)	342.4	636.2	2.6	3.9	17.1	391.2	0.66	1.71	249.1	498.4	12	25
Móricz Zs. Krt.	435.6	637.2	2.4	4.5	14.0	455.2	0.83	1.40	381.4	518.6	19	26
Bartók B. u.	205.7	256.5	1.5	2.3	10.0	258.0	0.93	1.00	205.7	256.5	10	13
Danube	186.0	581.0	2.0	8.4	10.4*	357.4*	0.37	1.04*	150.9*	548.6*	8 *	27 *

* data are calculated with low R^2

non-mechanical means, both $OCR(= OCR_S)$ and OCG remain constant with depth, and OCD increases linearly with depth.

Results based on the pervious mentioned method are analysed by the listed overconsolidation parameters:

- OCD_{min}: minimum of difference between estimated preconsolidation stress and effective vertical stress,
- OCD_{max}: maximum of difference between estimated preconsolidation stress and effective vertical stress,
- OCR_{min}: minimum of OCR, estimated preconsolidation stress divided by effective vertical stress,
- OCR_{max}: maximum of OCR, estimated preconsolidation stress divided by effective vertical stress,
- Slope: slope of PSL,
- $OCD_{M.lin}$: interception at the horizontal axis (vertical stress) using PSL in the meaning of mechanical preloading,
- R^2: R-squared value of regression line
- Λ_{MP}: ratio of mechanical preloading of overconsolidation using PSL,
- OCG_{lin}: overconsolidation gradient using PSL,
- $OCD_{M.min}$: possible minimum of mechanical preloading based on the maximum negative difference between estimated preconsolidation stress and PSL in the meaning of mechanical preloading,
- $OCD_{M.max}$: possible maximum of mechanical preloading based on the maximum negative difference between estimated preconsolidation stress and PSL in the meaning of mechanical preloading,
- $H_{min.erosion}$: height of minimum erosion, calculated by $OCD_{M.min} / 20\ \text{kN/m}^3$,
- $H_{max.erosion}$: height of maximum erosion, calculated by $OCD_{M.max} / 20\ \text{kN/m}^3$.

It should be noted that in order to simplify, it was assumed that groundwater was at a uniform depth of 3 m. The boundary of mechanical preloading follows the curve of the effective vertical stress chart, so in order to calculate $OCD_{M.min}$ and $OCD_{M.max}$, a decreasing factor was included to account for the effect of average groundwater (GWL), $(\gamma - (\gamma_s - \gamma_w)) \cdot \text{GWL} = (19\ \text{kN/m}^3 - (20\ \text{kN/m}^3 - 10\ \text{kN/m}^3)) \cdot (-3\ \text{m}) = -27\ \text{kPa}$.

An earlier paper [9] has stated that the Kiscelli Clay is preloaded, heavily overconsolidated, but no information was included about the components of overconsolidation.

Using linear trendlines to estimate preconsolidation stress, and the method presented in the present paper, the ratio of different overconsolidation effects (Λ_{MP}) were determined. The possible minimum and maximum values of Λ_{MP} are listed in Table 1 for different locations.

If the value of Λ_{MP} is 100%, the overconsolidation is purely the result of some sort of mechanical preloading (in the present case: erosion), while if the value is below 100%, the remainder

Tab. 3. Calculation results of preconsolidation pressure estimation from unloading-reloading modulus from triaxial test, based on Eq. (6)

	OCD_{min}	OCD_{max}	OCR_{min}	OCR_{max}	Slope	OCD_{lin}	R^2	OCG_{lin}	OCD_M min	OCD_M max	H_{min} erosion	H_{max} erosion
	[kPa]	[kPa]	[-]	[-]	[kPa/m]	[kPa]	[-]	[-]	[kPa]	[kPa]	[m]	[m]
Etele t. (Pajzsindító)	181.6	602.0	2.0	3.8	17.8	248.8	0.70	1.78	83.7	365.8	4	18
Tétényi út (Bikás park)	270.9	716.6	2.1	4.6	19.0	315.9	0.46	1.90	94.0	498.8	5	25
Bocskai (Újbuda-kp.)	279.4	619.0	2.6	4.5	16.6	395.0	0.70	1.66	213.2	480.1	11	24
Móricz Zs. Krt	266.9	759.5	2.1	3.8	18.8	301.7	0.67	1.88	96.4	494.2	5	25
Bartók B. u.	147.9	599.9	2.1	3.1	23.0	130.5	0.88	2.30	0.0	212.3	0	11
Danube	201.9	903.7	2.0	8.0	10.0*	504.5*	-	1.00*	174.9*	876.7*	9*	44*

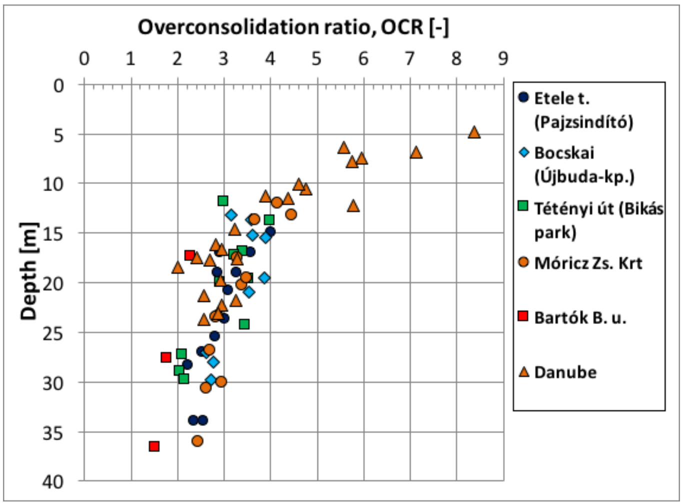

Fig. 7. Estimated overconsolidation ratio based on Eq. (5)

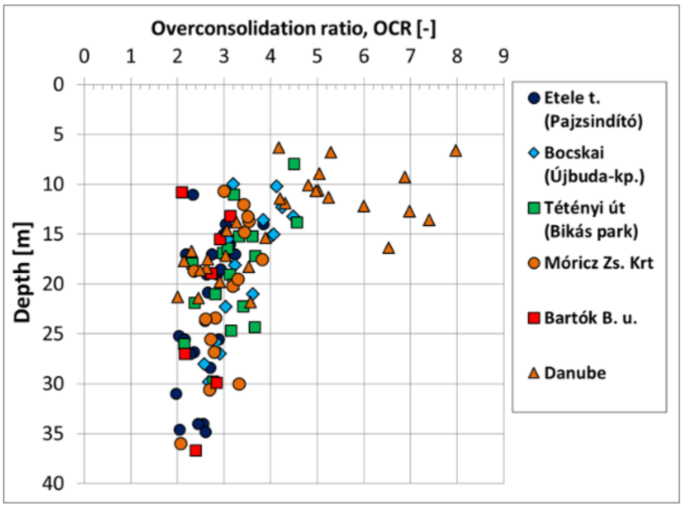

Fig. 8. Estimated overconsolidation ratio based on Eq. (6)

was elicited by some form of secondary effect.

The soil samples from the boreholes in Danube river bed belong to the Tardi Clay formation, the values of E_{ur} and E_{50} move in a large range, presumably due to tectonic effects. The stress history is unclear, correlation factor of trendline is low, but the more frequent data points allow the positions of the approximating trendline to be estimated. At the “Tétényi út” samples, low R^2 value of the trendline can be caused by the low number of the data points and expanded soil samples, but if the results from the other sites are also taken into account, they can still be evaluated. Additional criterion was defined to determine trendline: gradient of line should be minimum 10 kPa/m connecting to the effective vertical stress. Where gradient of trendline is higher, secondary effects of overconsolidation (beside mechanical preloading) must partially account.

Detailed calculation results based on Eq. (5) and Eq. (6) are presented in Table 2, Table 3, Fig. 11-22.

In addition, the estimated overconsolidation ratio is shown in Fig. 7 and Fig. 8 based on Eq. (5) and Eq. (6). On the basis of estimation method, a good approximation can be achieved in determining the *OCR* value (that changes in the function of depth) by using power function (Fig. 7). With the exception of the data from Danube river bed (Tardi Clay, $OCR = 2 - 8.4$), overall the Kiscelli Clay exhibits preloading levels of $OCR = 1.5 - 4.5$. in Fig. 7. In Fig. 8, $OCR = 2 - 4.6$ values are shown for Kiscelli Clay, but for the “Danube samples” (Tardi clay $OCR = 2 - 8$), present values move in a larger range.

Possible minimum and maximum height of erosion is determined from $OCD_{M.min}$ and from $OCD_{M.max}$ based on Eq. (5) and Eq. (6), and shown in Fig. 9 and Fig. 10.

It can be seen in Fig. 9, that the value of potential erosion is somewhat higher than in Fig. 10, i.e. according to the estimated preconsolidation stress and the gradient of trendlines on the basis of different modulus, but there are no significant differences.

4 Conclusions

Correlation between E_{ur} and E_{50} in Kiscelli Clay from the Buda area is determined, the ratio of E_{ur} and E_{50} is around 1, where the phenomenon may be related to the overconsolidation, and to the preloaded soil samples.

Using new approximation methods, the level of preconsolidation stress was determined for the Kiscelli Clay on the basis of oedometer and triaxial tests of soil samples obtained from the station areas along the route of Metro Line 4. Overall, the estimated *OCR* values were between 1.5 and 4.6.

The validity of the possible erosion of overconsolidation will be assessed with some laboratory tests, in-situ tests [9] and findings reported in the literature. Now, effects of overconsolidation were separated. Based on the new method, the definition and the separation of overconsolidation using main categories

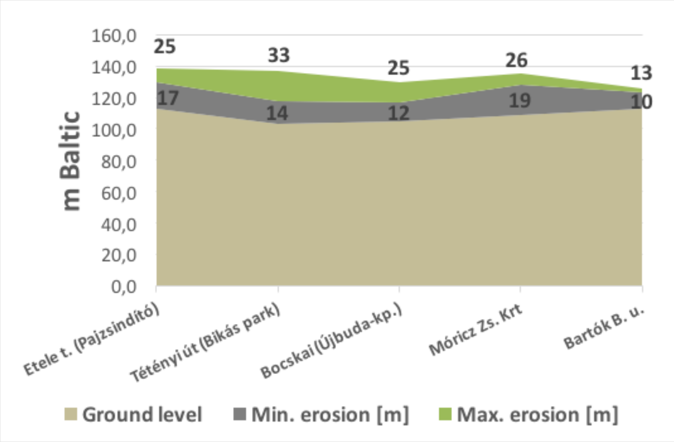

Fig. 9. Estimated erosion based on Eq. (5)

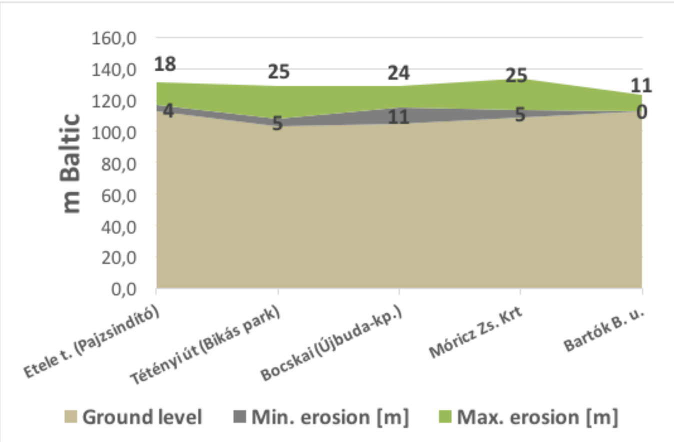

Fig. 10. Estimated erosion based on Eq. (6)

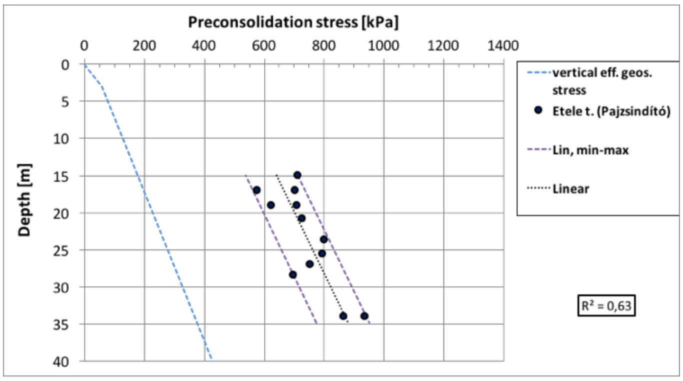

Fig. 11. Estimated preconsolidation stress based on Eq. (5), Etele t.

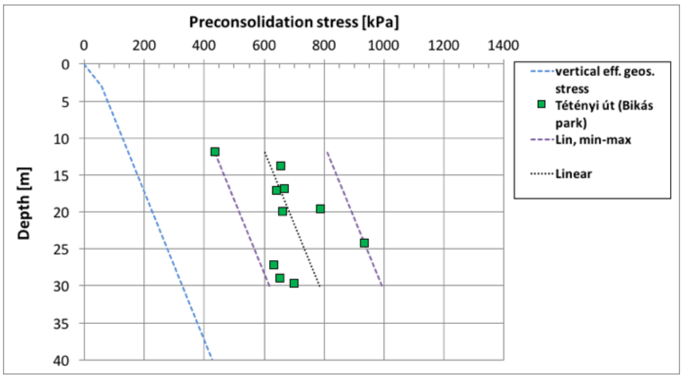

Fig. 12. Estimated preconsolidation stress based on Eq. (5), Tétényi út

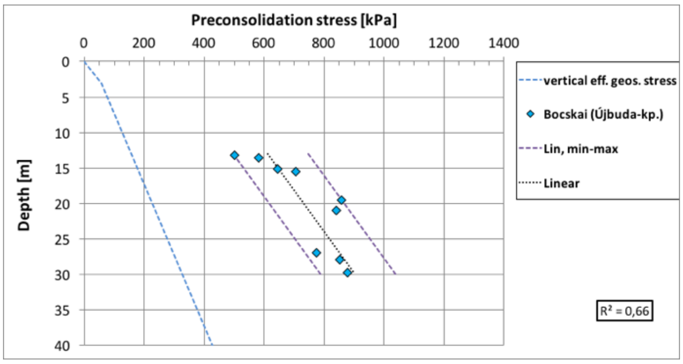

Fig. 13. Estimated preconsolidation stress based on Eq. (5), Bocskai út

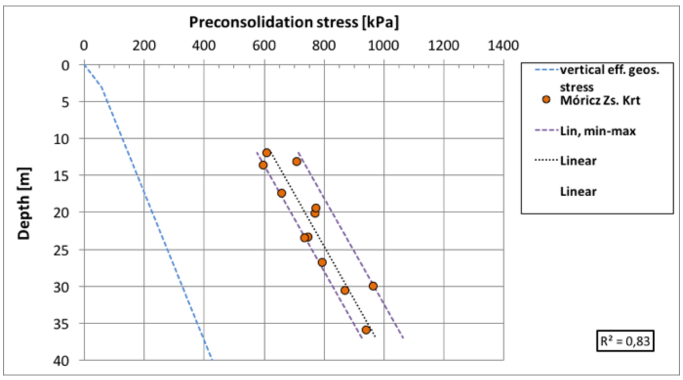

Fig. 14. Estimated preconsolidation stress based on Eq. (5), Móricz Zs. k.

as in [8], the possible causes of overconsolidation in Kiscelli Clay appears to be mainly erosion in the case of mechanical preloading (77 - 100%, 51 - 88% depending on method), while the additional possible causes of overconsolidation appear to be cementation, aging, and/or water table changes.

Based on the soil samples mainly from Kiscelli Clay related to the stations of Metro Line 4 from the Buda area, using the testing methods described above, the maximum and minimum levels of potential erosion, i.e. the possible level of the previous terrain was calculated on the Buda side, from Kelenföld (Etele Square) to Bartók Béla Road. The estimated minimum erosion varied between 0 - 18 m and the maximum erosion varied between 11 - 33 m.

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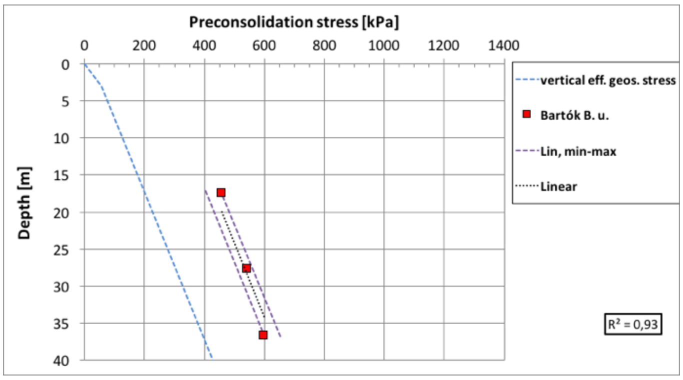

Fig. 15. Estimated preconsolidation stress based on Eq. (5), Bartók B. u.

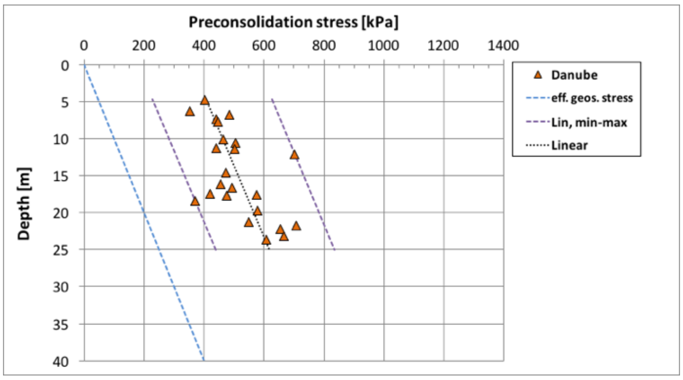

Fig. 16. Estimated preconsolidation stress based on Eq. (5), Danube

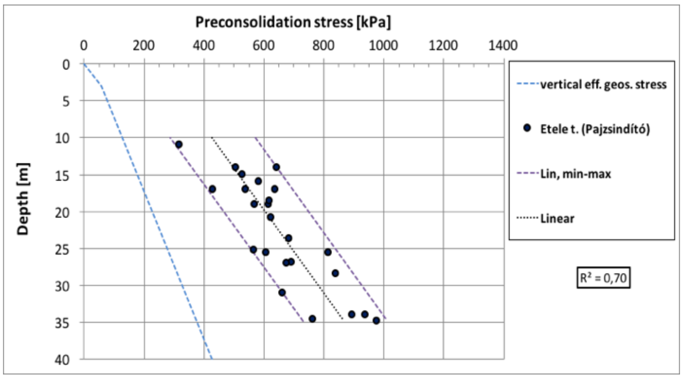

Fig. 17. Estimated preconsolidation stress based on Eq. (6), Etele t.

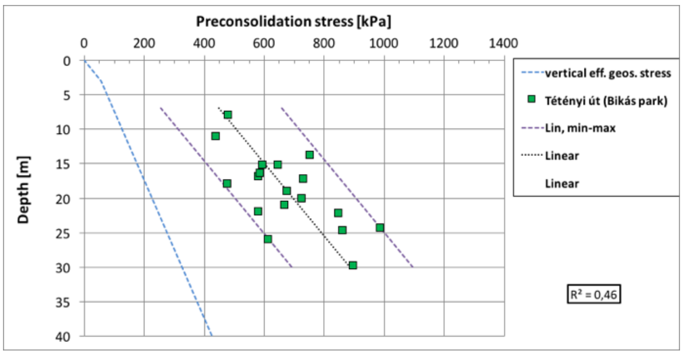

Fig. 18. Estimated preconsolidation stress based on Eq. (6), Tétényi út

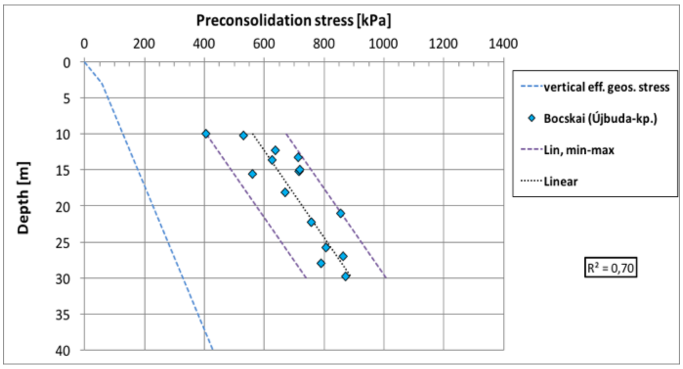

Fig. 19. Estimated preconsolidation stress based on Eq. (6), Bocskai út

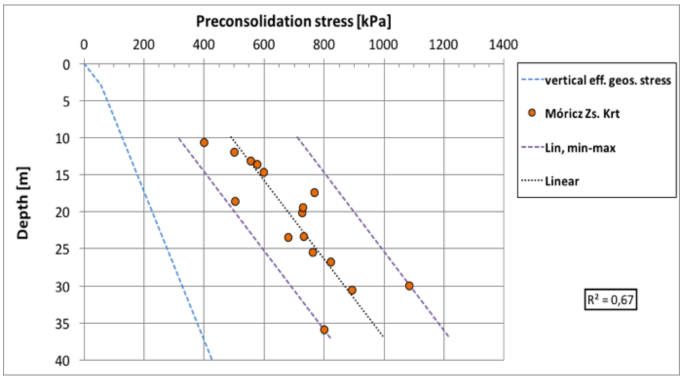

Fig. 20. Estimated preconsolidation stress based on Eq. (6), Móricz Zs. k.

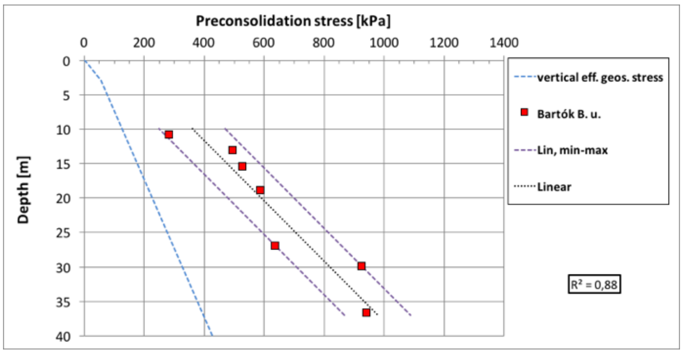

Fig. 21. Estimated preconsolidation stress based on Eq. (6), Bartók B. u.

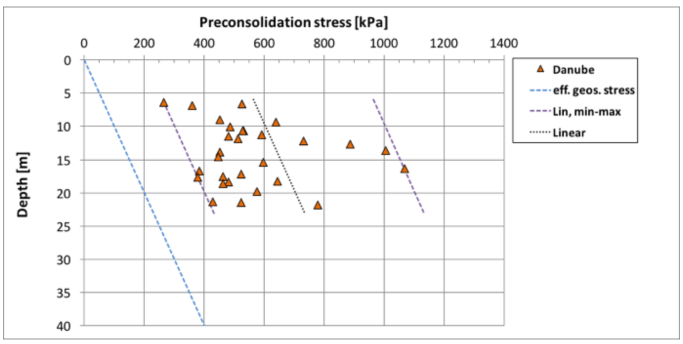

Fig. 22. Estimated preconsolidation stress based on Eq. (6), Danube

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