Budapest University of Technology and Economics
Department of Geotechnics

PhD theses

Determination of the coefficient of earth pressure at rest in overconsolidated Kiscelli clay

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1 Introduction, presentation of the problem

The demand for using underground spaces has increased in line with the rapid development of large cities over the last century, and the process is still accelerating these days. Underground construction necessitates increasingly wide-ranging exploration and understanding of the strata of soil and rock that need to be managed. The behaviour of overconsolidated soils is being explored and researched worldwide along with their effects on structures built in them. Studying the problem is justified by the fact that the significant horizontal stresses that obtain in overconsolidated strata or soil and rock may result in disproportionate horizontal loads on structures.

A large part of Budapest has **Kiscelli clay** under it. With the continuous development of the city, significant structures were built in this layer and many facilities are expected to be built in it in the future as well. Kiscelli clay is a soil stratum that has undergone extensive research and its geotechnical properties are well known. During my research, I did not determine the geotechnical and petrophyscial properties of Kiscelli clay.

The study of the geological formation and history of Kiscelli clay and its behaviour during exploration and construction projects led to the question whether Kiscelli clay may be overconsolidated, which may influence design and construction processes as it would mean that the “in situ” stress-state of the soil is completely different to what was previously assumed.

The ever growing networks of underground railways and ever larger underground car parks of large cities have justified and still justify increasingly wide-ranging exploration of deeper soil and rock strata.

The safety requirements applicable to the utilisation of underground spaces, be they underground car parks, metro lines, public road tunnels, shopping centres or even sports facilities, are increasingly stringent. As a result of increasingly stringent safety regulations, the corresponding standards that apply to built structures are also increasing.

The ever higher standards include, for instance, the requirements of complete rigidity and water-impermeability of structures. Today, these have become fundamental requirements applicable to underground facilities.

In order to allow increasingly strict safety standards to be met during construction work, it has become indispensable to perform as detailed an exploration as possible of the soil and rock strata around prospective underground structures.

This process has resulted in the discovery, in several cities, that the deeper soil/rock strata underneath those cities are overconsolidated.

Table 1 shows a selection of overconsolidated soil/rock strata found around the world along with their overconsolidation ratios and coefficient of the earth pressure at rest.

Table 1: Overconsolidated soils

Soil type	Angle of internal friction ϕ	Degree of overconsolidation OCR	Normally consolidated K_o	Overconsolidated λ_0	Reference
London Clay	20	44	0.65	2.4	Parry & Nadarajah
London Clay	17.5	32	0.66	1.9	Abdelhamid &Krizek
Weald Clay	26.2	8.6	0.58	1.5	Skempton & Sowa
Bearpaw Shale	15.5	32	0.7	1.8	Brooker & Ireland
Drammen Clay	30.7	50	0.49	3.6	Brown
New York Varved Clay	20.9	20	0.67	2.0	Leathers & Ladd
Hackensack Valley Varved Clay	19	4.1	0.65	1.0	Saxena
Seattle Clay	28.8	8.4	0.65	1.8	Sherif & Strazer
Hokkaido Clay	36.2	10.7	0.45	1.8	Mitachi & Kitago
Porthmouth Clay	32	8	0.47	1.4	Simon et al.
Boston Blue Clay	26.8	8	0.54	1.4	Kinner & Ladd
Chicago Clay	26.3	32	0.46	2.1	Brooker & Ireland
Bombay Clay	24	24.4	0.63	2.3	Kulkarni
Moose River Muskeg	47.7	13.6	0.3	2.1	Adams
Simple Clay	23.1	24	0.61	2.1	Ladd
New England Marine Clay	32	16	0.5	2.2	Ladd
Newfield Clay	28.6	20	0.5	2.1	Singh

Laboratory tests performed in 1999 at the Budapest University of Technology were the first to indicate that Kiscelli clay may be overconsolidated. The data measured in the laboratory (in triaxial tests, compression tests) indicated quite perceptibly that the core samples had “residual primal stresses”, i.e. loads were reduced on the geological timescale due to massive geological erosion. These “residual primal stresses” are known to occur in a number of locations around the world, in a wide variety of geological formations, e.g. in the granite solid of the Scandinavian massif, or on the island of Iceland, where load of the thick the Ice Age ice cover and its subsequent melting resulted in significant “residual primal stress”.

2 The subject and the objectives of the dissertation

Only a rather limited range of laboratory tests are available for determining the degree of overconsolidation and horizontal stresses in overconsolidated soils and rocks. Accurate results can only be achieved using special triaxial and oedometer test. The reason for this is precisely the overconsolidation of the soil.

Samples from overconsolidated strata begin to expand at the moment the samples are taken. It is possible to reduce this expansion process, but it cannot be entirely eliminated. This implies that laboratory testing of samples from overconsolidated strata is not suitable for determining the exact degree of overconsolidation or accurate horizontal stress values.

The objective of my research was to determine the natural, at rest horizontal and vertical stresses in Kiscelli clay.

On-site, “in-situ” measurements are best suited to determining horizontal and vertical stresses, as those measurements are the ones that least disturb the original state of stress of the soil stratum under investigation.

During the research I reviewed the international literature for the results of stress measurement test in soil strata with similar qualities and studied the behaviour of the strata concerned on the basis of the published test results I found. Then I selected the tests that are the most suitable for achieving my objectives, i.e. the determination of the natural, at rest horizontal and vertical stresses in Kiscelli clay. On that basis, I performed 3 different types of on-site tests, *earth-pressure cell stress measurements, borehole cell stress measurements and self-boring pressuremeter measurements*, and processed their results.

The objective of my dissertation was to study the overconsolidation of Kiscelli clay and to determine the horizontal stress resulting from its degree of overconsolidation. In my dissertation, I sought to furnish solutions to the following problems:

I. Determining the degree of overconsolidation of Kiscelli clay

II. Determining at rest horizontal stress

III. Determining stresses measurable in the horizontal plane

IV. Determining the amount of time required for reaching a new at rest state of stress after the soil stratum is disturbed

V. Determining the coefficient of the earth pressure at rest

3 Summary of research results

During my research I performed on-site tests for over two years in order to determine the degree of overconsolidation caused by preconsolidation stress in Kiscelli clay and the resulting horizontal stress values.

I performed measurements using three different on-site measurement technologies. I installed the on-site measuring instruments to determine the earth pressure at rest with the minimum possible disturbance of the medium. I processed the measurement data continuously.

I. My measurements aimed at determining ***the degree of overconsolidation of Kiscelli clay*** indicated that after its deposition, Kiscelli clay was consolidated under an overburden layer that was almost 400 m thick until its reached the state it is in now. I installed the borehole cell and performed measurements for over two years in order to determine the degree of overconsolidation. Finally, I processed the results of self-boring pressuremeter tests performed in 3 further locations, at a uniform depth of 4 metres, to determine the OCR values.

The Kiscelli clayey marl is significantly overconsolidated, the degree of overconsolidation varies between 10 and 16 as a function of depth (Figure 1).

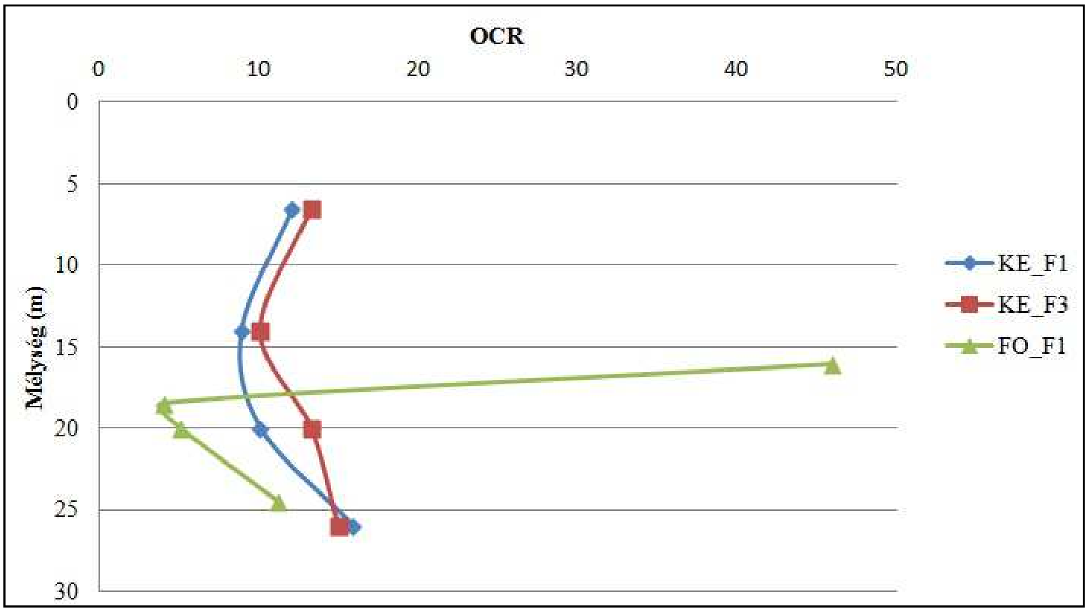

Figure 1:OCR as a function of depth

Mélység-Depth

II. I used the results of the sequence of borehole cell measurements that lasted over two years and the results from the measurements performed using the self-boring pressuremeter ***to determine at rest horizontal stress***. I presented the results from the borehole cell on a time-pressure chart. I found that the values of at rest horizontal stress vary along an elliptic curve, with design stress in the intact rock mass of the Kiscelli clay at ***4.62 bar***, i.e. ***462 kPa***.

The self-boring pressuremeter measurement results indicated that at rest horizontal earth pressure varies between ***270 and 1100 kPa*** as a function of depth.

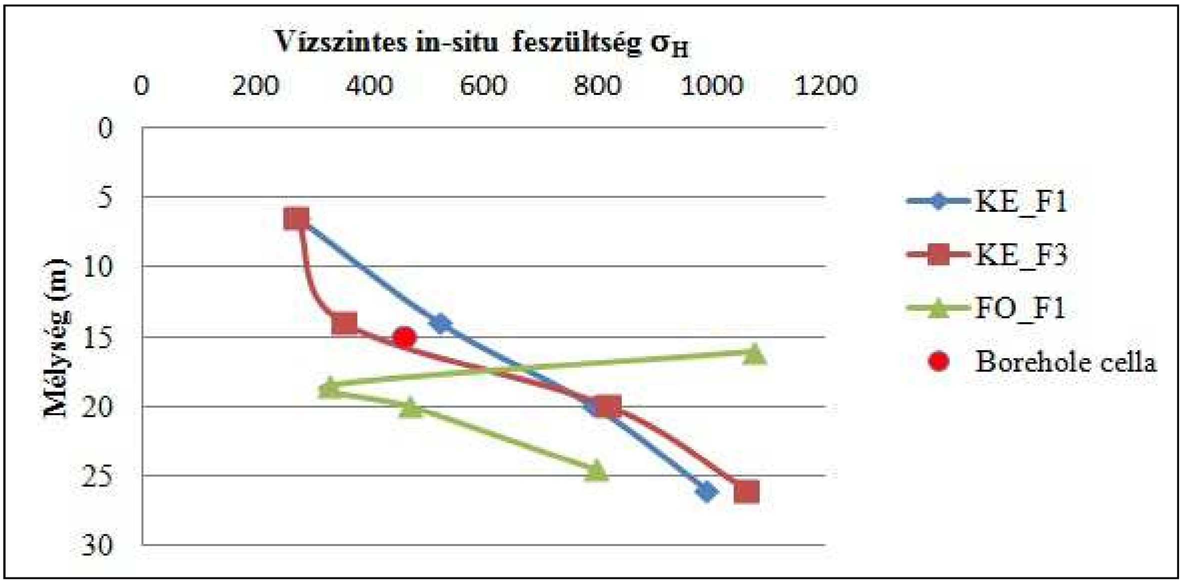

Figure 2: Horizontal stress as a function of depth; Mélység-Depth, Vízszintes in-situ feszültség-Horizontal in-situ stress

III. *Variations in stress values measured at a specific depth in various directions.* Measurements were performed in 4 directions in the horizontal section at a given depth in order to determine stress levels. The stress values measured in 4 different directions in an arbitrary horizontal plane must be on an ellipse. During my research, I performed measurements in 4 different directions at a depth of 15 metres. The instrument, placed in four directions, measured stress values at 45° intervals, in the directions north-south, northeast-southwest, east-west and southeast-northwest. The measurements did support the assertion that the stress values determined in four different directions in a single horizontal plane lie on an ellipse. The stress values I measured in a single horizontal plane do lie on an ellipse, with the major axis oriented to the northwest (Figure 3). If horizontal stress values are also included, the figure becomes an ellipsoid of stress whose major axis is oriented to the northwest. The measurement data from the sequence of tests performed using the self-boring pressuremeter yielded a similar result, lending further support to my finding.

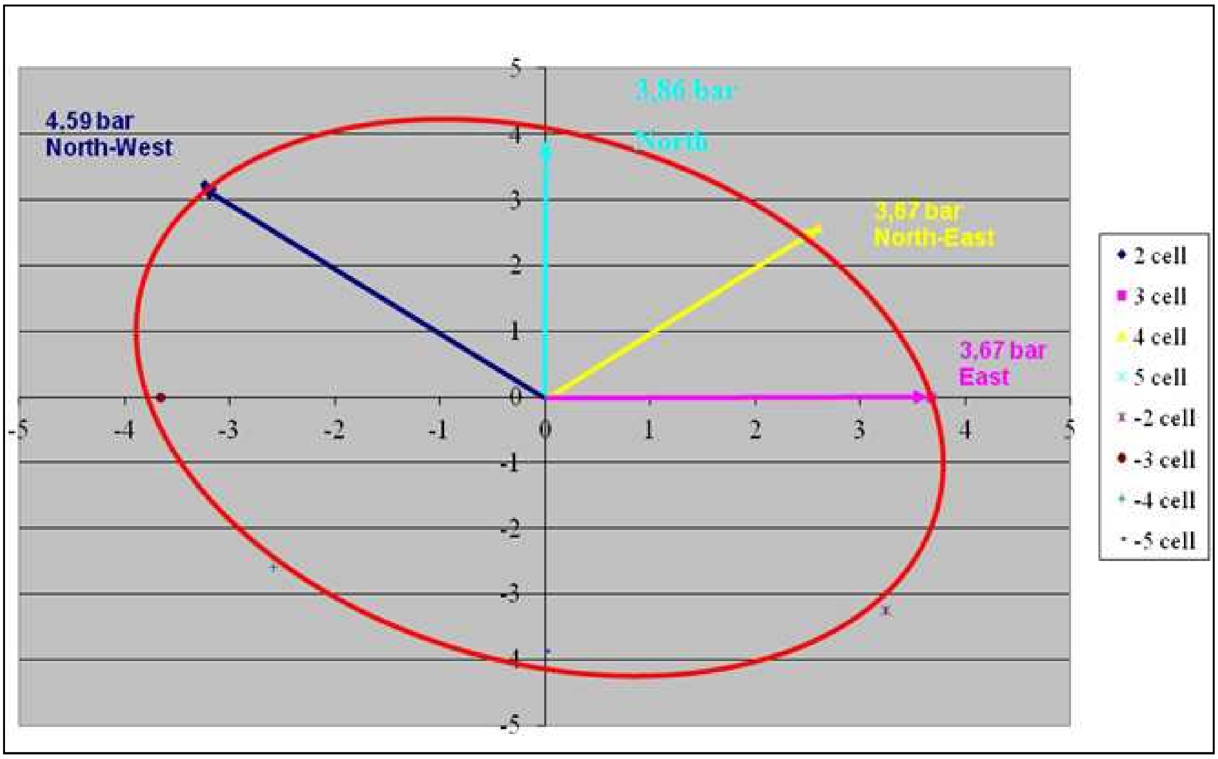

Figure 3: Elliptical curve of stress in the horizontal plane

IV. I also investigated ***the amount of time required for reaching a new stable state of stress after the soil stratum is disturbed.*** I did this by installing earth-pressure measurement cells, after which I also processed the results of the longitudinal sequence of measurements from the borehole cell.

If the surrounding rock is permitted to move horizontally, i.e. if it is not prevented from moving, there is no longer at-rest earth pressure or stress in the environment. In that case, after the surrounding rock is disturbed – in my case by the digging of a tunnel – a tertiary state of stress, that is to say a new stable state of stress will develop. I plotted the data obtained from the earth-pressure cells on a time-pressure graph, and found that ***the surrounding rock reached the tertiary, new stable state of stress 6 months after the tunnel cavity was opened*** (Figure 4).

If all horizontal displacement of the surrounding rock is prevented, i.e. if the surrounding rock is unable to move, after disturbance the structure is loaded with the at rest state of stress and the resulting horizontal earth pressure. In my tests performed using the borehole stress is investigated that situation. I plotted the results of the tests on a time-pressure graph. The measured results led to the conclusion that in cases of disturbance not accompanied by horizontal displacement, the horizontal at rest stress is re-established in 1 year. ***That is to say, 1 year after the disturbance, the structure is once more loaded with the horizontal at rest stress.*** (Figure 5)

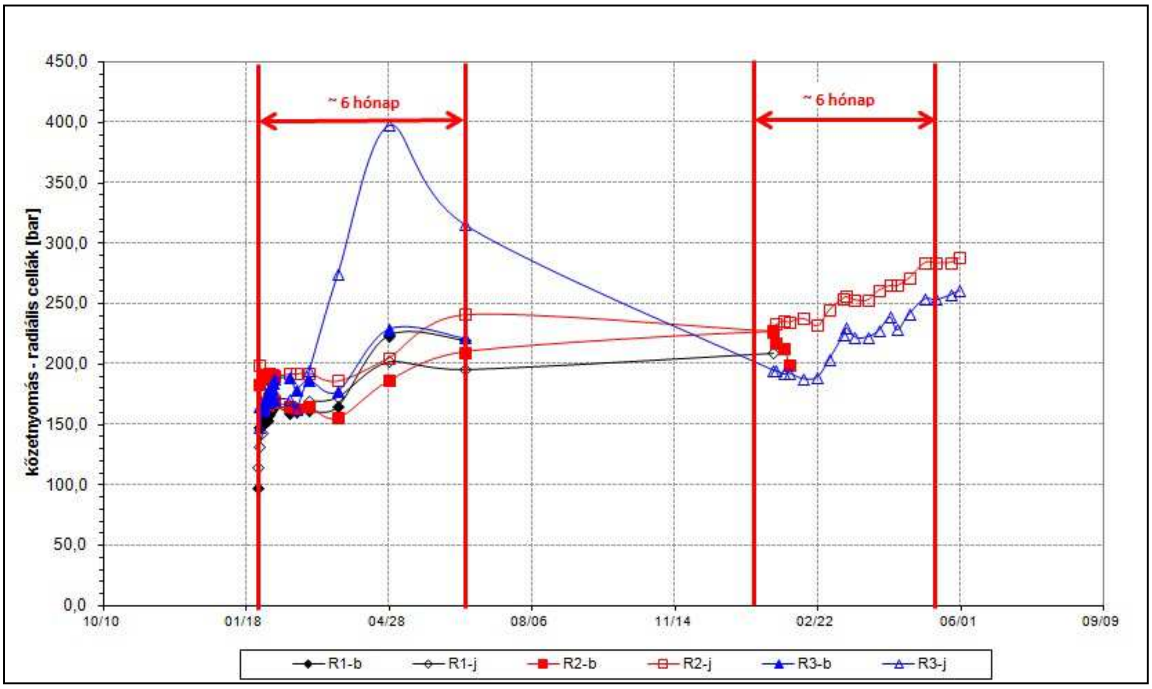

Figure 4: Earth pressure measurements in radial and tangential directions

6 hónap- 6 months, kőzetnyomás- earth pressure, radiális cellák- radial cells

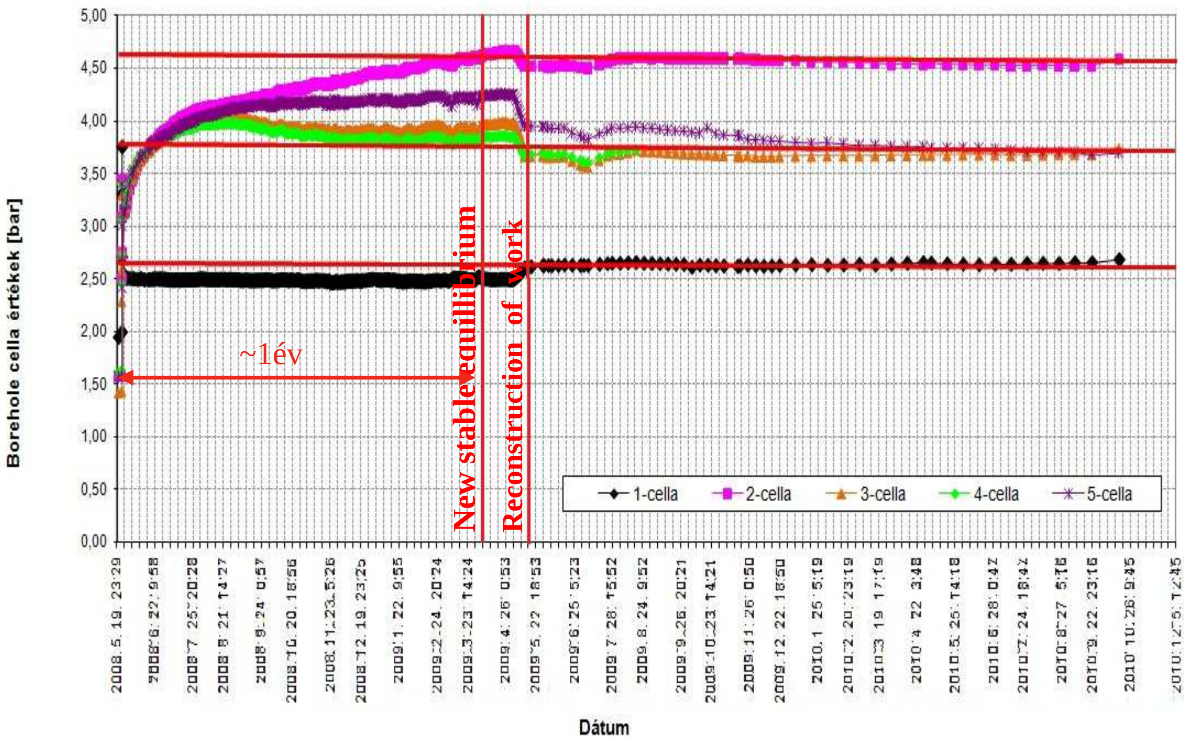

Figure 5: Time-pressure graph obtained from the borehole cell; Borehole cella értékek-Borehole cell values, Dátum- Data

V. I used the measurement data from the borehole cell and the self-boring pressuremeter for determining ***the coefficient of the earth pressure at rest***. In addition to determining the coefficient of the earth pressure at rest, I also studied its variation with depth during the research.

I found that ***in the Kiscelli clay, the value of the coefficient of the earth pressure at rest varies between 1.2 and 2.5 as a function of depth***. **(Figure 6)**

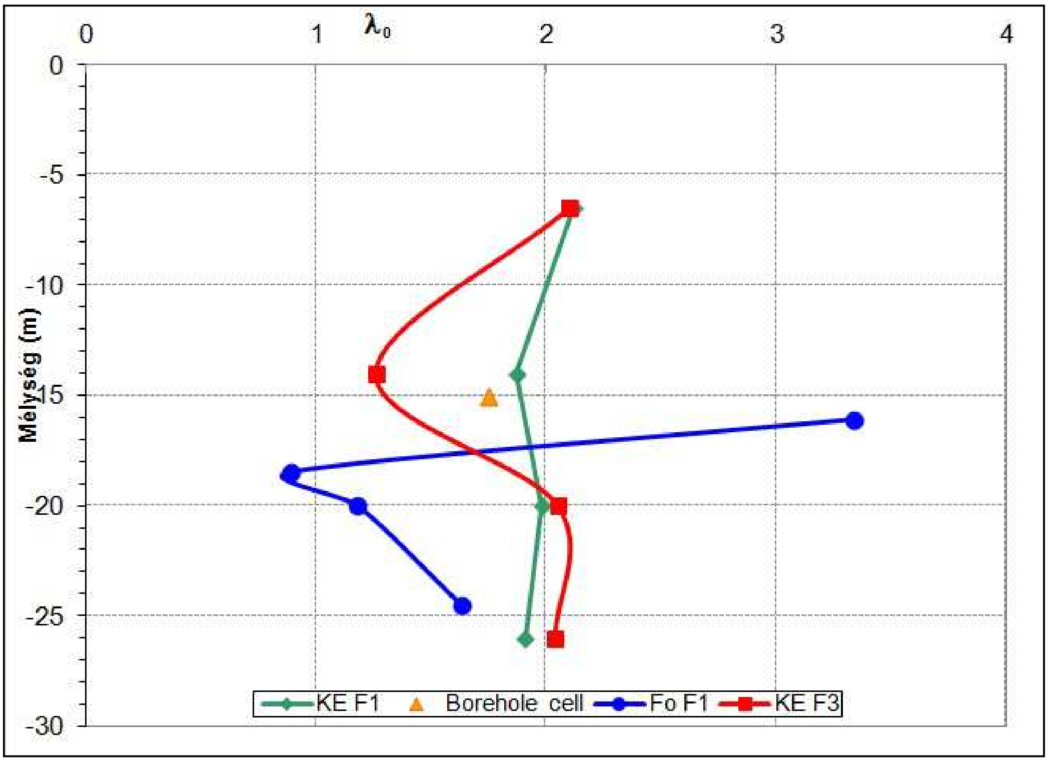

Figure 6: At rest earth pressure coefficient as a function of depth

Mélység- Depth

4 New scientific results

I have summarised the new scientific results I have reached in 6 theses. My publications about my findings are shown [in square brackets].

THESIS 1: DEGREE OF OVERCONSOLIDATION

I performed measurements to determine the degree of overconsolidation in Kiscelli clay, which varies with depth. The Kiscelli clay was once covered by an overburden layer that was almost 400 m thick, but this was later destroyed by erosion. According to my findings, *the overconsolidation ratio in Kiscelli clay is 10<OCR<16, and it varies with depth.* Kiscelli clay is *strongly overconsolidated*. [5][7]

THESIS 2: LEVEL OF HORIZONTAL EARTH PRESSURE AT REST

Based on the tests I have performed in Kiscelli clay, I found that the horizontal earth pressure at rest varies between *270 and 1100 kPa* as a function of depth. *The classical calculation methods of soil mechanics are not suitable for determining the at rest horizontal stress.* Even the values yielded by calculation methods for overconsolidated rock are only rough estimates. The appropriate method for establishing this characteristic is on-site testing and measurements. [4][7][8].

THESIS 3: DIRECTIONAL VARIATION IN AT REST HORIZONTAL EARTH PRESSURE

Based on the measurements I performed in Kiscelli clay I found that the stress values measured in 4 different directions in a single horizontal plane lie on an ellipse. The horizontal stress values I measured in a horizontal plane lie on an ellipse whose major axis is *oriented to the northwest*. [5][6][8]

THESIS 4: HORIZONTAL STRESS AS A FUNCTION OF TIME

The sequences of measurements aimed at establishing changes in horizontal stress showed that the stabilisation of horizontal stresses in Kiscelli clay requires different amounts of time depending on whether the disturbance of the stratum permits horizontal displacement or whether horizontal displacement is entirely prevented.

SUB-THESIS 4.1: When the disturbance of the stratum permits the development of horizontal movements, at rest horizontal stress does not develop, *a tertiary, that is to say new stable, balanced state develops*. I have established using measurements that the tertiary state of stress requires *approx. 6 months* from the disturbance of the stratum. [3][5]

SUB-THESIS 4.2: When the disturbance of the stratum *does not allow the development of horizontal movements, at rest horizontal stresses build up* and present a load on any rigid built structures. I have established using measurements that re-establishment of the at rest state of stress *takes approximately 12 months, i.e. 1 year*. [4][6]

THESIS 5: VALUE OF THE COEFFICIENT OF THE EARTH PRESSURE AT REST

After the processing of the measurements obtained during my research I determined horizontal and vertical stresses in Kiscelli clay. Then, following the determination of the horizontal and vertical stress values using in-situ tests and measurements, I determined *the coefficient of the earth pressure at rest in Kiscelli clay, which varies between 1.2 and 2.5 with depth.* [6][7][8]

5 The applicability of the results

My findings, which are based on measurements, provide guidance for the design and construction of structures in Kiscelli clayey marl. It raises awareness of the behaviour of overconsolidated rock strata and the determination of horizontal stresses using in-situ measurements.

The new scientific results obtained as a result of my research facilitate the safe and more economical design and implementation of structures in Kiscelli clayey marl.

6 Proposed future research

The results of my research indicate that the following directions of research may furnish new scientific results:

- Displacement and deformations of tunnels built in overconsolidated rock
- Development of a sizing principle for tunnel walls in overconsolidated rock, at various λ_0 values
- The effect of overconsolidation on the displacement and distortion of diaphragm walls
- The study of the stability of diaphragm walls at various λ_0 values

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