In-situ determination of the earth pressure at rest in overconsolidated clay

In-situ določanje mirnega zemeljskega tlaka v prekonsolidirani glini

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Abstract: In the paper, there is a study about the general genesis process of overconsolidated soils, as well as the effects of the overconsolidated ratio to structures. It will demonstrate the possible methods for the determination of the values of overconsolidated ratio and of earth pressure at rest; further, the processing of measurement results, through which the values of OCR (Overconsolidated ratio) and of λ_0 (Earth pressure at rest) in an overconsolidated clay have been determined.

Povzetek: V članku so opisani splošni proces nastanka prekonsolidiranih zemljin in učinki prekonsolidacijskega količnika na zgradbe. Prikazane so mogoče metode določanja vrednosti prekonsolidacijskega količnika in mirnega zemeljskega tlaka. Sledi razprava o rezultatih meritev, s katerimi so bile določene vrednosti prekonsolidacijskega količnika (OCR) in mirnega zemeljskega tlaka (λ_0) v prekonsolidirani kiscellijski glini.

Key words: coefficient of the earth pressure at rest, overconsolidated ratio, earth pressure cell, Borehole cell, Selfboring pressuremeter

Ključne besede: količnik mirnega zemeljskega tlaka, prekonsolidacijski količnik, celica zemeljskega tlaka, celica v vrtini, samouvrtalni presiometer

Review paper

INTRODUCTION

The need to utilise underground spaces was growing parallelly to fast expansion of large cities in the previous century, the growth-rate of which is further increasing these days. Building in underground spaces is supposed to be handled together with wider and wider exploration of soils and rock layers. The behaviour of overconsolidated soils is explored and investigated globally, because significant horizontal stresses emerging in overconsolidated soil- and rock-strata give rise to unproportionally high horizontal loads to structures.

In the process of the investigations the objective was to determine the natural horizontal and vertical stresses at rest in overconsolidated clay layer.

The stress condition at rest means a stress space free from human intervention, both in the rock- and in the soil-mechanical field. There are conditions used by both the soil- and rock-mechanics for the sake of simplification. These are for instance the homogeneity, the isotropicity and the elasticity of rock masses. The primary stress condition is the result of the dead-weight loads of rocks or soils but it can be changed by tectonic activities, desiccation or other physical influences. The determination of the coefficient of the earth pressure at rest differs significantly in the area of the classical soil-mechanics and in that of the classical rock-mechanics, which is demonstrated by Figure 1.[1, 2, 3]

In those cases, where the metamorphosis of soils to rock has already started, but the process has not yet been completed the rules of classical soil mechanics cannot be applied, but the rules of classical rock mechanics are not applicable either. They are in a transitionary condition, with its own specific rules and properties.[4, 16]

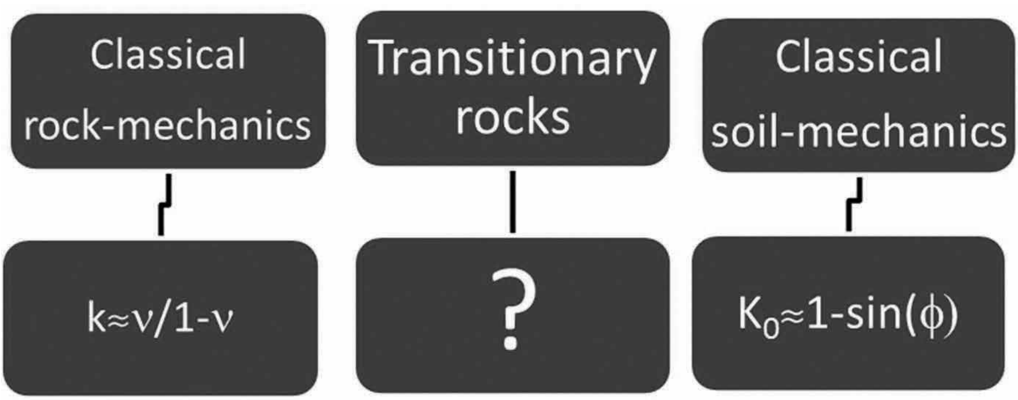

Figure 1. Coefficient of the earth pressure at rest

The laboratory tests are used for the soils and the rocks, the soil models are used for the soils[5] while the rock models are used for the rock masses. These models are not used for the transitionary rocks.

The best method to determine horizontal and vertical stresses is the use of local, in-situ investigations because these measurements have the least disturbing effects on the original stress conditions of a soil layer under test. The behaviour of the soils is determined by CPTu which is one of the world-wide best-known in-situ measurements[6] but horizontal earth pressure can be determined in indirect way.

Three different in-site investigations have been performed in order to determine the overconsolidated ratio and the earth pressure at rest: measurement with an earth-pressure cell; measurement with a borehole cell; and a measurement with a selfboring pressuremeter.

Geological, geotechnical environment

Place of the measurements

This study would like to show horizontal and vertical in-situ stress measurements around Budapest, Hungary. There are earth pressure cells around an SCL tunnel, one borehole cells sys-

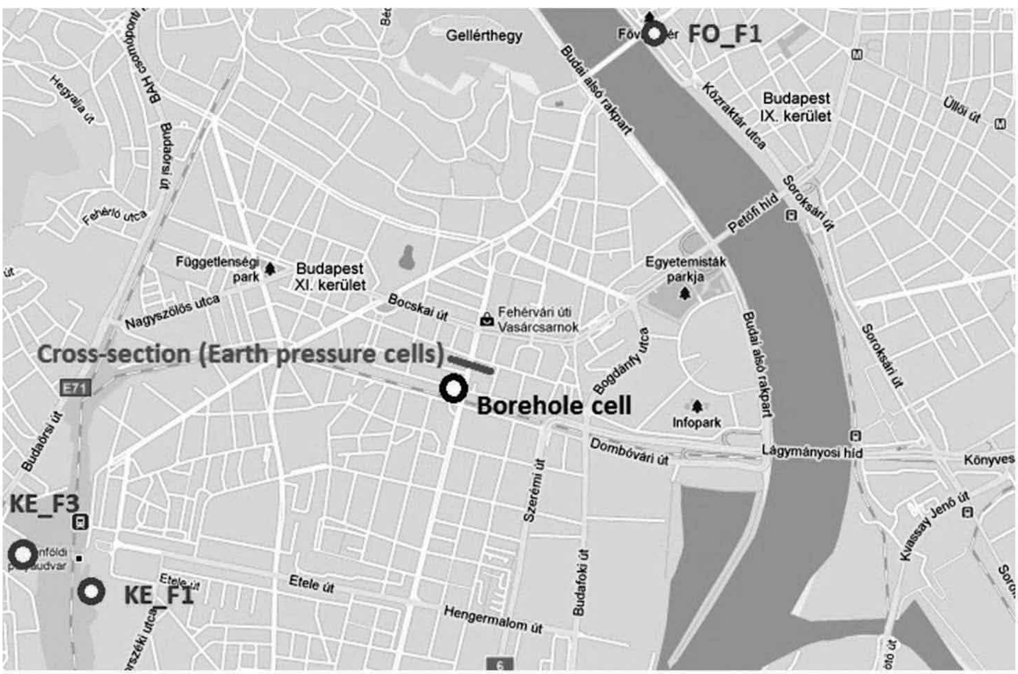

Figure 2. Place of the measurements

tem and three selfboring pressuremeter measurements.

In the map can show the place of the measurements. (Figure 2)

Geological environment

The rock layer of Kiscelli Clay Marl can be found beneath the major part of Budapest. It is situated on or near to the surface in the Buda-side of the city over a considerable area.

The thickness of the rock layer varies between 50 m and 500 m, but at certain spots it can reach even 1 000 m.

Kiscelli Clay was formed in the Cenozoic era of geohistory in the Tertiary period within that era.

The clay marl was depositing in the Oligocene, in its middle period when the location of the continents started to reach their today known location. Regarding the fauna of that period mammals were occupying an increasing area.

The Kiscelli Clay Marl is a marine deposit from the Middle-Oligocene. It was settling down among normal salty-water conditions in the Tethys-sea, which is considered to be the ancestor of the Mediterranean Sea of today.[7]

Geotechnical environment

Kiscelli Clay can be considered to be founding strata of the Quaternary period. After a rapid glance over geohistory it can be stated that Kiscelli Clay, after having deposited in the Oligocenic phase of the Tertiary period, became heavily consolidated later, upon the effects of soil layers deposited over it.[14, 15]

At the end of the Tertiary period of geohistory and in the Quaternary period the thick conglomerates lying over Kiscelli Clay underwent a significant erosion process. As a result of this major erosion vertical loads of Kiscelli Clay were removed and its upper layers became loose.

Table 1. The soil-physical properties of Kiscelli Clay

Soil type According to Msz. (14043-2-1979)	Bulk density of nat. State ρ_t/(t/m^3)	Angle of internal friction ϕ/°	Cohesion c/(kN/m^2)	Young modulus E_s/(kN/m^2)	Consistency index Ic	Void ratio e
Wethered zone of Kiscelli Clay	2.1	20–23	50–100	7–10	>1	0.4–0.68
Fissured zone of Kiscelli Clay	2.2	25–28	420	15–20	>1.2	0.32–0.4
Zone beyond the impact of expansion, Kiscelli Clay Marl	2.3	35–50	400–1000		>1.3	0.18–0.32

Kiscelli Clay cannot be considered as a homogenous layer: its vertical stratification must be taken into consideration both in the design and in the construction phase.

In general it can be broken down to three well-distinguishable zones:

- Weathered zone: This zone of Kiscelli Clay completely lost its properties characteristic of transitionary rocks during the process of losing its loads and now it is in a plastic or near-plastic condition.
- Fissured zone: The properties of the fissured zone are similar to those of the intact zone, no plasticity can be detected anymore. The fissures-textured rock bodies are in sound condition with high solidity.
- Intact rock mass zone, beyond the impact of expansion: the deeper layers of Kiscelli Clay were not exposed to the load-relief impacts of erosion, so this zone conserved the ancient soil-physical properties of clay. Obviously the highest load ever deposited over the clay layer before together with the resulting maximum consolidation have also been preserved in this zone. The impact of a formerly existing maximum load ever is called overconsolidation.

In-site investigations applied

Earth pressure cell

In the course of the investigations first-

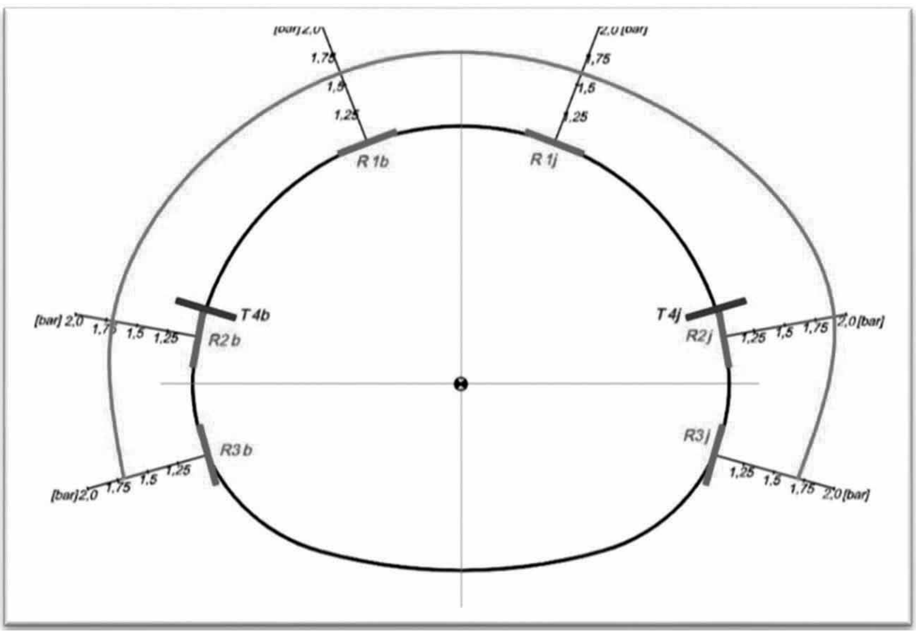

Figure 3. Points at which the earth pressure cells are located, and their alues

ly earth pressure cells (Figure 3) were used to determine the stresses to the tunnel being built in the Kiscelli Clay.[15] During the investigation radial and tangential cells made by company Glötzl have been installed. These cells determined the value of the normal force emerging in the shotcrete wall, as well as the value of the force exercised by the rock environment to the shotcrete wall. Six radial cells and two tangential cells were installed in the system.

Processing the measurement results it was outlined that the value of horizontal and vertical stresses in the neighbourhood of the completed tunnel are nearly the same.[9]

Borehole cell

An earth pressure cell system installed into a borehole called Stress Monitoring System (Figure 4) was installed during the investigations. Similarly to the pressure cells, the borehole cell is also made in Germany, by the firm Glötzl.[11]

The name borehole cell refers to the place of the installation: the cell system is installed into a borehole. The borehole cell means a system of individual cells always compiled in accordance with individual needs. The system used here is made up of five cells, but obviously either more or less cells could also be combined together.

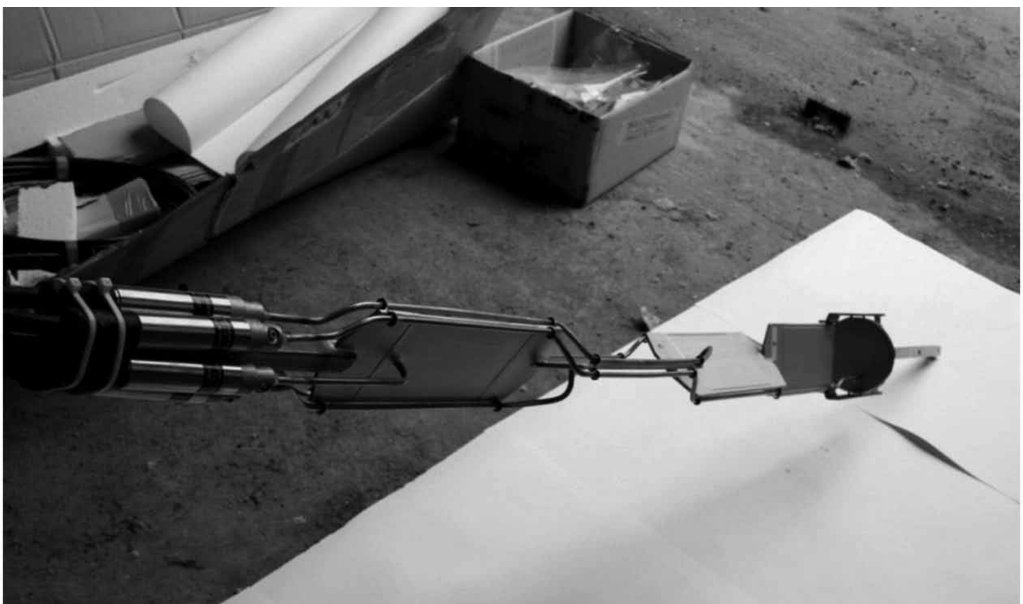

Figure 4. Borehole cell (Glötzl Ltd)

The purpose of the investigation was to determine the value of horizontal and vertical stresses in the overconsolidated Kiscelli Clay.

The borehole cell was installed in a stress-free area in a depth of 15 m. The installation depth was selected with regard to the RQD indices. The instrument was installed in the zone of the intact rock environment.

The borehole cell system was installed on 19 May 2008 and keeps performing its measurement tasks until today after appropriate reconstruction and protection.

In the first 7 months there were two reading per day. Subsequently to the first 7-month period the number of readings reduced to one per day until the end of the first year. In the second year the number of readings could be further reduced to once a week, while after the first eighteen months following the installation of the instrument, the number of readings was decreased to once in two weeks.

Selfboring pressuremeter (SBP)
During the research there was a big chance to take part in investigations carried out with selfboring pressuremeter at several locations in the city.[12, 13] The investigations were targeted at defining the overconsolidated ratio of the overconsolidated clay (Kiscelli Clay). Since the measurement results could be used for scientific purposes the research group had the opportunity to investigate the Kiscelli Clay at various sites.

In the case of a selfboring pressuremeter the rock environment cannot expand after the borehole had been completed as it is continuously supported until the completion of the investigation process. This device allows us to determine the real, in-situ stresses in any cases.[11]

SBP is a special device combining the tooling required for boring and the pressuremeter instrument. The device is 1.2 m long with a diameter of 83 mm ending in a boring crown head. (Figure 5).

The pressuremeter itself is a 0.5 m long polyurethane membrane, protected with a stainless steel mantle. Inside the membrane there is a six-branch displacement meter measuring the displacements in the wall of the borehole. The six-branch displacement meter makes it possible to determine also the main direction of the horizontal stress, in addition to the size of stresses measured in the process. With the help of the horizontal stress instrument the research group was able to measure the total horizontal stress. If groundwater or strata-water is present this device measures not the horizontal stress accumulated in the layer but the horizon-

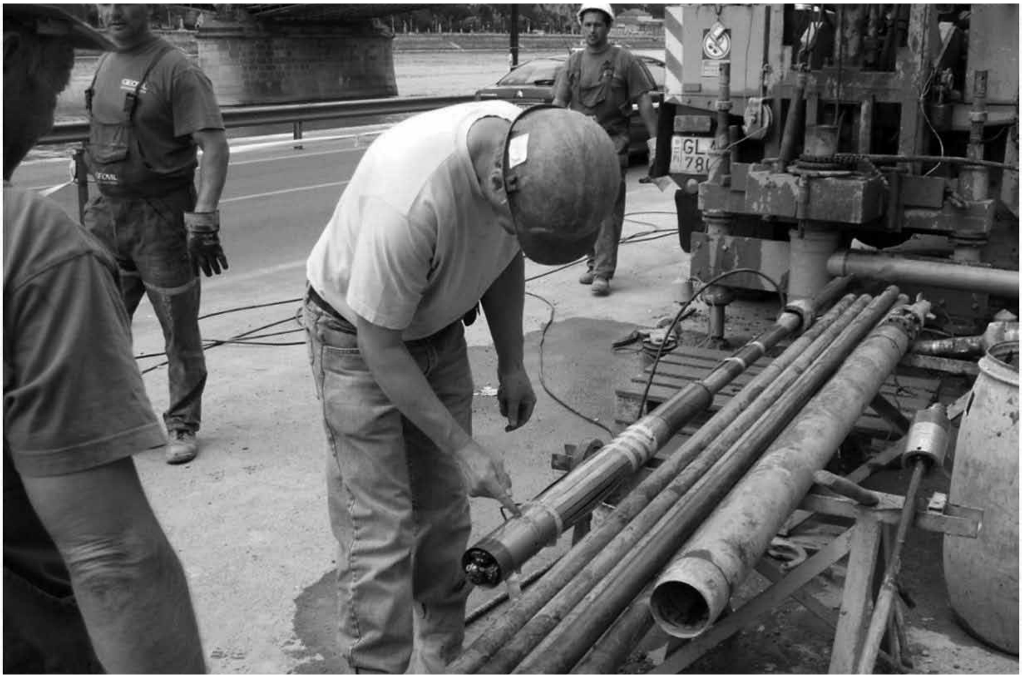

Figure 5. Selfboring pressuremeter

tal stress of the layer and the stress of the water in the layer. In order to enable the device to measure the effective stress of the soil/rock layer two cells are also installed outside the membrane to measure the pore-water pressure, the purpose of which is to determine the value of the neutral stress due to water pressure in the layer. If the total horizontal pressure and the neutral stress is known the effective horizontal stress can be determined.

Measurement results

In-situ measurements were carried out in the course of the investigations for more than two years to establish the overconsolidation ratio of the Kiscelli Clay caused by a preliminary loading, and the value of the resulting horizontal stress.

With the investigations performed to determine the overconsolidated ratio of Kiscelli Clay the research group established that the Kiscelli Clay, after its settling down, consolidated under the effect of a nearly 400-meter thick covering layer, and developed to its currently known condition. We were carrying out measurements through the installation of a borehole cell for more than two years, in order to establish the overconsolidated ratio. Then we processed the results of the measurements with a selfboring pressuremeter performed at three additional sites in four different depths to determine the OCR value (Figure 6). The Figure 6 shows the results of measurements. The blue and red lines (name of the measurements are KE_F1 and KE_F3) were made on Kelenföld station (Figure 2) where the ground is typical Kiscelli Clay. The measurement FO_F1 was made in the Fövam station where the ground is mix. There are Kiscelli Clay but it hasN't got the typical parameters.

The Kiscelli Clay Marl is heavily overconsolidated, its overconsolidation ratio varies between 10 and 16 depending on depth.[7]

To determine the horizontal stress at rest the group used the results of the series of measurements of more than two years with the borehole cell as well as those of the selfboring pressuremeter investigations. The place of the borehole cells can be seen on the Figure 2. The results of the borehole cell were depicted in a time/pressure graph (Figure 8). It was established that the values of the horizontal stress at rest were varying along an ellipse, and the maximum value of the stress in the intact rock mass zone of Kiscelli Clay is 4.62 bar.

As the result of the measurements with the selfboring pressuremeter we established that the value of the horizontal stress at rest varied between 270 kPa and 1 100 kPa depending on depth (Figure 7).

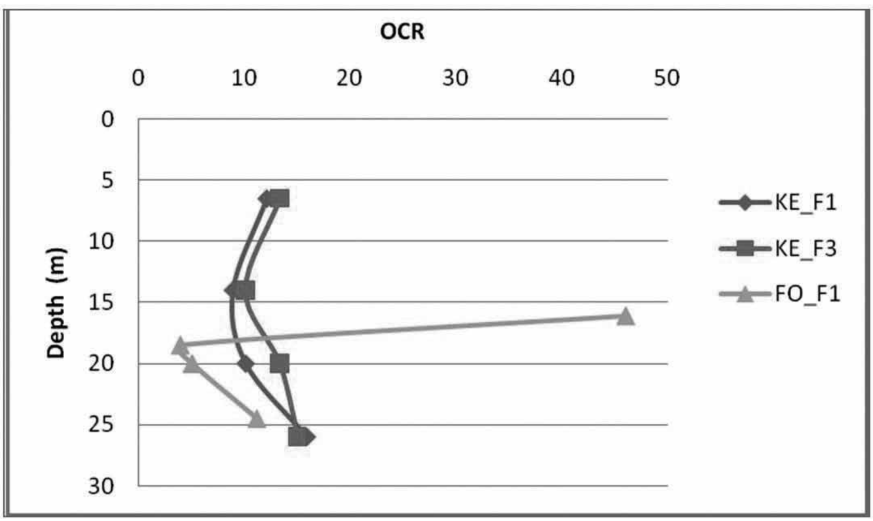

Figure 6. OCR value versus depth value E_F1; KE_F3; FO_F1- name of the measurments

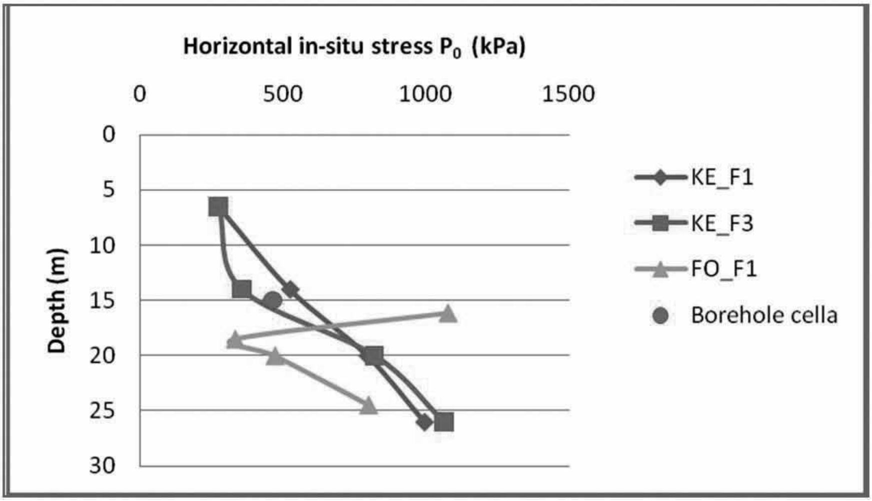

Figure 7. Horizontal stress values versus depth values, Borehole cella = Borehole cell

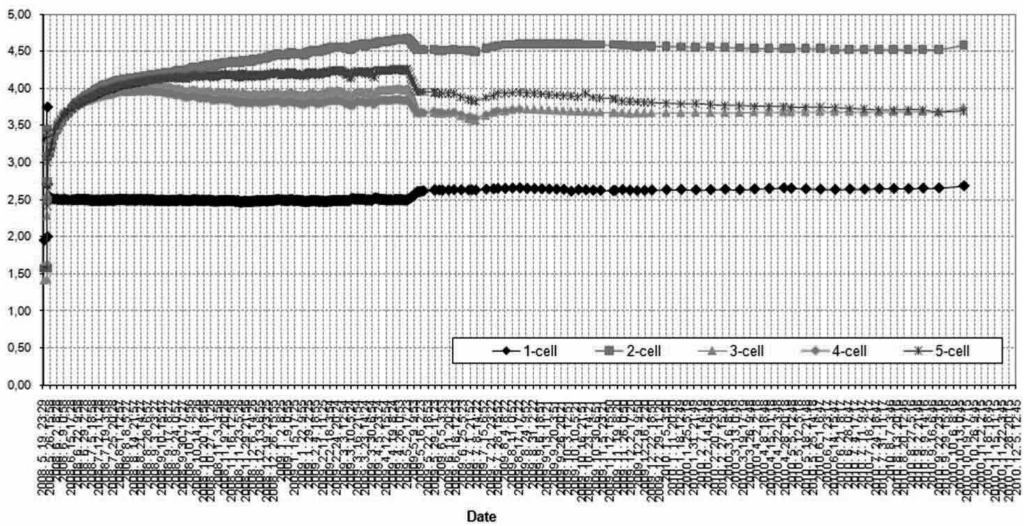

Figure 8. Borehole-cell-measurement values in a time/pressure diagram- 1cell- vertical cell;
2cell, 3cell, 4cell, 5cell-name of the horizontal earth pressure cells

We used to determine the value of the coefficient of the earth pressure at rest the measurement results provided by the borehole cell and by the selfboring pressuremeter investigations. In the course of these investigations we determined not only the value of the coefficient of the earth pressure at rest but the research group investigated its evolution in depth too.

The value of the coefficient of the earth pressure ($K_0 = \lambda_0$) at rest in Kiscelli Clay varies between 1.2 and 2.5 in the function of depth. (Figure 9).

To determine the guidedness of the horizontal stress, first it had to be considered that the value of stress in a plain is constant, that is its value is the same in every direction of the plain, or if could such a case occur where it is not constant. In that case, when the uniform stress distribution developed during the deposition process gets modified upon the effect of any external force, them this amount will not be constant any more, bur the maximum values of the horizontal stresses will be carried along an ellipse in a plain (Figure 10). The measurements right after the installation and until today verify the theory that the values of horizontal stresses have a guided character. The results of the series of investigations carried out by the selfboring pressuremeter have yielded the same output. I was able to determine the values of the horizontal stress in 4 different directions. It can be shown on the Figure 4. The Figure 8 shows the values of the 4 horizontal cells and 1 vertical sell during the research and the Figure 10 shows the values of the maximum hori-

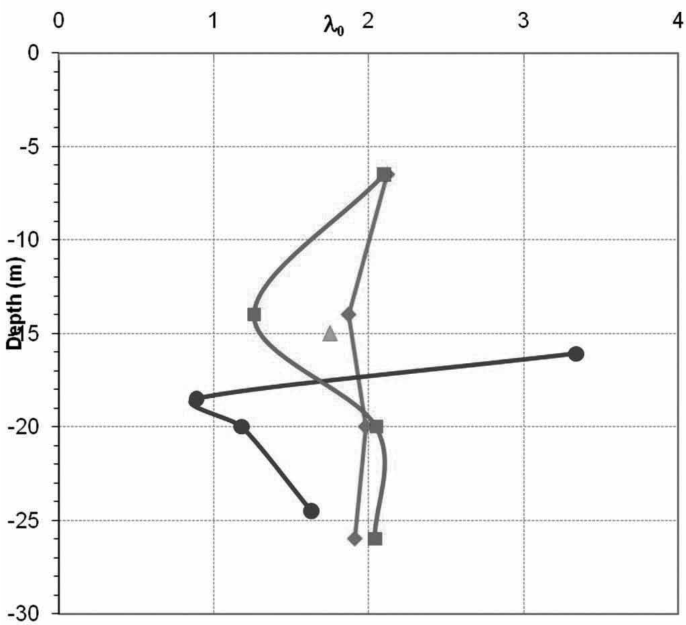

Figure 9. Changes of the value of the coefficient of earth pressure at rest in the function of depth

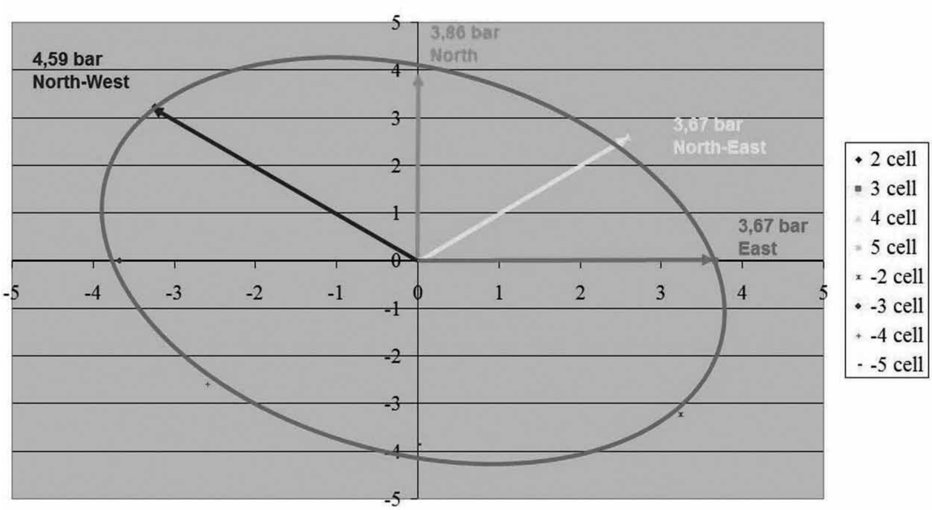

Figure 10. Ellipse of the horizontal earth pressure from the borehole cells system

zontal stress in the horizontal section. When I drew the ellipse I had used the theory of horizontal stress of Glötzl Company.

Conclusions

It can be established through the investigations that the method applied by classical soil mechanics and classical rock mechanics for the determination of the value of earth pressure at rest cannot be applied in the case of overconsolidated soils. In those situations where the stress values at rest for an overconsolidated soil must be determined, not even approaching calculations are recommended with the application of the rules of classical soil mechanics or classical rock mechanics. The most accurate results for the determination of primary stresses are provided by in-site investigations. From among the scale of in-site investigations the measurements recommended for use are where the rock environment to be tested cannot expand.

People could measure the values of the horizontal stress, the coefficient of the earth pressure at rest (λ_0) and the OCR but sometimes this information are not enough because the direction of the measurements is indispensable.

In the course of the research work we demonstrated that the Kiscelli Clay is heavily overconsolidated and consequently the value of the horizontal stress is 1.5 to 2 times higher than the value of the vertical stress.

This result highly influences the statical force impacts of the structures that are going to be built in the overconsolidated clay layer.

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