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17 SEAGC

The Seventeenth Southeast Asian Geotechnical Conference

May 10~13, 2010, Taipei, Taiwan

Geo-engineering for Natural Hazard Mitigation and Sustainable Development

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Plenary and Special Sessions

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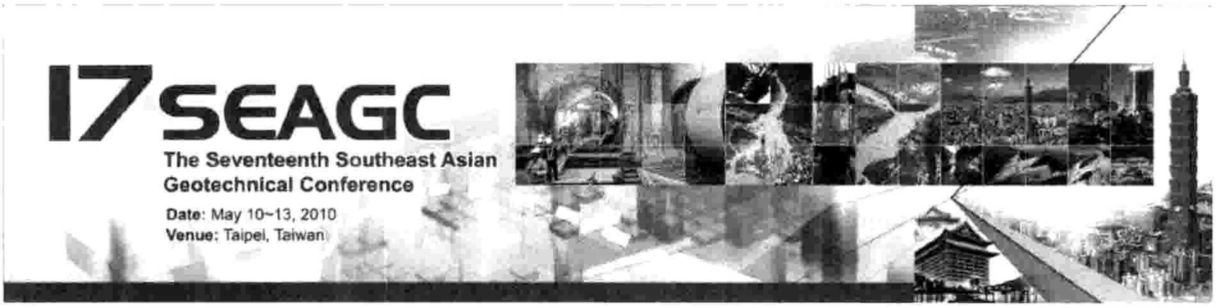

Proceedings of the Seventeenth Southeast Asian Geotechnical Conference

- Geo-engineering for Natural Hazard Mitigation and Sustainable Development

Vol. II. Plenary & Special Sessions

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17SEAGC

Foreword

The Southeast Asian Geotechnical Society (SEAGS) mainly consists of the members from SEA countries. When SEA country societies became the members of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), the SEAGS retains its role in providing the platform for exchange and sharing of the knowledge among its members and the allay with other SEA societies. Since 1967, sixteen SEAGC conference have been held in the major cities in Southeast Asia, i.e., Bangkok (1967, 1977, 1987, 2004), Singapore (1970, 1993), Hong Kong (1972, 1982, 2001), Kuala Lumpur (1975, 1985, 1996, 2007) and Taipei (1980, 1990, 1998). After the 16th SEAGC, the Association for Geotechnical Societies of Southeast Asia (AGSSEA) was founded to enhance the connections between the SEAGS and other SEA societies. This is the forth time Taipei hosts the SEAGS conference. The Conf. is organized by SEAGS with the major help from Taiwan Geotechnical Society (TGS).

The main theme of 17SEAGC is Geo-engineering for Natural Hazard Mitigation and Sustainable Development. Nine theme topics are covered as follows,

1. Site characterization and laboratory testing
2. Ground improvement and reinforcement
3. Design, construction and performance of foundations
4. Ground excavations and tunneling
5. Landslide and debris flow hazard mitigation and rehabilitation
6. Geotechnical earthquake engineering
7. Geo-environmental engineering
8. New generation design code developments
9. Geo-information and land reclamation technologies

As a result, two keynote lectures, two guest lectures, one special guest lecture and a Forum as well as the theme sessions are scheduled. The special sessions are organized by TGS, ATC3, ATC10, JWG-DMR/TC39 and GEOSNet/TC304, respectively. More than 130 papers are contributed by more than 200 delegates from 21 countries in the 17SEAGC program. The Conf. Proceedings have two volumes. The Vol. I collects the papers presented in the Theme Sessions; Vol. II presents the articles collected for plenary sessions and special sessions. The minutes of the discussions, Q&A, Forum and GC/Member Meeting of SEAGS and Council Meeting of AGSSEA as well as other activities during the Conf. shall be prepared as e-copies and retained by CD ROM after the Conf.

Special thanks are due at this stage to all the delegates, the members and referees of the technical committee. The supports given by the members of the Organizing Committee and Conference Committee are gratefully acknowledged. Thanks are also due to those individuals and organizations who have supported and assisted either financially or in other manner. Without all these supports, a successful 17SEAGC cannot be reached.

Dr. John Chien-Chung Li
Chairman, Organizing Committee, 17SEAGC

Prof. Meei-Ling Lin
Chairperson, Conference Committee, 17SEAGC

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ATC10 Session

GEOSNet/TC304 Session (I)

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1st Za-Chie-Moh Distinguished Lecture

Prof. Michele Jamiolkowski, Technical University of Torino (Italy)

Chair: Dr. Chung-Tien Chin
Star Energy Corporation (Taiwan)

The geotechnical problems of the second world largest copper tailings pond at Zelazny Most, Poland

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ABSTRACT: The paper summarizes the experiences of the writers in assisting KGHM (the Polish acronym for Copper Mine and Mill Company) in the development of one the world's largest copper tailings disposal facility, located in South-West Poland. This paper describes the tailings disposal facilities, the geological features of the area with particular emphasis on the considerable influence of the various Pleistocene glaciations, and the geotechnical aspects of the design and construction. The geotechnical characterization of the tailings and of the foundation soils is described, focusing on their shear strength, on the mining-induced seismicity and on the factors controlling the stability of the ring-dam that confines the tailings. Finally, the results of the analyses of the stability of the dam, together with the details of the intensive monitoring of the performance of the dam, the latter carried out by KGHM, are presented.

1. INTRODUCTION

The paper illustrates the geotechnical aspects involved in the development of one of the world's largest copper tailings disposal at Zelazny Most in South-west Poland, close to the borders with the Czech Republic and Germany, Fig. 1.

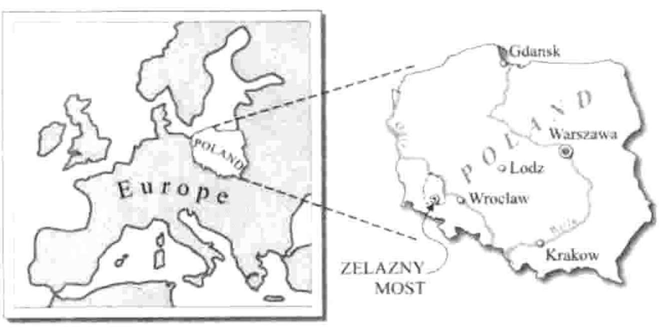


Figure 1. Zelazny Most copper tailings disposal location in Poland.

KGHM, a government owned mining company, started extracting copper ore in 1972, planning to continue until exhaustion of the ore body, estimated to occur in 2042. The ore-body is exploited by means of three different mines. At present, more than 480 Mm3 of tailings are stored in the disposal area, and the maximum height of the dam is close to 60 m. An aerial view of the Zelazny Most disposal is shown in Fig. 2.

Figure 2. Tailings disposal, aerial view.

As with all tailings dams, Zelazny Most poses a number challenges to the geotechnical engineers involved in their design and construction, and particularly the recurring subject of the possibility of flow liquefaction of the stored tailings, a phenomenon which has been responsible for the collapse of several tailings dams, and which frequently involve casualties. Another issue of concern for the designers of tailings dams is the stability of the dams, which depends on the height of the dam and the mechanical behaviour of the foundation soils.

The Zelazny Most tailings disposal is situated in an area of Poland that during the Pleistocene experienced at least three glaciations, see Fig. 3. The ice sheets that over-rode the Zelazny Most area induced substantial glacio-tectonic phenomena, the most important of which was the formation of extensive, sub-planar shear zones of remarkable depths in the underlying high plasticity Pliocene clay. Where these shear surfaces are present the available shear strength is close to residual, and consequently they pose a particular challenge to the geotechnical engineer responsible for the stability of the dams. In consideration of the magnitude and extent of the Zelazny Most scheme (the ring-dam is almost 15 km in circumference), and its importance for the continuing operation of the mining operations, KGHM appointed a four-member International Board of Experts (IBE). The IBE was formed in 1992, with the task, in cooperation with the Polish geotechnical expert (PGE) Prof. W. Wolski, of overseeing the safe development of the tailings dams by applying the observational method (Peck, 1969; 1980).

Figure 3. Maximum extension of the Pleistocene glaciations in South-West Poland.

This paper, co-authored by the IBE members, by the PGE and by a KGHM representative, summarizes the work carried out over the last 18 years to improve the geotechnical characterisation, to enhance the monitoring system, and to gain a deeper insight into the geotechnical problems related to the safe development of the Zelazny Most tailings disposal.

2. TAILINGS DISPOSAL

Each year, the international mining industry processes hundreds of millions of tonnes of earth and rock to extract the industrial, construction, and energy minerals that are the foundation of our modern technological civilization. A large portion of ore is waste mineral material, commonly referred to as tailings. In some cases, such as copper, the tailings often constitute more than 99% of the original ore. In most cases, the tailings are transported hydraulically from the mine beneficiation plant to a disposal area, referred to as a tailings pond. There the tailings are deposited; the water is decanted and re-cycled back to the beneficiation plant. The tailings pond includes a dam to retain the tailings; depending on the local topography, the dam may simply cross a valley, or it may form a dike around the entire pond. Tailings ponds are probably the largest man-made structures on Earth (ICOLD 2001). Typically, they are constructed over a period of decades. There are three basic types of tailings dams: downstream, upstream, and centreline (Vick 1983; Carrier 2003). Downstream construction is used when there is a sufficient volume of the coarse fraction of the tailings to construct the entire dam. A downstream dam is raised in a series of lifts as the level of the tailings rises during the course of mining and processing. Because the centreline of the crest of the dam and the downstream slope and toe move downstream as each new lift is added, the topography and property boundaries must also be appropriate. In certain cases, none of the tailings is suitable for raising a dam. Instead, local earthen materials are utilized, similar to conventional water supply dams. These are also often referred to as downstream tailings dams, in order to distinguish them from upstream tailings dams.

Upstream construction is used when the tailings are suitable for raising a dam. The coarse fraction of the tailings (i.e. sand) is separated from the fine fraction (i.e. silt and clay, usually called "slimes") by means of either spigots or cyclones that are periodically moved along the crest of the embankment as it is raised. A slurry of fine material runs down the beach into the pond; the coarse material is used to construct the shell in a series of lifts. The centreline of the crest moves upstream as each new lift is added. Centreline construction is a hybrid of the downstream and upstream methods. Coarse shell material is added in lifts, both upstream and downstream, so that the centreline of the crest of the dam remains in the same location throughout the life of the structure.

The Zelazny Most tailings dam is being raised by the upstream method, Fig. 4. It receives approximately 80,000 tonnes/day of tailings from the three underground copper mines. The tailings from the Lubin and Rudna Mines are siliceous and coarser, and are used to construct the shell of the dam by means of spigotting; the tailings from the Polkowice Mine are carbonaceous and finer and are deposited directly into the pond.

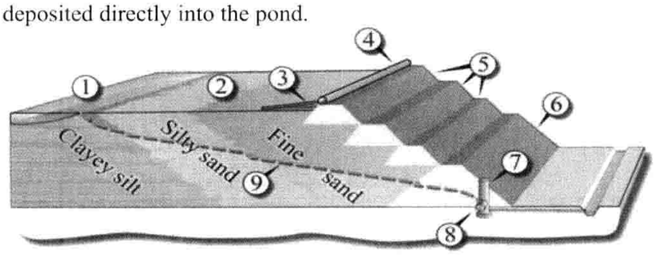


Figure 4. Schematic cross-section of Zelazny Most tailings disposal.

The Zelazny Most upstream tailings dam completely surrounds the pond; in plan view, it looks roughly like a motorcycle helmet, Fig. 5. The original ground surface was saddle-shaped, such that the eastern and western portions of the dam are higher than the Northern and Southern portions. A small stream, the Kalinówka River, had its headwaters in the central area of the Zelazny Most pond, and flowed eastward. Presently, the crest of the dam is at approximately elevation 170 m above sea level (asl). The height of the dam above the downstream natural grade varies from approximately 22 to 60 m. Zelazny Most is the largest tailings dam in Europe, and it is among the largest upstream tailings dams in the world.

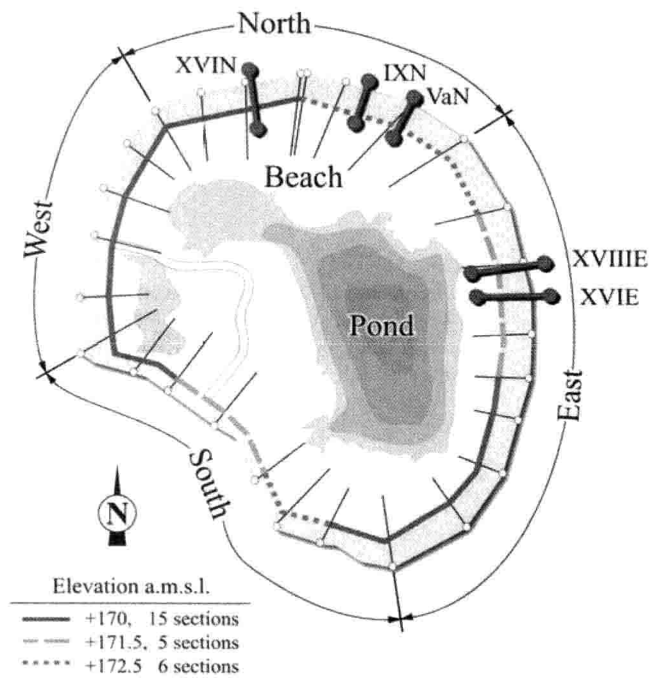


Figure 5. Dams elevations and relevant cross-sections.

Construction of the Zelazny Most starter dam from local earthen materials began in 1975; and deposition of tailings began in 1977.

Since then, the crest of the tailings has risen at a rate of approximately 1.25 to 1.5 m/yr, with a downstream slope of approximately 3.5 horizontal to 1 vertical. Furthermore, the beach (the distance from the crest to the edge of the pond) has been maintained at a minimum distance of 200 m. These are conservative practices that have the effect of displacing the softer, weaker slimes farther inward and produce a thick, strong, dilative shell. In addition, three levels of internal drains have been installed in the shell as the dam has been raised (Fig. 6), in order to depress the phreatic surface; a fourth level will be constructed at elevation 175 m. As a result, the stability of the dam is not controlled by the tailings, but instead is controlled by the foundation soils (see Sections 6.2 and 6.3).

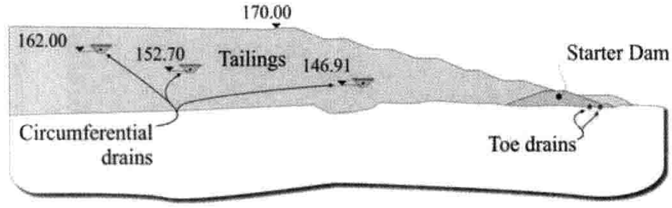


Figure 6. East Dam, location of the circumferential drains.

The observational method has always been a major component of the design and operation of the Zelazny Most tailings dam. In order to monitor the deposition of the tailings and the performance of the dam (see Section 5), there are approximately 300 surface monuments for measuring horizontal and vertical movements. In addition, a total station with 23 micro-mirrors has recently been installed to more closely monitor one particular section of the dam. There are also approximately 1800 piezometers, of which 870 piezometers have their tips in the tailings, 830 in the foundation soils, and 100 in the starter dam. Finally, there are 42 deep inclinometers. In the future, the dam may also be monitored by means of satellite radar interferometry.

There are approximately 480 Mm^3 of tailings presently stored in Zelazny Most. The end of deposition is projected to occur in 2042 (an astonishing 65-year filling period: all of the authors of this paper will be in Geotechnical Heaven by that time), with a total volume of approximately 933 Mm^3. There are more than five disposal alternatives presently under consideration, including:

- Zelazny Most only: final crest elevation of 207.5 to 210 m asl;
- Zelazny Most plus a South-west expansion, possibly including some dry-stacking: final crest elevation of 195.0 m;
- Zelazny Most plus re-activation of an older tailings pond (named Gilów), with or without the South-west expansion: final crest elevation of Zelazny Most 180 to 185 m and Gilów 199 to 202 m;
- Zelazny Most only but drains the pond and continue with dry-stacking: final elevation 207.5 to 210 m;
- Zelazny Most plus paste thickening a portion of the tailings for disposal back into the underground mine workings plus either the Southwest expansion or Gilów: final crest elevation of 195 m.

The history of tailings disposal at Zelazny Most is roughly at the halfway point. Deposition (and then reclamation) will occur many years into the future. Different disposal technologies are under study (e.g. dry-stacking and paste thickening) in order to manage safely this enormous volume in an environmentally sound manner.

3. LOCAL GEOLOGY

The Zelazny Most tailings dam is situated on a complex sequence of geological deposits, the basic stratigraphy of which is summarised in Table 1. From the ground surface downwards these consist of Pleistocene deposits, which are lake clays and out-wash sands and gravels. These are underlain by Pliocene deposits, which include thick strata of plastic clays and also thin brown coals, below which are Triassic deposits (including beds of halite: sodium chloride), below which in turn lies the ore body. The presence of the halite is significant, since ground-water from the mines, which is used for processing the ore, is consequently saline. As a result, the decant water in the tailings lagoon is also saline, giving rise to potential environmental problems.

The complexity of these deposits, particularly of those immediately below the dam, results largely from the Pleistocene history of the area. During this period a succession of ice sheets moved from North to South over central Europe. At least eight major ice advances are recognised in Poland, the Southern limits of six of which occur in the country. At least three of these glacial limits lie South of Zelazny Most, though one of these only does so by few kilometres (Ber, 2006). Thus at three extensive ice sheets passed over Zelazny Most (Fig. 3), where at times the ice thickness probably exceeded a kilometre.

It is no surprise, therefore, that the upper part of the geological sequence has been significantly affected by glacio-tectonics induced by the over-riding ice, probably to depths of about 100 m. As a consequence, the Pliocene deposits, particularly, are intensely sheared, folded and generally disturbed. In places, the initially horizontally bedded freshwater Pliocene sediments (sands, silts and clays), now have Quaternary deposits thrust within them.

Where there are thicker layers of Pliocene clay the glacial thrusting has resulted in the formation of shear zones, presumed to have been moved in a North- South direction. These shear zones have major implications for the stability of the tailings dam; one of these has a North- South extent of at least 600 m within the Pliocene clay.

Table 1. Summary of geology and index properties.

Age	Thickness	Lithology and index properties
Holocene	up to 4m	Alluvium. Variably clays, silty clays, sands, gravels. All these were removed from the dam foundations at construction.
Quaternary	up to 10m	Stratified glacial lake sediments: usually silty clay but sometimes clay.
	up to 30m	Fluvio-glacial sediments: usually sand (occasionally gravelly), often thinly (20cm) interbedded with silt or clay.
	up to 50m	Moraine clays: variable silty, more usually sandy clays, which become more sandy or gravelly with depth. All the Quaternary clays have properties in the ranges: w_{nat} = 7 - 26%; w_L = 20 - 50%; w_P= 10 - 18%; I_P = 10 - 30%; I_L = 0.02 - 0.22.
Pliocene	100- 150m	Clays, silty clays, silty sands, sands; rarely coarse sand and/or gravel. w_{nat} = 9-26%, w_L = 50-80%, w_P = 15-25%, I_P = 30-50%, but more plastic under North and East Dams, with w_L sometimes >90%, w_P >60%.
Trias		
Ore body		

3.1 Solifluction

As a consequence of the cold climate towards the end of the Pleistocene, after the last ice sheet to have reached Zelazny Most had melted, the phenomenon of solifluction is likely to have occurred. This process, which involves shearing at shallow depth probably due to mud slides, results in the presence of polished shear surfaces at or close to residual strength (e.g. Skempton 1964). As with the glacio-tectonic shear zones, but on a much smaller scale, these also have implications for the stability of the dam where they occur.

Experience in the UK, particularly in areas South of the major Pleistocene glacial limit, shows that solifluction shear surfaces occur extensively at shallow depths in clay soils. Where the slopes exceed about 7-8°, the mudslides were fairly extensive, and the shear surfaces run approximately parallel to the existing ground surface. Where the ground surface is less than 7-8°, down to inclinations as small as 2°, the solifluction shear surfaces are discontinuous, where the mud slides were tiny. Solifluction shears are usually encountered at relatively shallow depths, usually not much greater than 4-5m, often less. A classic example of a failure involving the presence of discontinuous solifluction shear surfaces is the Carsington Dam (Skempton 1985; Skempton and Coates 1985; Skempton and Vaughan 1993), which collapsed during construction when the dam had reached a height of about 40 m.

Detailed investigations at Zelazny Most, where the natural ground slopes rarely exceed 4-5°, showed that, as in the UK, there was soliflucted clay with discontinuous shear surfaces.

Three categories of solifluction were reported: low; medium; and high intensity; and also 'clay with/without solifluction structures'.

However, the solifluction shear surfaces did not occur below depths of 1.5 m, and were rather infrequent, and moreover were rarely inclined in a direction critical for the stability of the dam.

Consequently, for the medium and high intensity soliflucted clay it was assumed that strength parameters $c_r'=0$, $\varphi'=\tan^{-1}(1.4 \times \tan \varphi_r')$ were assumed to apply to a depth 1.5 m below the original ground surface. The multiplying factor of 1.4 allows for the discontinuous nature of the shear surfaces in the soliflucted clays. These parameters are used for design where clay soil occurs in the dam foundation just below the original ground surface.

4. GEOTECHNICAL SITE CHARACTERIZATION

4.1 Foundation Soils

Characterisation of the foundation soils is needed for several reasons. These include: (1), to establish the foundation geology, including its index properties; (2), to determine strength properties for limit equilibrium stability analyses; and (3), to estimate the in-situ stress state, stress-strain behaviour, and undrained and effective stress strength parameters for finite element analysis. This has been done by sampling from downstream of the toe of the dam (the "fore-field") so as far as possible to be sure that the soil is unaffected by the construction of the dam.

In doing this for the foundation soils it was quickly recognised that for stability the Pliocene clays were the most important element of the foundation, and so it is the characterisation of the clay that for this purpose is of greatest concern.

There are very few precedents for the construction of a major structure on stiff plastic clay which has been subject to glacio-tectonics. Perhaps the closest analogy that has been reported in the literature is Empingham Dam, in the United Kingdom, which is founded on the Upper Lias clay at a location where it has been subjected to the periglacial phenomenon of cambering (Kovacevic et al. 2007; Chandler 2010). Both at Zelazny Most, and at Empingham, the dam foundations have been affected by a stress field that is presumed to approximate to simple shear, and in both cases the consequential strains are substantial, probably well in excess of 100%. In these situations where the ground has been pre-sheared, the properties of the clay are very different from those expected of a conventional overconsolidated clay, which is usually presumed to have had a much simpler stress history, affected only by vertical unloading due to erosion.

Once the clay has been sheared, either by glacio-tectonics or by cambering, it is likely to be much less brittle than conventional stiff clay. Moreover it is to be expected that there will be extensive shear zones along which the strength has been reduced to, or close to, residual strength. The in-situ stresses will have changed, and may be close to passive if the ground surface is more or less horizontal (as at Zelazny Most), or less than passive if the ground is sloping and is unable to sustain the full magnitude of the passive stresses (as at Empingham).

Where clays exist below the dam foundation any existing shear zones will have an important influence on stability, and the in-situ stresses and undrained strength of the clay will also be important. The effect of the glacio-tectonics has resulted in extremely variable soil conditions, and it is to be expected that the in-situ stresses and undrained strength of the clay will be similarly variable.

These properties have all been examined with an extensive programme of undisturbed sampling and laboratory testing so as to provide information on the degree of variability of the physical properties of the foundation soils, particularly the clay soils which are critical for the stability of the dam, and hence allow a rational choice of the relevant parameters for design purposes, both for limit equilibrium and finite element analyses.

4.1.2 Estimating the in-situ Stress State in the Pliocene Clay.

The suction in samples of the Tertiary clay from the fore-field of the dam was measured so as to assess the in-situ stress state, knowledge of which is required for finite element analysis of the performance and deformation of the dam. This characterisation must be affected by the geological history of the clay, which is complex. First, erosion, including that resulting from the passage of Pleistocene ice, will have induced considerable over-consolidation, and second the glacio-tectonics are to be expected to have deformed the clay extensively, resulting in the clay being in a different state from that expected if it had only been subjected to K_0 conditions during normal consolidation and subsequent vertical unloading by surface erosion.

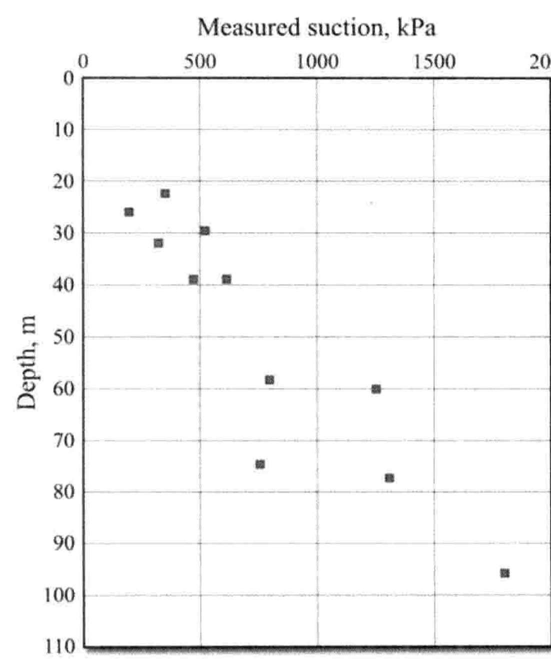
All samples were taken using a double-tube rotary sampler; they were of high quality. They were extruded shortly after extraction from the ground, trimmed to remove any disturbed material that might have caused a change in the suction of the sample due to pore water migration towards the centre of the sample, and then wrapped in aluminium foil to prevent evaporation. The samples were then either transferred to the testing laboratories for the triaxial testing, or were used for suction measurements at the on-site laboratory. This latter testing was carried out as soon as practical after sampling, sometimes within an hour, using the Ridley/Burland suction probe (Ridley and Burland, 1993), following the procedure they describe.

If it is assumed that the samples behave perfectly elastically when extracted from the ground, then the measured suction is related to the coefficient of earth pressure by the equation

$$p_k = \sigma_v'[K - A_S(K - 1)] \qquad (1)$$

where p_k is the measured suction, σ_v' is the vertical effective stress, and A_S the pore-pressure coefficient (Skempton 1954) due to sampling, which is taken as ⅓, and K is the coefficient of earth pressure, σ_h'/σ_v'. Since it is anticipated that the ice sheets will have applied a stress state akin to simple shear, the earth pressure coefficient K is unlikely to be K_0.

The values of p_k measured are given in Fig. 7 and the corresponding computed values of K are reported in Fig. 8.



N.B.: Samples with significant amounts of silt have been removed from this plot.

Figure 7. Suction measured in Pliocene clay, Ridley (2008).