Early Swedish Contributions to Geotechnical Engineering

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ABSTRACT Geotechnical engineering in Sweden has a long tradition due to the presence of soft and sensitive clay deposits along lake and sea shores, where most settlements were established. As the country increasingly took on the difficult tasks of constructing harbors, canals, and foundations for roads and railways, novel foundation concepts had to be developed. The establishing of an interdisciplinary "Geotechnical Commission" in 1914 consisting of geologists and civil engineers with the task to study landslides and slope failures laid the foundation for modern geotechnical field and laboratory testing methods and began the key role of geotechnical engineering in Swedish civil engineering. A very important aspect is the spirit of close cooperation between practitioners, engineers, and scientists, manifested in the Swedish Geotechnical Institute and the Swedish Pile Commission. The Swedish geotechnical practice has a long history of important accomplishments by individual engineers. A few notable contributions to geotechnical engineering by Swedish engineers and scientists from the early stages of civil engineering around 1600 until about 1960 are listed in the paper. The contributions encompass mining, canals, railways, harbors, foundations, earth retaining structures, dams, slope stability, and information systems.

1. INTRODUCTION

Geotechnical engineering in Sweden has a long tradition and early contributions by several Swedish engineers and scientists have had a profound influence on the current foundation design in and beyond Sweden. One contributing factor for the early development of soil and rock mechanics was the difficult geological conditions in Sweden with a dominance of thick deposits of soft, compressible clays — still a challenge to geotechnical engineers — and glacier-polished hard rock. Several important engineering works were carried out during the 19th century, such as the construction of the Göta Kanal, the growth of a network of railway lines and expansion of harbors. In connection with these projects, significant problems were encountered, involving driving tunnels through rock, embankment settlement, and landslides, and need for deep foundations.

2. THE VIKING PERIOD (790-1100 AD)

The Vikings selected their primary settlements and trading places along shore lines. For instance, the town of Birka, (located some 100 km west of Stockholm), probably constructed around 700 AD, became an important trading place with about 500 to 1,000 inhabitants. Vikings often chose to build houses and villages in inhospitable wet environments, such as along lake shores and riverbanks. These locations were ideal defensive habitats, but it was often difficult to construct settlements in such environments. Roads over soft soil areas made extensive use of 'fascine' types separation between road material and the soil — precursors of modern geotextile solutions. Piles were often needed and they were installed by digging post holes or by driving them into the ground. As in most of Northern Europe, where soft soil deposits dominated along shore lines, wood piles were driven down to 4 to 5 m depth, including where permanently flooded sediments existed. Menotti and Pranckenaite (2008) gave a detailed account of a technique for installation of wood piles into soft sediments at near-shore lacustrine deposits, as illustrated in Figure 1, showing how the piles were placed almost ‘effortlessly’ and very quickly by rotating the pile.

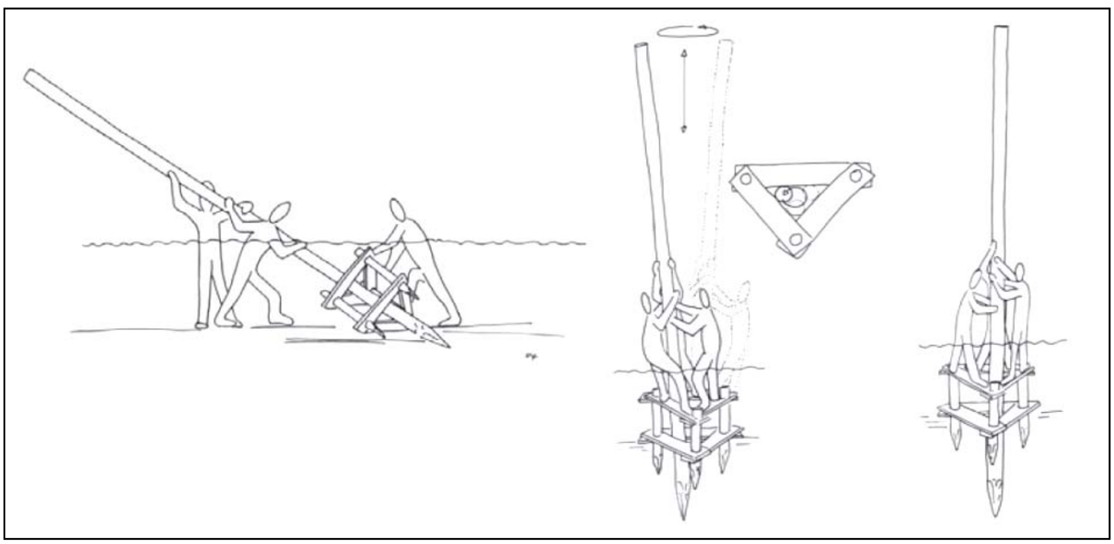

Fig. 1 Schematic illustration of the Bronze Age method of installing wood piles over water (from Menotti and Pranckenaite 2008)

Excavations at Birka have shown that the Vikings were able to construct a sophisticated harbor. During recent excavations, some 100 wood piles were found below water, forming a half-circle wave barrier. Thus, the harbor offered protection during warfare, but as Birka was as a major trading place, the piles also served to provide support for heavy, pier-like stone structures, as found during the archeological excavations. One of the best preserved Viking settlement has recently been discovered in County Louth, Ireland. Archeologists believe the settlement dates back to 841, the same year as Dublin was founded. The excavations show evidence of impressive engineering work, with an artificial island built to provide protection against attacks by the native Irish.

2. EARLY CONTRIBUTIONS (1600 – 1900)

2.1 Christopher Polhem (1661–1751)

Christopher Polhem was an outstanding scientist and engineer. After studying mathematics and mechanics at Uppsala University, he started in 1697 the first “Engineering School” in Sweden. Being recognized for his inventions, he was appointed by the Swedish King as “Director of Rock Mechanics” and later became responsible for the operation of several important mines. He was responsible for the design of sluices and locks along the Göta River and also designed numerous dams for mines. He introduced significant and revolutionary engineering design and construction solutions at projects in Sweden and abroad. Early Swedish piling methods were developed and refined by Christopher Polhem as they were applied to piled foundations for the Stockholm harbor. He developed a piling rig for driving inclined piles, which is described in the 1753 proceedings of the Swedish Royal Academy of Science.

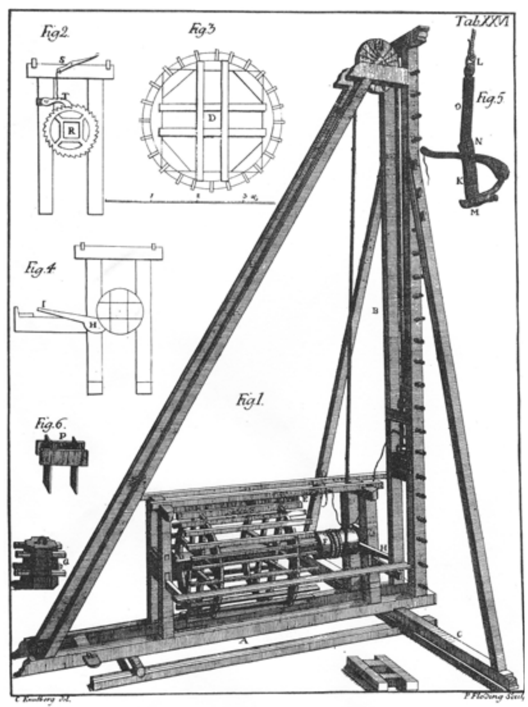

Fig. 2 Christopher Polhem in 1741 and a piling rig designed by Polhem for the construction of the sluice and lock in Stockholm

2.2 Baltzar von Platen (1766-1829)

Baltzar von Platen is considered "Father of the Göta Kanal", the 195 km long canal that links the Baltic Sea with the North Sea across southern Sweden. Baltzar von Platen was in charge of the construction of several canals in Sweden. Work on the Göta Kanal canal started in 1810 and von Platen, in collaboration with the British engineer Telford, designed and oversaw the construction of the canal, which comprises 58 locks and sluices and extensive excavations (more than 2 million cubic metre); some at locations with very difficult soil conditions (soft, compressible clays). The eastern section of the canal was completed in 1822 and the western section in 1832.

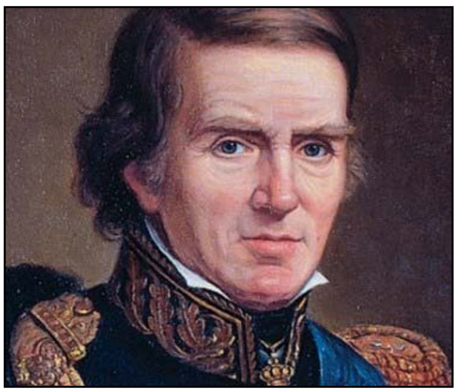

Fig. 3 Baltzar von Platen, and a Göta Kanal view after completion about 1840

2.3 Alfred Nobel (1833 – 1896)

Alfred Nobel was born in Stockholm. His father was an engineer and inventor who built bridges and buildings in Stockholm. Together with his father and brother, Alfred Nobel performed experiments to develop nitroglycerine as a commercially and technically useful explosive. He soon found that mixing nitroglycerine with silica would turn the liquid into a paste which could be shaped into rods of a size and form suitable for insertion into drilling holes. In 1867, he patented this material under the name of dynamite. To be able to set off the dynamite rods, he also invented a detonator (blasting cap) that could be ignited by lighting a fuse. Nobel's inventions were made at the same time as the diamond drilling crown and the pneumatic drill came into general use. Together, these inventions drastically reduced the cost of blasting rock, constructing tunnels, and building canals, which processes are necessary for developing mines and for performing many other forms of construction work. As a result of the work by Alfred Nobel, mining, railroad building, and other construction, not least dam construction, became safer, more efficient, and cheaper.

2.4 Albert Atterberg (1846–1916)

Albert Mauritz Atterberg was a leading chemist and agricultural scientist. He carried out important studies of the mineralogical composition of soils and introduced the now well known and generally accepted particle size limits of 0.002, 0.02, 0.2, 2, 20, and 200 mm, and 0.006, 0.06, 0.6, 6, 60, and 600 mm. Atterberg also investigated the flocculation of different soil fractions, which he obtained by sedimentation, and most of his soil classification system is still used world-wide. He proposed simple tests to differentiate between highly plastic (clay) and slightly plastic (silt) and non-plastic soils. Atterberg classified clays according to consistency, using water content as limiting parameter (plasticity index, plastic limit and liquid limit). Terzaghi accepted the consistency limits proposed by Atterberg and included these in his book "Erdbaumechanik" published in 1925. Atterberg also studied permeability and capillarity and contributed to the assessment of soils subjected to freezing.

Fig. 4 Alfred Nobel

Fig. 5 Albert Mauritz Atterberg

2.5 Gerard DeGeer (1858-1943)

Gerard Jacob DeGeer was a Swedish geologist who made significant contributions to Quaternary geology, in particular the late Quaternary deposits and landforms of southern Sweden. In 1897, DeGeer was appointed Professor of Geology at Stockholm University, and, later, University President (1902-1910). His early studies of raised beaches, used to reconstruct glacio-isostatic sea level changes, and his mapping of glacial moraines to reconstruct the extent of the last Scandinavian ice sheet and its pattern of deglaciation, are widely recognized. Through DeGeer's work, quaternary geology was established as a key part of the evolving Swedish work on civil engineering foundation design. DeGeer noticed that the appearance of laminated sediments deposited in glacial lakes at the margin of the retreating Scandinavian ice sheet at the end of the last ice age closely resembled tree-rings, and he pioneered their use in geochronology. DeGeer called these annual sedimentary layers "varves", a Swedish word that now has gained international status. (An additional term minted by DeGeer is "trap rock", which describes a sedimentary rock eroded stepwise. The Swedish word for "step" is "trappa"). DeGeer recognized the potential of varves in establishing annual chronologies of past climatic and environmental change. DeGeer was the first Chairman of the Swedish Geotechnical Commission.

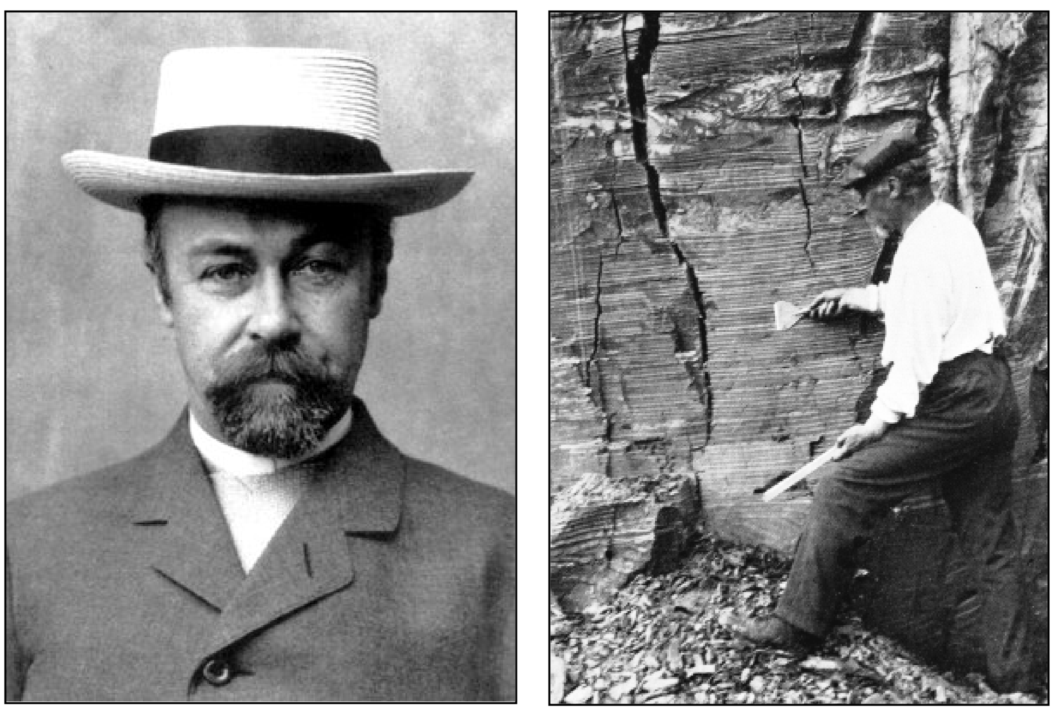

Fig. 6 G. DeGeer in 1900 and sampling varves in New England in 1920

3. SWEDISH GEOTECHNICAL COMMISSION (1914 – 1922)

An important development of Swedish geotechnical engineering took place when a commission consisting of geologists and engineers was appointed by the Swedish State Railways to investigate the cause of a number of landslides that had recently occurred. The committee constituted itself as the "State Railways Geotechnical Commission" and worked between 1914 and 1922. Its final report, the first publication ever using the word "geotechnical", is regarded as a milestone in modern geotechnical engineering. During the work, a permanent geotechnical laboratory was set up within the Swedish State Railways as probably the first of its kind in the world. The Geotechnical Commission worked first under the chairmanship of Professor Gerald DeGeer and, then, under Professor Wolmar Fellenius. The Secretary of the Commission was John Olsson.

The Swedish Railways Geotechnical Commission investigated more than 300 embankment failures and land slips, introduced field and laboratory investigation methods, and, thus, developed a rational approach to field investigations and geotechnical analysis. The following closing remarks were made in the report.

"*The Committee calls special attention to the fact that in several cases it is not yet possible to exactly determine the conditions of balance in loads on weak ground. By means of some examples, the Committee shows that the demand for absolute safety is not defensible financially and roughly estimates the costs of similar measures on the system of state railways to rather more than less than one hundred million Swedish crowns. At such places where there is a risk, but where to ensure complete security is not within reason on account of the expense, the Committee considers it better to endeavour to eliminate the risks of railway disasters, and this can be done by introducing effective guard arrangements, especially the automatic warning system. The Committee lastly calls attention to the fact that the solution of the geotechnical question lies in a considerably deeper and more extensive study of the same, and emphasizes the wish that the building department of the state may arrange a special medium for geotechnical investigation.*"

The report was notable for an effective quantitative soil classification system and its wide application of field and laboratory techniques in conjunction with improved methods of sampling and strength determination. The Swedish Weight Sounding Method, which still is in use, became an efficient tool to investigate soil stratification. Note that in Figure 7, in accordance with the instructions by the geotechnical commission, the engineer (the man to the right), touches the top of the sounding rod in order to detect rod vibrations when the sounding point penetrates from soft clay to sandy layers, as this information was considered important for assessing drainage conditions.

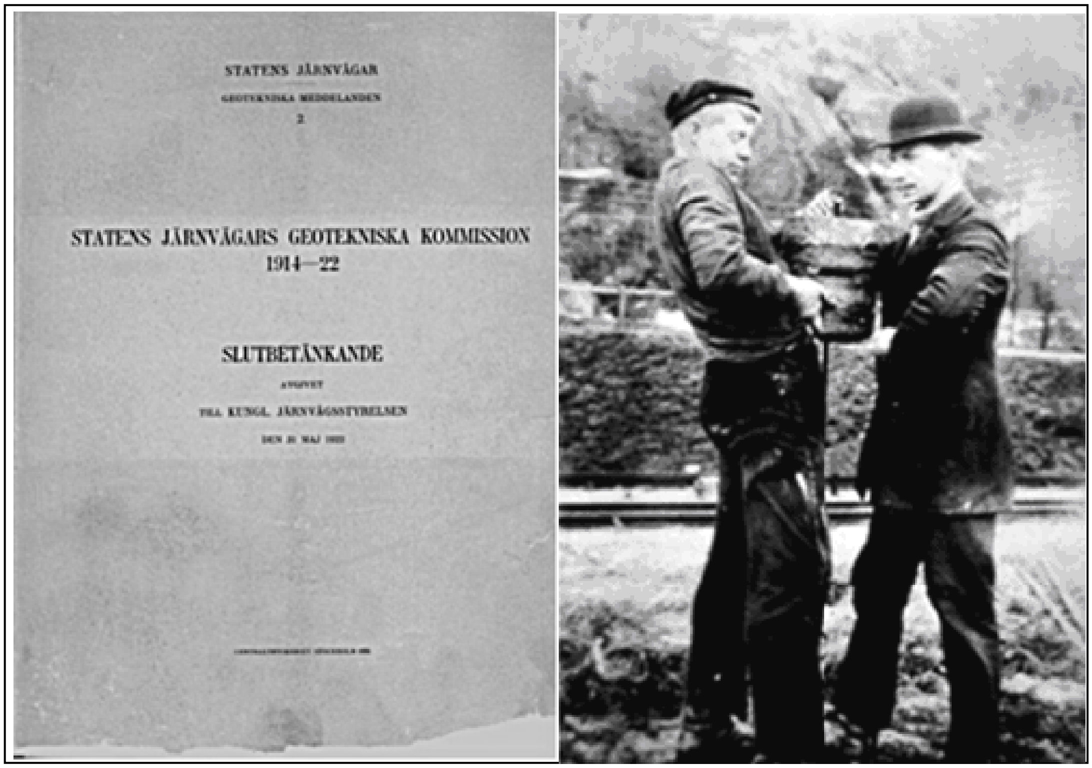

Fig. 7 The Swedish Geotechnical Commission Final Report, Meddelanden 2 (1922) and an illustration of the weight sounding method taken from the report

3.1 Swedish Method of Stability Analysis

Two years after the inception of the Railway Commission, the now classical slide of the Stigberg Quay in the Göteborg harbor occurred in March 1916, one year after its construction. Here too, a special committee was set up with the task of discovering the reasons for the slide and of making recommendations for the design of a new quay. The analysis of the Stigberg slide employed a slip circle method developed by Sven Hultin (1889–1952), Professor at Chalmers Institute of Technology, and Knut Pettersson, engineer with Göteborg Harbor. The method is based on the assumption that the clay could be treated as a cohesionless material. The back calculation gave a friction angle value as low as 9°.

3.2 Wolmar Fellenius (1876-1957)

Wolmar Fellenius was professor of Hydraulic Engineering at the Royal Institute of Technology (KTH) in Stockholm, and actively researching the stability of slopes, quays, and dams. He held honorary doctorate degrees from the German universities of Karlsruhe and Darmstadt.

Wolmar Fellenius extended the slip circle method to cohesive soils and soils with both friction and cohesion. He also introduced the concept of safety factors for foundations as they are used today (Fellenius 1926a, 1926b), as ratio between available total strength and acting forces, or for slope stability, as the ratio between resisting and forcing rotating moments. The work resulted in the development of the "Swedish Slip Circle Method", or "Fellenius Method", in which the most dangerous failure surface is determined by combined analytical and graphical method (see Figure 8). The method was brought to international attention by K. Terzaghi and D.W. Taylor and became widely adopted. Fellenius published several papers on the analysis of stability of slopes and foundations between 1916 and 1927, of which the best known is his “Erdstatische Berechnungen” in 1926 (which acknowledges the early work of Petterson and Hultin) and "Calculation of the Stability of Earth Dams" presented to the 1936 Second Congress on Large Dams, Washington, DC. His several publications on reinforced concrete construction in 1902 - 1910 were the base for early Swedish reinforced concrete design. He was one of the initiators of the International Society of Hydraulic Research, for which he acted as President from its foundation until after the WWII.

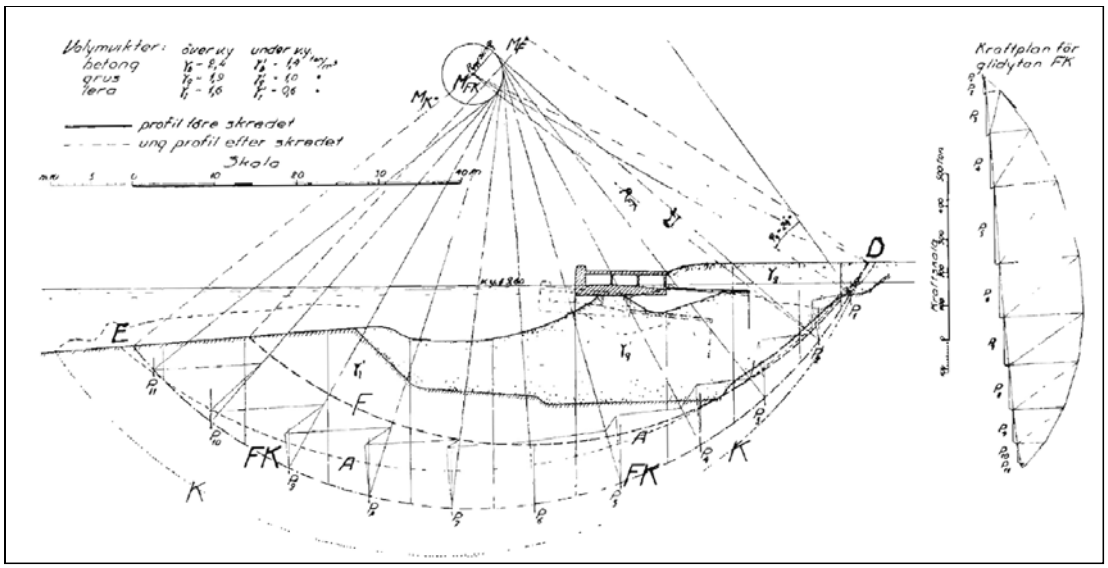

Fig. 8 Construction of circular failure plane at Stigberg Quay, in Göteborg Harbor (from Fellenius 1926a)

3.3 John Olsson (1880 – 1969)

John Olsson was the secretary of the Commission and made outstanding contributions to the work of the Commission. When the State Railways Geotechnical Laboratory was formed, he was appointed chief of the laboratory, where he served until 1946. John Olsson became the "father of Swedish Geotechnical Engineering practice".

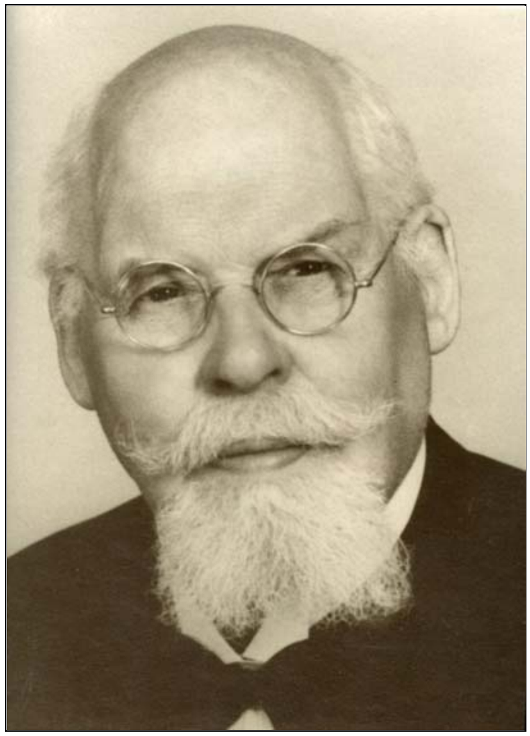

Fig. 9 Wolmar Fellenius

As Secretary, John Olsson, developed a simple unconfined compression apparatus and invented the fall cone test in 1915 to measure the strength of soft clay. He introduced the concept of sensitivity and investigated the shear strengths of clays as affected by remolding and disturbance through the fall cone apparatus. The fall cone was also used to determine the "fineness number" of a soil, today called the fall cone liquid limit. Moreover, the very first vane borer, as far as can be determined, was designed by John Olsson, and first used in 1919 during the construction of the Lidingö Bridge near Stockholm. The objective was to determine in-situ the soil stiffness (modulus of reaction) to assess potential for buckling of long piles. Two tests were performed at the same depth with two sizes of blades (both with blade height 500 mm; widths were 300 and 700 mm, respectively). The torsional moment of both blades was determined and a measure of the soil resistance was obtained by subtracting the two values (Bjerrum and Flodin, 1960). About 1923, John Olsson developed also the first piston sampler, which he presented in a report to ICOLD in Washington. The Swedish weight sounding method (Figure 7) originates from the Commission and is a development of the method used by W. Fellenius for the Göteborg Harbor as early as 1908. A soil boring manual, Meddelande 1 (Statens Järnvägar 1917) published by the Commission became an early guide for site exploration, handling of samples, classification of soils, and presentation of field and laboratory data.

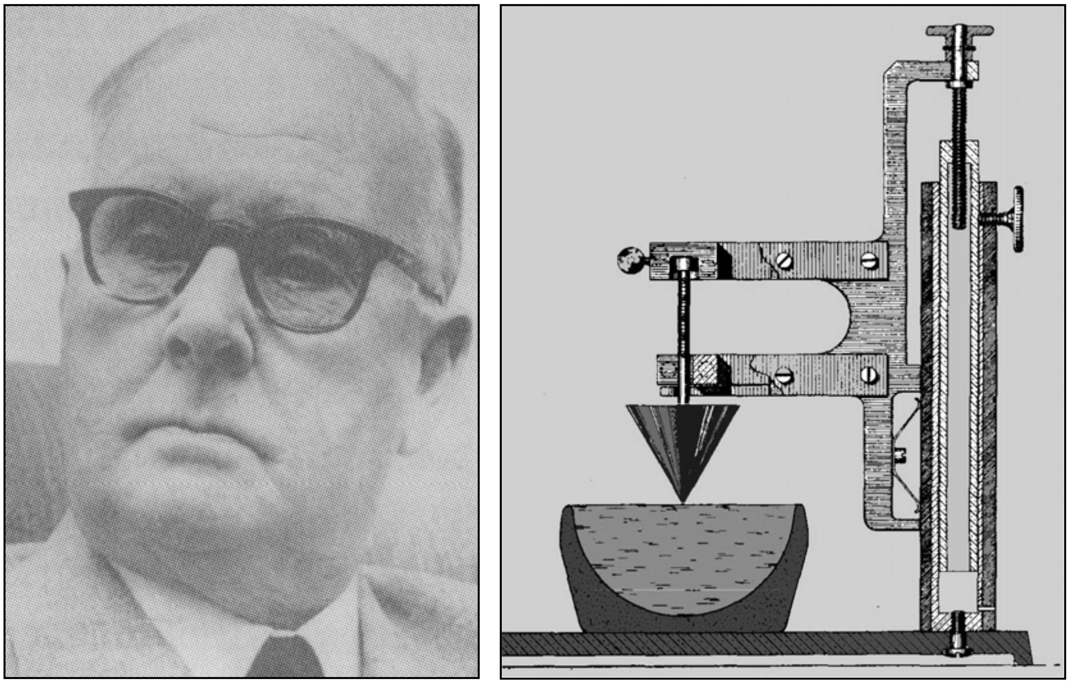

Fig. 10 John Olsson who also developed the fall cone test for determination of clay strength and sensitivity

3.4 Gunnar Beskow (1901-1991)

Due to the harsh climatic conditions in Sweden, the construction of roads and railways had to take into account the effect of soil freezing. Beskow was first to point out the importance of the capillarity of soils for the proper understanding of the frost and thaw mechanism. In 1927, at the age of 26, Beskow developed a laboratory testing device and worked out a method to quickly determine even great capillary rises using small quantities of soil specimen. He established a correlation between the capillary rise in granular soils and their grain size. In 1949, Beskow became professor of geology at Chalmers Technological Institute in Göteborg. His work on capillary rise and soil freezing became internationally acknowledged and is still widely accepted.

4. SWEDISH GEOTECHNICAL INSTITUTE

The Swedish Geotechnical Institute (SGI) played and continues to play an important role in the practical application of research and innovative foundation methods. Since its start in 1944, the SGI has been the fertile breeding ground for many geotechnical engineers who have since made their own contribution to the progress of Swedish geotechnical practice and international store of knowledge. SGI also became an international meeting place for leading geotechnical and foundation engineers from different parts of the world, several of them spending months at the institute to practice Swedish geotechnical engineering concepts.

4.1 Walter Kjellman (1905-1955)

Walter Kjellman, a student under Terzaghi in Vienna, was appointed head of the Geotechnical Department of the National Swedish Road Authority at its start in 1936. The department was reorganized as the Swedish Geotechnical Institute (SGI) in 1944. Considerable uncertainty existed at that time concerning the evaluation of the shear strength of clays. Kjellman was amongst the first to suggest that drained triaxial and shear tests should be used for the analysis of slopes and excavations in clay and embankments on clay. He constructed a true triaxial apparatus, initially intended for sand, using cubical samples where the principal stresses could be varied independently. In the early 1940s, he invented the first wick drain, the Kjellman wick, a thin, 100 mm wide bandshaped drain made from cardboard with internal channels for water. He also developed a drain stitcher for the installation of wick drains. Test embankments for full-scale study of the acceleration of consolidation using vertical drains were constructed, employing vacuum treatment to improving the surcharge loading. Walter Kjellman and the many engineers working with him at SGI contributed significantly to many other developments of Swedish geotechnical engineering.

Kjellman appreciated early on the importance of geotechnical design based on information from in-situ testing, such as different sounding methods. In 1940 he invented an ingenious device, the Iskymeter, based on the umbrella principle as shown in Figure 11. The Iskymeter consists of two wings which can be retracted to form a penetrometer. The Iskymeter is pushed in the ground and the penetration resistance is measured, providing information regarding soil stratification. Once the maximum penetration depth has been reached, the Iskymer probe is expanded and the pulling resistance is measured continuously, providing a measure of the undrained shear strength. This concept is similar to the ball and bar probed developed by Randolph more than 50 years later. The Iskymeter concept is still one of the most ingenious geotechnical field testing devices and a forerunner of the “T-bar penetrometer” (Randolph and Stewart, 1994).

5. Contributions by Engineers at SGI

Walter Kjellman and the many engineers working with him at SGI contributed significantly to many other developments of Swedish geotechnical engineering.

Torsten Kallstenius (1910 – 1979) was head of the mechanical department of SGI where he was responsible for the development and construction of geotechnical equipment. He constructed in 1947 the first drain stitcher for the paper wick, used at Stockholm Arlanda airport, developed different types of geotechnical equipment, such as hydraulic piezometers, settlement measuring devices, and the SGI inclinometer. As chairman of the Swedish penetration testing committee, he developed concepts for the practical application and interpretation of different types of penetrometers, including the Iskymeter, (Kallstenius 1961). He became internationally most well known for the development of the SGI piston and foil sampler. He received in 1963 a doctoral degree for his work on an innovative piston sampler (Kallstenius, 1963).

Fig. 11 Walter Kjellman and demonstration of the drain stitcher in 1945 at Upplands Väsby, Sweden with Karl Terzaghi attending

Fig. 12 The Iskymeter

Nils Flodin (1915 - 1991) started at the Geotechnical Institute as a field engineer but developed keen interest in Swedish geotechnical history, notably books, papers, and reports, which he actively gathered into a library that became the SGI Library with him as head. The SGI Library is today recognized internationally as one of the leading libraries with geotechnical information systems and literature source freely available to the geotechnical community. He was deeply involved since the initiation in 1953 with the international classification system for geotechnical literature. He is the co-author of “A History of Civil Engineering in Soft Clay” (Flodin and Broms 1981). Nils Flodin's contributions to the Swedish Geotechnical Society were extraordinary. A member from 1955 until his death, he served as secretary from 1963-81 and provided an invaluable element of continuity in the Society's affairs. The appreciation which he earned is perhaps best shown by the fact that he is the only member of the Society to have been invited to serve as a permanent member of the society's board of directors. He was elected an Honorary Life Member of the Society in 1978.

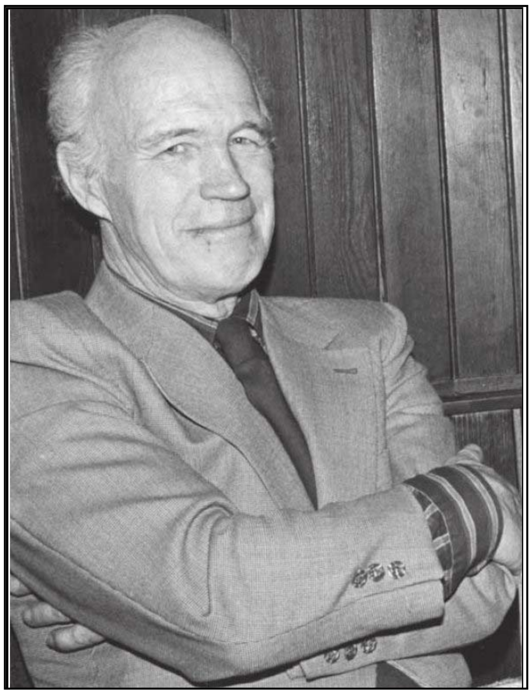

Fig. 13 Nils Flodin

Oleg Wager (1915 - 1992) worked at the National Swedish Road Authority with Walter Kjellman as supervisor and accompanied Kjellman to the Swedish Geotechnical Institute in 1944. Wager worked both in consulting and research and took part in the development of new field equipment, particularly the Swedish foil sampler—a device for taking very long undisturbed samples (Kjellman et al. 1950). He was responsible for the many field experiments required in its development. In the early 1950s, he supervised the field trials of the Kjellman vacuum preloading method. In the 1960s, he further developed the wick drain designing it with a central plastic core surrounded by a pervious synthetic filter. His development became the model for modern wick drains. In the 1970s, Wager also pioneered the design and use of horizontal reinforcement using geotextiles. Holtz and Massarsch (1976) described a particular geotextile application for stability of embankments on natural slopes in combination with relief piles (Holtz et al. 1994).

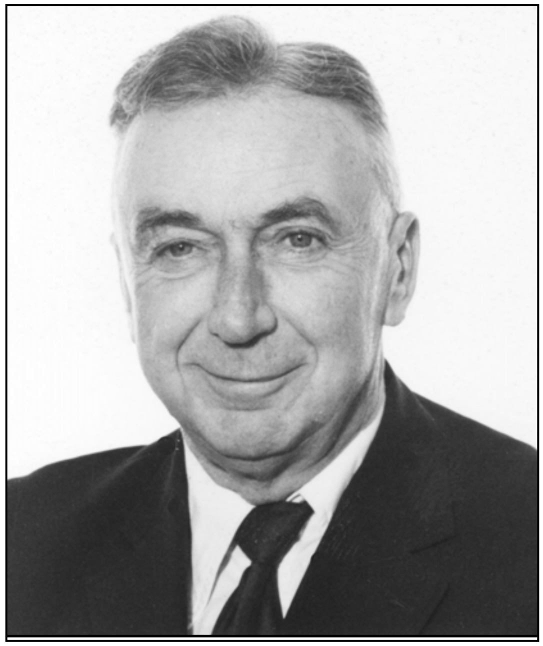

Fig. 14 Oleg Wager

Lyman Cadling (1917 - 2010) obtained a Masters degree from Harvard University under Casagrande and is most well-known for the development of the modern vane test device. While the first vane borer with two blades was designed by John Olsson, the vane borer as used today was presented for the first time by Lyman Carlsson (later changed name to Cadling) in 1948 at the Second International Conference in Rotterdam. A report on a more advanced device was published two years later (Cadling and Odenstad 1950). The original Cadling vane borer, which was designed for soft soil, was pushed into the soil without preboring. The rod was encased to eliminate friction, and torque required to rotate the vane was measured at the ground surface by a separate instrument. From the torque and geometry of the vane, the shear strength of the soil was calculated. The blades were made as thin as possible to reduce the disturbance when the vane was pushed into the soil. The vane was initially unprotected, but was later provided with a protective sheath to prevent damage from encountering stones in the clay.

6. THE SWEDISH COMMISSION ON PILE RESEARCH

The Swedish Commission on Pile Research was founded in 1957, when the Geotechnical Department of the Swedish State Railways was faced with uncertainties regarding deep foundations of the extensive new railway work in the cities of Göteborg and Stockholm. The head of the department, Bror Fellenius, brought together representatives of academia (e.g., Hans-Christian Fischer of Uppsala University) and practitioners (e.g., Sölve Severinsson of Nya Asfalt AB), to establish a committee for research in piling and piled foundations. The committee was later appointed to the Swedish Academy of Engineering Sciences as the Commission on Pile Research.

From its inception, the Commission it served as an "interdisciplinary forum" for sharing of information and efforts, as it was made up of essentially all contractors, geotechnical engineering consultants, researchers, and representatives of building authorities in Sweden. It also has several members from the neighboring countries. In 1959, the Commission performed and reported the first ever dynamic measurements on very long ordinary reinforced, precast concrete piles, clarifying many of the question pertaining to damaging tension forces during initial driving and set-up of capacity with time. The Pile Commission has had a major positive effect on the Swedish development of piling techniques and building codes, and has published a large number of reports and practical guidelines.

6.1 Bror Fellenius (1903-1990)

Bror Fellenius—son of W. Fellenius and father of the second author—started his geotechnical career at the harbor office of the City of Göteborg, and later moved to the National Swedish Road Authority in Stockholm. He developed methods for determining undrained shear strength of clay and showed that it increased linearly with depth (published in the 1936 First International Conference on Soil Mechanics and Foundation Engineering). His research work in the 1930s also shed light on many of the then unsolved questions about long piles in clay, such as demonstrating the existence of negative skin friction and that even very slender piles in very soft inorganic clay cannot buckle provided they are installed straight, i.e., not bent or doglegged, demonstrating that straight piles will yield structurally before buckling develops.

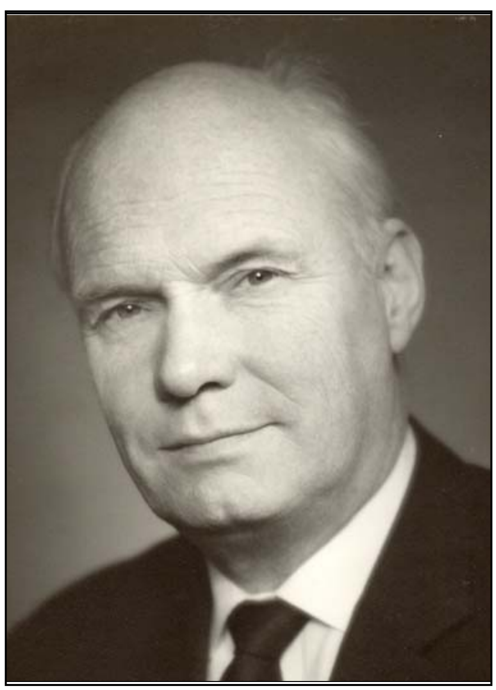

Fig. 15 Bror Fellenius

In 1946, Bror Fellenius succeeded John Olson as head of the Geotechnical Department of the Swedish State Railways. He was a member of the group who in 1948 started the Swedish Geotechnical Society. In 1970, he was appointed Honorary Member of the Society.

7. CONCLUSIONS

One of the main reasons for the early development of Swedish geotechnical engineering was the many challenges that arose due to the existence of very soft and sensitive clay deposits along lake and sea shores, where most settlements were established. In order to deal with the difficult tasks of constructing harbors, canals and foundations for roads and railways, novel foundation concepts had to be developed.

The Swedish geotechnical practice has a long history of innovations in geotechnical engineering with important accomplishments by individual engineers; only a select few are mentioned in the paper. Establishment of an interdisciplinary "Geotechnical Commission" consisting of geologists and civil engineers with the task to study landslides and slope failures laid the foundation for modern geotechnical field and laboratory testing methods and helped to establish the key role of geotechnical engineering in civil engineering. Swedish universities recognize geotechnical engineering as a central part of the civil engineering curriculum, which is promising for the future of Swedish engineering, civil as well as geotechnical.

Sweden has produced some outstanding geotechnical engineers, however, the most important aspect is the spirit of close cooperation between practitioners, engineers and scientists drawn from the Swedish culture of collaboration and consultation. Applied to geotechnical engineering, this resulted in the creation of the Swedish Geotechnical Institute and the establishment of a unique breeding ground for piling technology, the Swedish Pile Commission.

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