The Heritage of Swedish Foundation Engineering

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ABSTRACT The geology of Sweden is characterized by the most recent glacial period with deposition of very soft clays and loose sand. Due to these difficult geotechnical conditions, new, innovative foundation and ground improvement methods were developed, which today are used in many other countries. Over centuries, Swedish scientists and engineers have made important contributions to the developments in foundation engineering. An important aspect of the success of Swedish foundation engineering in practice is the spirit of close cooperation between practitioners, engineers, and scientists. This has been achieved by the establishing of commissions, with the aim of finding solution of geotechnical problems. The paper focuses on developments in foundation engineering during the last century and does cover present activities in Sweden.

Introduction

Soil mechanics and geotechnical engineering play an important role in Swedish society, as most construction activities require the consideration of foundation conditions. The objective of the paper is to summarize important developments in foundation engineering, primarily during the past century, which have influenced geotechnical engineering also in other countries. These achievements are the result of contributions by scientists, engineers and practitioners, only a few of which can be named. The paper does not claim to cover all aspects of geotechnical engineering, as emphasis is on the solution of foundation engineering problems from an international perspective. Thus, ongoing or recent research and development projects and activities within the geotechnical community are not included, as this would exceed the scope of the paper.

Over the centuries, Swedish scientists and engineers contributed to the development of civil and foundation engineering. One important reason is the geology of Sweden, which is characterized by the most recent glacial period, resulting in the deposition of soft clays and loose sands in the coastal areas and dense glacial till in the interior of the country. 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. A description of early Swedish geotechnical engineering has been presented in several publications by Flodin and Broms (1981), Broms and Flodin (1988), Massarsch and Fellenius (2012). The historic development of Swedish geotechnical and foundation engineering can be divided into four periods. During the “Early Era”, engineers were active in different sectors of military, civil, and mining engineering. Next, the “Industrial Era” comprised developments during the industrial revolution, when the transportation infrastructure of the country was modernized and extended. During the third period, possibly the “Golden era” of Swedish geotechnical engineering, which started at the end of the 19th century and lasted the following fifty years, geologists, engineers and scientists helped to establish modern geotechnical engineering. But also during the recent past, the “Modern Era”, several important contributions to geotechnical and foundation engineering which originated in Sweden, are used in many countries today.

The “Geotechnical” Commission

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 embankment failures and landslides that had recently occurred. The committee constituted itself as the "State Railways Geotechnical Commission" and worked between 1914 and 1922. The Geotechnical Commission worked first under the chairmanship of Professor Gerald DeGeer and, then, under Professor Wolmar Fellenius. Fellenius was professor of hydraulic engineering at the Royal Institute of Technology (KTH) in Stockholm, and actively researching the stability of embankments, quays, and dams. Fellenius introduced the concept of safety factors for foundations as they are used today, as ratio between available total strength and acting forces, or for slope stability, as the ratio between resisting and forcing rotating moments. The concept was brought to international attention by K. Terzaghi and D.W. Taylor and became widely adopted. Fellenius also published several papers on reinforced concrete construction in 1902 - 1910, which became the base for early Swedish reinforced concrete design. John Olsson, who became secretary of the Geotechnical Commission, made outstanding contributions to its work and is known as the "father of Swedish Geotechnical Engineering practice". The final report by the Geotechnical Commission - the first publication ever using the word "geotechnical" - is regarded 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 investigated more than 300 embankment failures and "land slips", introduced new field and laboratory investigation methods and developed a rational approach to field investigations and geotechnical analysis. The following closing remarks were made in the report by the Geotechnical Commission:

"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 endeavor to eliminate the risks of railway disasters, and this can be done by introducing effective guard arrangements, especially the automatic warning system. The Committee largely 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 conclusions of the Geotechnical Commission can be interpreted as the first formulation of the “Observational Method”, a practical concept of solving difficult problems by instrumentation and monitoring, which has been adopted as a design concept in Eurocode 7, EN 1997.

The Swedish Geotechnical Institute

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 in 1944. 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. kjellman and the many engineers working with him at SGI contributed significantly to many developments of Swedish geotechnical and foundation engineering. For many years, SGI became a meeting point between Swedish geotechnical engineers and visitors from around the globe. This tradition, which was initiated by kjellman, has continued until today. Nils Flodin, who started at the Geotechnical Institute as a field engineer, developed a 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. He was deeply involved since the initiation in 1953 with the international classification system for geotechnical literature. The SGI Library is today recognized internationally as one of the leading libraries covering all aspects of geotechnical information. The geotechnical information system is freely available through the Internet-based SGI Line to the geotechnical community (http://www.swedgeo.se/). Especially under the leadership of Bengt Broms, SGI 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 learn about, and get acquainted with Swedish geotechnical engineering concepts.

The developments in foundation engineering described in the following sections, would not have been possible without the innovative spirit at SGI, which made it possible for many engineers—with and without formal training—to realize new, innovative ideas.

Geotechnical Engineering Organizations

Swedish Geotechnical Society

The Swedish Geotechnical Society (SGF) plays a central role in all areas of geotechnical engineering. Founded in 1950, it is one of the oldest – and largest - member societies of the international geotechnical society, ISSMGE. SGF members have been active in many activities of ISSMGE, for instance as representatives in technical committees and organizing committees of regional and international conferences. SGF hosted the X International Conference on Soil Mechanics and Foundation Engineering (ICSMGE), held in Stockholm in 1981, with Prof. Sven Hansbo as Chairman. Prof. Bengt B. Broms served as ISSMGE president from 1985 – 1989.

SGF acts also as the turnstile of information exchange within Sweden and internationally, especially thanks to a number of very active technical committees. SGF has taken an active role in the preparation of the Eurocodes and ISO standards. Under the leadership of Gunilla Franzén and in cooperation with other organizations, SGF has initiated and operates a special commission (“Knutpunkten Geostandarder“) with the task of implementing Eurocodes in practice. SGF publishes also a series of reports in Swedish and English, covering many aspects of geotechnical and foundation engineering.

SAFE – Swedish Association of Foundation Engineering

SAFE, the Swedish Association of Foundation Engineering, is a member of the European Federation of Foundation Contractors (EFFC), founded in 2008 with the aim to provide an open and neutral arena for all participants in the Swedish construction sector. The focus is on the execution process in the foundation industry including questions of safety, mutual qualification and a more transparent procurement. Another important task for SAFE has been to facilitate and sponsor the development of execution standards in the foundation sector.
Sweden has chaired several working groups on foundation engineering standards - Execution of special geotechnical work:

- EN 12699 - Displacement piles (Convenor: Björn Lundahl; Secretary: Carl-John Grävare)
- EN 14679 – Deep Mixing (Convenor: K. Rainer Massarsch; Secretary: Sven Hansbo)
- EN 15237 – Vertical Drainage (Convenor: K. Rainer Massarsch; Secretary: Sven Hansbo)
- EN 14490 – Soil Nailing (Convenor: Gunilla Franzén; Secretary: Sven Hansbo).

**SBUF – Development Fund of the Construction Industry**

Research and development activities in Sweden are carried out at several technical universities, in close cooperation with the construction industry. A major part of foundation engineering research has been – and still is - funded by “The Development Fund of the Swedish Construction Industry” (SBUF), the construction industry's organization for research and development. SBUF has actively supported international cooperation and participation in standardization activities. An important aspect of SBUF-sponsored research has been the dissemination of research results to the construction industry in Sweden and abroad.

**Research and Development**

Research in the area of foundation engineering is carried out at technical universities but also within the private sector, such as consulting and contracting companies. Also governmental organizations sponsor and participate in foundation engineering research. The Royal Institute of Technology (KTH) and Chalmers Technical University (CTH) are the two leading technical universities, carrying out research and development activities. Their activities are largely funded by contributions from the construction industry (SBUF). A significant number of doctoral students from different parts of the world have carried out research related to foundation engineering. After completing their studies, they have often returned to their native countries as “ambassadors” of Swedish foundation engineering.

This paper cannot summarize the many research projects in the field of foundation engineering, which have been carried out at universities, often in close cooperation with the construction industry.

Since 1974, under the guidance of Prof. Bengt Broms and Prof. Håkan Stille and their co-workers, many research projects in the area of foundation engineering have been carried out, such as investigation of static and dynamic piling problems, deep mixing, soil compaction and behavior of anchored sheet pile walls. Optimizing grouting of dams and foundations has had a major impact on foundation design in Sweden and abroad. A series of research project have addressed the management of geotechnical risks. Another research topic has been reliability-based geotechnical design of ground improved by deep stabilization.

At CTH, Prof. Sven Hansbo and Prof. Göran Sällfors and their co-workers have carried out extensive research related to foundations on soft, improvement of compressible soils (drainage, deep mixing, soil nailing) and research regarding pile-foundation interaction. Also at other universities, such as Lund Technical University (LTH) and Luleå Technical University (LTU), research has been devoted to the solution of foundation engineering problems.
Ground Improvement Methods

Vertical Drains

Swedish engineers have made important contributions to the development and practical application of vertical drains. In the mid to late 1930s, Walter Kjellman began experiments and was awarded patents on the prototype of a prefabricated drain, made entirely of cardboard. Field tests with the first wick drain were carried out in the mid 1940s, known as the Kjellman wick drains (Figure 1). These drains consisted of a thin, 100 mm wide band-shaped drain made from cardboard with internal channels for water flow. Kjellman also developed a drain stitcher for the installation of wick drains. Torsten Kallstenius, then head of the mechanical department of SGI, was responsible for the development of geotechnical equipment. He constructed in 1947 the first drain stitcher for the wick drain, to be used at a test site for the Stockholm Arlanda airport. A limitation of the cardboard drains was the rapid deterioration of the drain material, particularly close to the top of the drained clay layer. In spite of these difficulties, Kjellman wick drains have been used occasionally in Europe and Japan during the past 50 years.

Until early 1970, a common vertical drain was the driven sand drain, installed using a closed-end mandrel. Hansbo (1960) studied the effect on consolidation of driven sand drains at the SGI test site at Skå Edeby (set up in 1944), outside Stockholm, where many other important field tests have been carried out over the years. Drain installation by driven mandrel causes disturbance of the soil compared to auger or water jetting. However, Swedish experience showed that in spite of the disturbance effect, driven sand drains were effective. An excavation of driven sand drains showed that vertical, sand-filled cracks had formed around the sand drains. This observation showed that the rapid soil displacement during driving of the mandrel produces vertical fissures in the clay, which can be filled with sand when the mandrel is withdrawn (Holtz and Holm, 1973). This effect explains also the, sometimes observed, rapid initial dissipation of induced excess pore water pressure after driving of piles in soft clay. Hansbo has made many important contributions to the design of soil improvement solutions using vertical drains. He showed, based on field observations, that a better agreement is obtained if the design is based on exponential flow rather than conventional Darcian flow (Hansbo, 2001).

In 1971, Oleg Wager at SGI further improved the wick drain, designing it with a central plastic core surrounded by a pervious synthetic filter. This drain was called “Geodrain”. This development became the model for modern prefabricated vertical drains (PVDs). Wager was responsible for many field experiments required in the development of field investigation and ground improvement methods. He was first to attach vertical drains to piles in order to accelerate dissipation of pore water pressure after driving, Holtz and Boman (1974). In recent years, vertical drains have again become increasingly used as a cost-effective ground stabilization method. Sweden played an important role in the international harmonization of vertical drain methods, having been responsible for the preparation of the European Standard, EN 15237 2007 “Execution of special geotechnical works - Vertical Drainage”.

Vacuum Preloading

The cost of loading berms—preloading by the use of a fill—adds considerably to the total cost of a vertical drain project. To alleviate this, Kjellman (1952) invented vacuum preloading method in the early 1950s. In the vacuum method, a suction is created by means of a vacuum pump in the drainage blanket—and, consequently, also in the vertical drains. The vacuum
method—also known as “vacuum consolidation” — is of special interest in sloping terrain and where soft soil with limited bearing has to be consolidated. Test embankments for full-scale study of the acceleration of consolidation using vertical drains and vacuum treatment were constructed at Skå Edeby. They showed the efficiency of the method and formed the basis for design, still used in different parts of the world. Since then, the vacuum preloading method has evolved into a mature and efficient technique for the treatment of soft clay. This method has been successfully used for soil improvement or land reclamation projects in many countries (Holtz, 1975).

Demonstration by Kjellman of the drain stitcher in 1945 at Upplands Väsby, Sweden with Karl Terzaghi attending


Figure 1. Application of prefabricated drains in Sweden.

Deep Mixing

Deep mixing by lime-cement columns is a ground improvement method developed simultaneously in Sweden and Japan in the mid-1960s. In Sweden, Kjeld Paus proposed – based on his experience with surface treatment of roads - to construct stabilized soil columns by mixing lime with soft clay. Bengt Broms, then director of SGI, suggested the use of unslaked lime, which is more efficient in absorbing water, which is necessary in the very soft Scandinavian clays. In a close cooperation, Broms, Paus, and Per Boman embarked on a comprehensive R&D project with the aim of developing a method for deep stabilization of very soft, compressible Swedish clays (Boman and Broms, 1975). The method is most effective in soft clay, silt, and peat and can improve the shear strength and deformation properties. Columns are manufactured by pushing a mechanical mixing tool into the ground. At the required treatment depth, the mixing tool is retracted while the binder (unslaked lime, cement, fly ash, and additives in appropriate proportions) is blown by air pressure from the rotating mixing tool into the surrounding soil, Figure 2.
In order to support the development of deep soil mixing, the Swedish Deep Stabilization Research Centre (SD) was established in 1995. SD was active between 1995 and 2006 with the aim to perform research, development, demonstration and implementation in the field of deep soil mixing. Participants in the ground improvement industry, such as academia, governmental authorities, research organizations and industry participated in its activities. SD implemented a comprehensive research program, comprising theoretical research at universities and research institutes and also research and development in connection with actual construction projects. The results have been published in two series (Research Reports and Work Reports) of publications from the SD. Many of these reports are available in English and can be downloaded from the SD URL (http://www.swedgeo.se/sd). Sweden took an active role in the international cooperation on deep mixing research, where Göran Holm of SGI played an important role in the international cooperation and exchange of information. An important European research project was “EuroSoilStab”, in which the SD participated actively. The project was aimed to prove that soft organic soils can be stabilized by soil mixing. Design Guides were developed which deal with all aspects of the application of column and mass stabilization (Eurosoilstab, 2002).

One of the milestones of SD activities was the organization of the “International Conference on Deep Mixing – Best practice and Recent Advances”, which can be considered an important milestone in the development of Deep Mixing methods. The Conference was held on May 23-25, 2005, in Stockholm, Sweden. The proceedings showcase recent advancements in all facets of the Deep Mixing-industry. Almost 100 technical documents are available in printed version or on CD-ROM. Volume 1 includes Technical Papers, Regional Reports and Keynote Lectures. Volume 2 includes State of Practice Reports.
Sweden has taken an active role in the international collaboration and development of deep mixing methods and chaired the working group responsible for developing the EN standard on deep mixing, EN 14679 2005 “Execution of Special Geotechnical Works - Deep mixing”.

**Soil Reinforcement**

Already the Vikings used bundles of wood for strengthening paths and roads across wet terrain, which was already used by the Romans. Different types of soil reinforcement have been used ever since. In the 1960s, approximately at the same time that Henri Vidal developed the reinforced earth method (“terre armée”), Oleg Wager at SGI invented a new concept of reinforcing road embankments. Figure 3 shows the use of horizontally placed steel tie rods, attached to short vertical steel plates, for stabilization of a road embankment on soft clay. Initially, the purpose of the steel tie rods was to absorb dynamic loads caused by vehicle traffic. Full-scale tests were conducted in the 1960s which proved that the system worked also for static loading. Some design rules, which were developed based on these tests, are used today for geotextile reinforced embankments. The Wager system has been used successfully more several projects in Sweden and Denmark for both highway and railroad embankments.

Figure 3. Reinforcement of road embankment using horizontal steel bars and short anchor plates.

During the 1970s, Bengt B. Broms, then director of SGI, pioneered the design of geotextile reinforcement of soils, (Broms 1977). In 1971, Wager initiated the first use of a woven geotextile for reinforcement of an embankment constructed on soft foundation. 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), Figure 4.

Soil reinforcement and soil nailing have been the subject of extensive research projects and Sweden chaired the working group which prepared the standard on soil nailing: “SS-EN 14490 Execution of special geotechnical works - Soil Nailing”.
a) Cross-section, showing completed embankment with piles and woven fabric reinforcement.

b) Placement of third layer of woven geotextile on top of fill. Note the wave shape of the embankment fill.

Figure 4. First application of woven geotextile as lateral support for embankment supported on vertical piles, Holtz and Massarsch (1976).

**Surface Compaction**

Vibratory rollers are widely used for compaction of road embankments, earth dams and landfills. Swedish manufacturers have contributed to development of vibratory rollers. An important step in compaction technology was the introduction of an electronic compaction control system. The initial development of roller integrated measurements dates to 1974 when Heinz Thurner of the Swedish Highway Administration performed field studies with a 5-ton
tractor-drawn vibratory roller, instrumented with an accelerometer. The tests indicated that the ratio between the amplitude of the first harmonic and the amplitude of the excitation frequency could be correlated to the compaction effect and the stiffness of the soil as measured by the static plate load test, Figure 5a). In 1975, Heinz Thurner and Åke Sandström of Geodynamik AB developed the roller-mounted compaction meter with the objective of optimizing vibratory roller performance. In cooperation with Lars Forssblad of Dynapac, Geodynamik developed and introduced the compaction meter and the compaction meter value (CMV) in 1978. The roller-integrated compaction meter continuously registers the compaction state of the soil. The new method was introduced at the First International Conference on Compaction held in Paris, France in 1980 (Thurner and Sandström 1980, Forssblad 1980). Many of the roller manufacturers have subsequently adopted the CMV-based system. A further step in the development of compaction control was the introduction of Continuous Compaction Control (CCC) with the objective of increasing quality and efficiency of soil compaction, Figure 5b), Thurner and Sandström (2000). CCC is recognized as an important tool for the roller operator to achieve a homogeneous compaction result in a minimum of time. Located weak spots can be improved by means of directive measures. Since 1994, Continuous Compaction Control is included in Swedish, Finnish, German, and Austrian compaction specifications.

![Compactometer monitoring of vibrating roller](image1)

![Continuous compaction control (CCC)](image2)

Figure 5. Optimization of vibratory roller compaction, using electronic monitoring system, from Thurner and Sandström (2000).

**Deep Vibratory Compaction**

Deep vibratory compaction has been used in Sweden and abroad for improvement of granular soils. Following a study tour to Japan, where they were introduced to soil compaction using vibrating rods, Swedish engineers developed the VibroWing method, Figure 6a). The first major application was deep compaction of a 15 m deep hydraulic fill at the construction of a harbor in Rostock, Germany, (Broms and Hansson 1984). Another new compaction concept was a vibratory plate, which was used to densify the top 3 m of the soil deposit, which could not be improved efficiently by deep compaction (Figure 6b).
A further development of deep vibratory compaction was the introduction of hydraulic vibrators with variable frequency. Based on extensive research at KTH, it was found that the efficiency of the compaction process could be increased by changing the operating frequency of the vibrator during the penetration, compaction, and extraction phase. The most effective transfer of vibrations from the compaction probe to the surrounding soil is achieved when the vibrator is operated at the frequency of the vibrator-probe-soil system. The entire compaction process can be monitored by an electronic compaction control system (Massarsch 1991), Fig. 7a. The vibration frequency is variable and geophones are placed on the ground to measure the vibration response. In this way, it is possible to gradually adjust the vibrator frequency as compaction progresses. An important advantage of the resonance compaction system is that the measured dynamic parameters (vibration frequency, ground vibration velocity, and probe penetration speed) can be used to monitor and optimize the required degree of compaction, similar to the above-described compactometer concept.

Soil compaction can be further improved by the use of flexible compaction probe, which increases the compaction energy and the interaction between the probe and the surrounding soil. Fig. 7b. As a result of the reduced mass of the compaction probe the vibration amplitude and thus the compaction effect are enhanced. Deep vibratory compaction can be used in granular soils to a depth of 15 to 20 m.

The vibration monitoring system using geophones can also be used to reduce environmental impact during vibratory driving of piles and sheet piles. In this case, resonance effects can be minimized by avoiding resonance frequencies of surrounding soil deposits or building elements.
**Piling Technology**

**Historic Development**

Piling has been used for the solution of different types of foundation problems since northern Europe became populated. Already at a very early historic time, most settlements were founded along sea shores, lakes, and the banks of major rivers, where the soil conditions generally provided poor foundation support. The selection of appropriate sites for settlements and harbors required understanding of the geological situation. In order to construct defense structures, churches, and other structures on very soft, unstable soils, the ground had to be improved. The Vikings often chose to build houses and villages in inhospitable wet environments. Thus, we find their primary settlements and trading places along shore lines. For instance, the town of Birka (located some 100 km west of Stockholm, and, probably, constructed around 700 AD) became an important trading place with about 500 to 1,000 inhabitants. 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, timber 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 timber piles into soft sediments at near-shore lacustrine deposits, as illustrated in Figure 8, showing how the piles were placed almost ‘effortlessly’ and very quickly by rotating the pile.
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.

Christopher Polhem (1661-1751) was an outstanding scientist and engineer. After studying mathematics and mechanics at Uppsala University, he started in 1697 the first “Engineering School” in Sweden. He was recognized for his inventions by receiving appointment by the Swedish King as “Director of Rock Mechanics” and he later became responsible for the operation of several important mines. He was in charge of 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 harbour. He developed a piling rig for driving inclined piles, which is described in the 1753 proceedings of the Swedish Royal Academy of Science.

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, son of Wolmar 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 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. 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.

Figure 9. Christopher Polhem designed a piling rig for the construction of the sluice and lock in Stockholm.

Bror Fellenius started his geotechnical career at the harbor office of the City of Gothenburg, 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. The Pile Commission received international recognition, serving, for example, as an inspiration at the start of the Deep Foundations Institute in 1974 (Fellenius 1994).

**Export of Swedish Piling Technology**

As director of the Swedish Geotechnical Institute and chairman of the Pile Commission, Broms made important contributions in many areas of pile foundations, both from a theoretical viewpoint, but also with respect to their practical applications. His early work in the 1960s on laterally loaded piles has become a reference method for land and offshore projects. Broms solutions are still recommended for routine design. The Swedish precast piling system, based on the concept of spliced, prefabricated concrete piles, experienced a rapid development during the 1960’s and 1970’ and was introduced internationally under the
trade names of “Balken Piling System” (Göteborgs Betongpålar) and “Hercules Piling” (BINAB) to the global market. The basis for its success was the installation of spliced precast piles of high-quality concrete, installed by relatively small, but efficient pile driving equipment. Swedish precast piling technology was introduced successfully not only in European countries, but also in the Middle East, Far East and Australia, thanks to the efforts of forward-looking engineers such as Sölve Severinsson, Bengt Grävare and Christer Bådholm.

![Installation of modern precast concrete piles in close vicinity of railway embankment. Photo: Hercules Grundläggning.](image)

Sweden chaired the working group which prepared the European Standard, EN 12699, “Execution of special geotechnical work - Displacement piles”.

**Pile Driving Equipment**

Due to the prevailing geotechnical situation with deep deposits of soft clay or loose sand, and the climatic conditions, installation of preformed piles (wood, concrete, and steel) is often the preferred foundation method. The hexagonal section “Herkules” pile type has six main tensile reinforcement bars. An advantage of a hexagonal pile cross-section is a slightly better distribution of stress along the pile section during driving, and potentially less susceptibility to damage from torsional stresses. Today, spliced concrete piles are usually of square section, but other shapes, such as hexagonal and octagonal sections are also produced. Because handling stresses are much smaller for shorter length segments (generally less than 15 m), there is less danger of over-stressing. The pitching and raising time is also shorter for the spliced piles. In suitable ground conditions, spliced precast concrete piles have been driven deeper than 100 m, although the vast majority does not exceed 30 m.
In 1957, the Swedish engineer Sölve Severinsson invented the mechanical splice used for splicing concrete pile segments together during driving (Herkules splice) for precast piles. Precast concrete piles can have bayonet connection or bolted connection (ABB-splice). The splice must be as strong as the pile and have the same moment of resistance. The quality of the splice must be high, as otherwise during driving, a significant amount of energy can be lost. Severinsson also developed "rock shoes" with a separate hardened, small diameter dowel, which are used to seat piles on inclined bedrock.

In Sweden, several inventions were made with the aim of improving the efficiency of impact hammers. In the early 1980s, Kjell Landaeus developed a novel pile hammer with the aim of increasing the duration of the stress wave during impact on the pile, thereby increasing driving efficiency and reducing the risk of damage to the pile head. In order to achieve this effect, he used an inner steel cylinder provided with a lead core. In 1983, Kjell Landaeus and Bertil Borg patented a further development of the method. The steel/lead mixture produces a longer stress wave in the concrete pile and leads to a reduction of the peak forces in the pile resulting in a larger penetration depth per impact. In addition, the use of the mixture reduces the noise level. The Uddcomb and Rambo impact hammers, now marketed internationally, were initially manufactured in Sweden.

**Stress Wave Measurements**

In 1956, when the Swedish Railways (SJ) expanded the Stockholm Central Station, the piling contractor proposed to use light pneumatic hammers instead of conventional drop hammers to drive a large number of steel piles. Therefore, it became necessary to learn what actually happens during the driving of a pile. Realizing that pile driving with pneumatic hammers must have a good deal in common with percussion drilling, Bror Fellenius, head of the SJ Geotechnical Office, contacted Atlas Copco, a company marketing large-size drilling equipment and met with Prof. Hans Christian Fischer, who had done research using strain gages to determine dynamic forces in drill rods. The testing on the steel piles gave very interesting results and Fischer could demonstrate, using his technique of grapho-dynamic representation of stress waves (Fischer 1960), the effect of various hammers on the magnitude of the reflected stress wave and provide a rational for the hammer selection and termination criteria. The contributions by Lars G. Hellman have been very important, as he worked as close liaison with Fischer in Uppsala on the practical application of stress-wave measurements, (Fischer, 1984).

In 1959, the Pile 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 (Fellenius 1996). Although the Pile Commission continued to research in the area of pile dynamics, the next important development in pile dynamics took place in the USA, where George Goble and his co-workers developed the modern concept of stress wave measurement and analysis. The successful introduction and practical application of stress wave measurements in Europe and in particular in the Nordic countries was the result of cooperation between Carl-John Grävare and Ingemar Hermansson with Prof. George Goble, (Grävare et al., 1982). Håkan Bredenberg at KTH carried out extensive measurements on steel piles, which now are commonly used in the Nordic countries. Research on pile dynamic measurements continued also in Sweden, where also the first and second international stress wave conferences were held in 1980 (Bredenberg, 1981) and 1984 (Holm et al., 1985).
Negative Skin Friction and Unified Pile Design

Bengt H. Fellenius, grandson of Wolmar, continues a long tradition of Swedish geotechnical engineering. While working at the Swedish Geotechnical Institute he became involved in many aspects of pile engineering. Bengt Fellenius studied the development of negative skin friction and drag force in full-scale piles. His work on negative skin friction is based on ground-breaking tests at the Bäckebol test site, where he installed instrumented concrete piles and studied the effect of pile installation and load distribution during and after driving. His work helped to clarify the development of how drag force and downdrag should be approach in piled foundation design. One of his important contributions was the development of a “unified design concept” of pile-soil interaction for single piles and pile groups in settling soil. The unified design of piles and pile groups considers capacity, drag force, settlement, and downdrag. In 1984, he published the design and analysis method for foundation design known as the “Unified Method of Design for Capacity, Drag Load, Settlement, and Downdrag” (Fellenius, 2004).

Piled Raft – “Creep Pile” Foundations

Wood piles—driven at close spacing and to a limited depth— have been used as ground improvement method with the objective of creating a stabilized soil block. Early on the method called “pligg pålning”, was used in granular soils, where an additional, beneficial effect was soil densification. Important research and development of this foundation technique was carried through by two outstanding pioneers in geotechnical engineering: Wendel (1900) and Hultin (1928). Their work increased the understanding of friction pile behavior and formed a basis for friction pile design.

In the Gothenburg area and other regions, the subsoil consists of soft, highly plastic clay to very great depths, exceeding 100 m. Foundation on piles driven to termination in underlying bearing strata are expensive and therefore floating piles have been extensively used. In the mid 1980s, Sven Hansbo, then professor at Chalmers University of Technology and his co-workers, developed a new foundation concept, which he called “creep piles”, (Hansbo 1984 and Hansbo and Jendeby 1998). According to this design principle, the building is founded on a piled raft. The load of the building in excess of the preconsolidation stress of the clay is assumed to be carried by the piles while the remaining load (i.e. the stress increment up to the preconsolidation stress) is assumed to be supported by direct contact stress at the raft/soil interface. The design load of the piles chosen is equal to the so-called "creep load", meaning the pile load that causes a state of creep failure. In cases, where the average net load increase exceeds the preconsolidation stress of the clay, the objective of creep piling is to reduce consolidation settlement. This is achieved by the fact that the stress increment exceeding the preconsolidation stress of the clay is transferred to greater depths where the preconsolidation stress is higher. Yet another advantage is attained. Since the piles are in a state of creep failure, the design of the raft with regard to the influence of the piles is made simpler: the piles can be considered as upward toe loads is equal to the creep load. Moreover, the piles can be distributed in such a way that the differential settlement of the building is minimized which, in turn, also represents the most cost-effective solution. The above concept of load-sharing between a raft foundation and settlement reducing piles is today widely used for many types of buildings and other structures, resulting in significant cost savings.

The design of vibrated concrete elements as settlement-reducing foundations have been applied as ground reinforcement method, (Massarsch et al. 1997). At a foundation project in Halle, Germany, conical concrete elements were vibrated to a depth of 10 m within less than a
minute, stabilizing random fill, which could not have been improved by conventional ground improvement methods such as stone columns, Figure 11. Due to their structural integrity, preformed elements can be installed even in highly variable soils or man-made fill.

Figure 11. Installation of conical concrete elements by vibrator with variable frequency
b) Foundation on conical concrete elements vibrated into random fill

Expander Body
The Expander Body (EB) concept was developed by the Swedish engineer Bo Skogberg during the 1980s and its initial application was the “Swellex” rock anchor. Later on, the Expander Body soil anchor was introduced. It consists of a folded steel tube with a square cross section. By injection of grout, the EB can be inflated, which creates a water-tight concrete-filled, steel balloon of high strength (Figure 12).

Gradually, new applications of the EB system were developed, such as for soil anchors, driven, and vibrated and bored piles (Broms and Nord 1985). Extensive field tests were carried out to verify the bearing capacity of piles with EB base, on which the Swedish Commission on Pile Research published design and installation recommendations and monitoring procedures (Berggren et al. 1988). Initially, the most common application of the EB system was for underpinning of structures and for use as soil anchors (Figure 13).
The EB pile system is also included in Eurocode CEN 2000 “Execution of special geotechnical work - Displacement piles”. During the past decade, the design and construction of the EB was further improved in Bolivia (Terceros and Massarsch 2014). The present EB system has a cylindrical shape, instead of the square cross section used originally. Also, a new post grouting system has been implemented, which makes it possible to inject grout through the inflated body into the soil below. This feature can increase significantly the performance of the EB pile. Today, the system is used increasingly in the Far East (Japan) and South America, where the geotechnical conditions are favorable for piles with expanded toe.

Offshore Foundations

Swedish contribution to offshore foundation engineering started at the end of the 1950s, when the Swedish Navigation Authorities drew up a comprehensive programme for the construction of new lighthouses. Swedish engineers have over the years designed off-shore lighthouses along the Swedish coast. Considerable operational experience has been gained, particularly as regards ice action on the structures located in the Gulf of Bothnia. Bengt B. Broms, while
working in the USA, developed a new design method for piles by assuming that a number of plastic hinges could form at failure of the platforms. The proposed design method could be used for both cohesive and cohesionless soils. At that time, he was involved in the construction of an oil platform at about 40 m water depth, which was the largest water depth for an oil platform at that time. The structure was provided with large square boxes at the four corners to improve the lateral and the pull-out resistance of the platform. The steel boxes were supposed to be pushed down into the soft clay by four large steel pipe piles, which had been driven first as reaction at the four corners. The piles were later used to carry part of the weight of the platform besides improving the lateral resistance. In the early 1970s, Broms invented a new foundation concept, the “Grid Mat” method, which has many different applications, (Broms and Massarsch 1976). It is applicable as foundation element for different types of offshore structures and the forerunner of skirted offshore structures. The foundation elements are composed of open triangular or square cells, which are joined together to form a grid (Figure 14).

![Diagram of Grid Mat method](image)

Figure 14. Application of different foundation grids in different bottom conditions, Broms and Massarsch (1976).

The grid mats can be adjusted to fit different foundation conditions. This foundation method is particularly suitable when structures are subjected to vertical and horizontal cyclic loading. Today, skirted foundations are used for gravity platform jackets, jack-ups, subsea systems, and seabed protection structures.

In mid-1980, Bo Andreasson, WSP, formerly J&W Offshore, developed and patented a subsea foundation element, which consists of a number of interconnected open-bottom cells
which are closed at their top and can be evacuated. The elements are arranged to penetrate into the sea bottom soil until the cells are filled with soil. The foundation system was first used for the Snorre Field TLP, the largest Tension Leg Platform at that time. The foundation elements, which were installed in 1991, were constructed under license from J&W (WSP). Suction anchors, also called Suction Caisson Foundations, are today widely used as offshore foundations.

Another Swedish engineer, Rune Dahlberg, moved to Norway in 1975 to work with Det Norske Veritas (DNV) and has since then made important contributions within different areas of offshore foundation engineering. Particularly, he played a leading role in the development of methods for design and installation of the three most commonly used deep-water offshore anchors (fluke anchors, plate anchors and suction anchors). This work, which started in the early 1990s, was accomplished through a series of “Joint Industry Projects” and lead to the development of DNV Recommended Practices (RP) for design and installation of these types of anchor. The first editions of these RPs were published by DNV in the period between 1998 and 2006 and are regularly updated as required. They are all based on the limit state method of design, and the partial load and resistance factors have been quantified based on results from reliability-based code calibrations carried out to satisfy a prescribed target annual probability of failure level, see Dahlberg and Mathisen (2002). In the current (2013) edition of the ISO standard for “Stationkeeping systems for floating offshore structures and mobile offshore units” (ISO 19901-7), the recommendations in these RPs are frequently referred to, in particular the RP for fluke anchors (current edition from 2012), which also takes advantage of a unique tailor-made design tool developed by DNV, see e.g. Dahlberg and Rességui (2009).

**Summary**

This presentation of Swedish heritage in foundation engineering can only give a brief overview of contributions to foundation engineering, which have found international attention. Focus has been on developments during the past 100 years. 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. The Swedish Geotechnical Society is the center of geotechnical engineering, with international links to, and cooperation with, ISSMGE. The center of Swedish cooperation within the foundation industry has been SAFE, the Swedish Foundation Engineering Association, which is also a member society of the European Federation of Foundation Contractors, EFFC:

Research in the area of foundation engineering is strongly linked to the construction industry, facilitated by the creation of an industry-sponsored development fund (SBUF). In spite of its
small size, 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 commissions with the task of solving foundation engineering problems. This culture of cooperation has been a unique breeding ground for the introduction of new, innovative concepts, such as in piling technology (Swedish Pile Commission) and deep mixing (Swedish Deep Stabilization Research Centre).

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