Design, construction and maintenance of infrastructure

Conception, construction et entretien de l'infrastructure

S.Lacasse, K.H.Andersen, S.Hermann, T.Kvalstad, V.Kveldsvik, C.Madshus – *Norwegian Geotechnical Institute, Norway*

ABSTRACT: Increasing demand for sustainable transportation systems and for modernised infrastructure pose new challenges to geo-engineers. The contribution of geotechnical engineering to infrastructure is indispensable, yet often underestimated. The Theme Lecture focuses on: engineering more economical solutions, developing improved and safer transportation solutions, encouraging innovation and preserving the environment. To meet these challenges, an alliance of good practice and research is required. Achievements and challenges are illustrated with examples of on-land and offshore engineering. More than before, our profession needs to focus on both the art of engineering and engineering art. We need to achieve an effective dialogue and collaboration among the geo-sciences, include automatically the environmental component and integrate consequence analysis and risk assessment to foundation solutions, meet with ingenuity the challenges of natural hazards and contribute to increased understanding between client, designer, consultant and contractor. To a greater degree than before, geotechnical engineering should add value by saving lives, improving performance, reducing costs and exploiting natural resources in a responsible manner.

RÉSUMÉ: Le besoin d'apporter de nouvelles solutions pour la conception, construction et entretien de l'infrastructure urbaine et offshore pose un défi important à la profession géotechnique. Sa contribution est indispensable, mais pourtant sous-estimée. Cette conférence plénière a choisi de porter sur quatre thèmes: ingénierie de solutions plus économiques, conception de solutions valables et optimum pour le transport urbain, promotion de l'innovation et préservation de l'environnement. Afin de relever ces défis, une association judicieuse de résultats de recherche et de solutions pratiques est requise. Quelques succès sont illustrés avec des exemples à terre et en mer. De façon plus urgente qu'auparavant, il est nécessaire pour l'ingénieur de se concentrer sur l'art de l'ingénierie. La profession se doit d'entreprendre un dialogue réel avec les autres géo-spécialités, intégrer l'évaluation du risque aux méthodes traditionnelles, relever le défi posé par les risques géologiques et les désastres naturels, et contribuer á une meilleure interaction client, concepteur, entrepreneur et consultant. Le génie géotechnique doit contribuer à la sauvegarde de vies, l'amélioration du comportement, la réduction des coûts et l'exploitation des ressources naturelles d'une manière responsable.

1 INTRODUCTION

The increasing demand for sustainable transportation systems, for underground construction in cities, and for modernised infrastructure for freshwater, sewerage and waste disposal pose new challenges to geotechnical engineers. Although the contribution of geotechnical engineering to infrastructure is indispensable, it is often underestimated by both public and government. Geotechnical engineers influence alignment, planning, design and maintenance of traffic and transportation arteries. Geotechnical engineers decide location and orientation of runways, and are the key to the safe foundation of coastal and offshore structures. Geotechnical engineers have the required expertise for the evaluation of the risks involved in their designs as they have the knowledge, judgment and experience and know about the uncertainties involved.

The Theme Lecture is to provide an overview of recent accomplishments and develop an outlook and prospect for the future, thus preparing an arena for discussion on two main topics: (1) road, railway and runway construction, and (2) coastal and marine engineering. Faced with such a vast subject, the authors opted to discuss achievements and challenges in terms of four all-encompassing objectives of our profession:

- Engineering more economical solutions
- Developing improved and safer transportation solutions
- Encouraging innovative solutions
- Protecting and preserving the environment

To meet these challenges, an alliance of good practice with the results of recent research is required.

Achievements, future directions as well as challenges are illustrated with examples from transportation infrastructure and from coastal and marine engineering.

2 OUR CHALLENGING INFRASTRUCTURE

Infrastructure includes roads, bridges, airport facilities, navigable waterways and harbour installations, dams, energy facilities, installations for drinking water, and disposal of wastewater, solid waste and hazardous waste. These are basics for society and yet there are growing problems with our infrastructure, environment and exposure to natural hazards (Clough, 2000).

- Population is increasing alarmingly, and yesterday's technologies for housing, transportation water and energy supply, response to natural disasters and land use are not sufficient for tomorrow's challenges.
- Freshwater supply is drying up with water tables falling in China, India and the USA. By year 2025, 3 billion of the world's population will live in places where fresh water resources have fallen below sustainability levels.
- Infrastructure fails to keep up with demand. Rupture of old underground water pipes or gas lines cause flooding, water cut-offs, cave-ins and sliding failures. In the USA, there are thousands of kilometres of old pipelines, and they leak more oil each year than the volume that was spilled from the Exxon Valdez off the coast of Alaska.
- Waste keeps piling up.
- Transportation demands are increasing, roads are often in poor and mediocre conditions, bridges structurally deficient or functionally obsolete, railways need to be upgraded for higher loads and speeds.
- The demand for energy increases. And yet, in the USA alone, there are more than 2100 unsafe dams, and 61 dam failures have been reported in the past two years (ASCE, 2001). Thousands of megawatts capacity must be added each year to keep up with the annual growth in energy demand.

– At the same time, because of land-use patterns, population growth and more extreme weather than before, more people and more property are at risk for natural disasters.

Effects of population growth, increasing transportation needs, decaying infrastructure, shrinking waste management options, environmental deterioration, threats from natural disasters should be on the agenda of the geotechnical profession. More than before, the profession needs to focus on "engineering for life", highlighting the value added by engineering to society and the need to constantly reinvent itself. The profession needs to innovate more than before.

3 MORE ECONOMICAL SOLUTIONS

The geo-profession needs to focus on more economical solutions. Optimum designs, taking responsibility for sustainable solutions in accord with society's needs, should also promote innovation.

Examples of more economical solutions are presented below: first, how a new soil investigation method contributed to large savings; second, the cost-effectiveness of additional soil investigations; third, new contracting philosophy and last, the benefits of focused quality assurance.

3.1 *Cost-effective alternatives*

The 1.5-km long rail crossing at Nykirke, southwest of Oslo, is part of the modernisation of the railway network in Norway. Construction work is organised as a turnkey project where the contractor is responsible for engineering, planning and construction. The contract has a new format with target estimate and incentives for enhanced efficiency and quality.

The terrain along the proposed track was rather hilly with maximum elevation difference about 40 m. The soil conditions were dominated by outcropping bedrock and soft silty marine clay deposits that could be very sensitive and even quick. The geology and topography required a 140-m long tunnel about halfway on the link (Fig. 1).

The initial site investigations, done in a traditional manner with 54-mm dia tube sampling, gave the soil profile in Figure 2: natural water content of 25-35%, total unit weight of 19.5 kPa, plasticity index between 4-9%, clay content between 20-55%. The index strength tests suggested low shear strength (10-25 kPa) at depths 4-12 m, in part due to sampling disturbance. This shear strength profile corresponds to approximately 0.2 times the *in situ* effective overburden stress.

The project owner had done a preliminary design using these initial soil characteristics. For the railway link at Nykirke, the contractor asked NGI to optimise the foundation design. In the tender phase, the bidders could prepare alternative solutions as long as the bidder "guaranteed" their feasibility.

A study of the topography and geology suggested that erosion had probably occurred and that the clay was overconsolidated and should have higher shear strength than assumed in the original design. With the geology that included ravines and areas with massive quick and soft clay deposits, NGI recommended cone penetration tests and large size block sampling of the soil with subsequent laboratory testing.

Supplementary site investigations were done, including block sampling with the Sherbrooke sampler (Lefebvre & Paulin, 1979).

Figure 3 compares the stress-strain curves and the effective stress paths of two specimens from depths of 9.5 and 10.1 m. They were recovered with a 54-mm sampler and a 250-mm block sampler respectively. NGI has worked over a number of years to establish relationships between cone factors and engineering parameters using the 250-mm Sherbrooke sampler (Lacasse *et al*, 1985, Karlsrud *et al*, 1996 and Lunne *et al*, 1997, 1998). Figure 3 illustrates the completely different behaviour, contractant-dilatant, for the disturbed and undisturbed sample.

Figure 4 presents the derived cone factors N_{KT} and $N_{\Delta u}$ as a function of overconsolidation ratio (OCR) for six Norwegian soft clays:

$$N_{KT} = (q_T - \sigma_{vo}) / s_u$$
$$N_{\Delta u} = \Delta u / s_u$$

where

q_T corrected cone resistance
σ_{vo} *in situ* total vertical stress
s_u undrained shear strength
Δu excess pore pressure

Figure 5 gives the triaxial compression undrained shear strength derived with cone factors N_{KT} and $N_{\Delta u}$ of 10 and 8 respectively. The shear strength profiles agree well. A linear s_u-profile was used for design. For comparison purposes, an s_u-profile corresponding to a normally consolidated triaxial compression undrained shear strength of $0.3 \cdot \sigma'_{vo}$ and the triaxial test results on 54-mm samples are also shown.

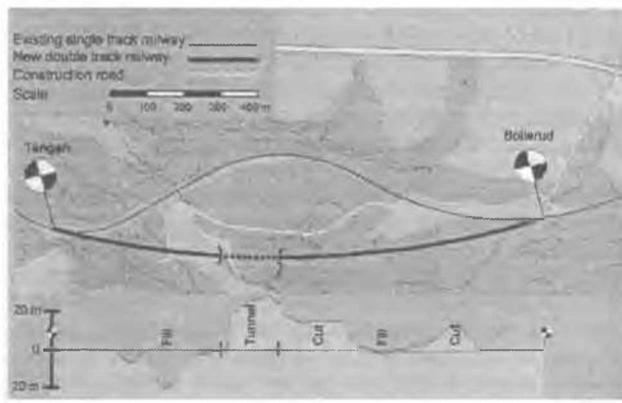


Figure 1. Plan view and profile, Tangen to Bollerud, Nykirke railway link (Hermann & Jensen, 2000).

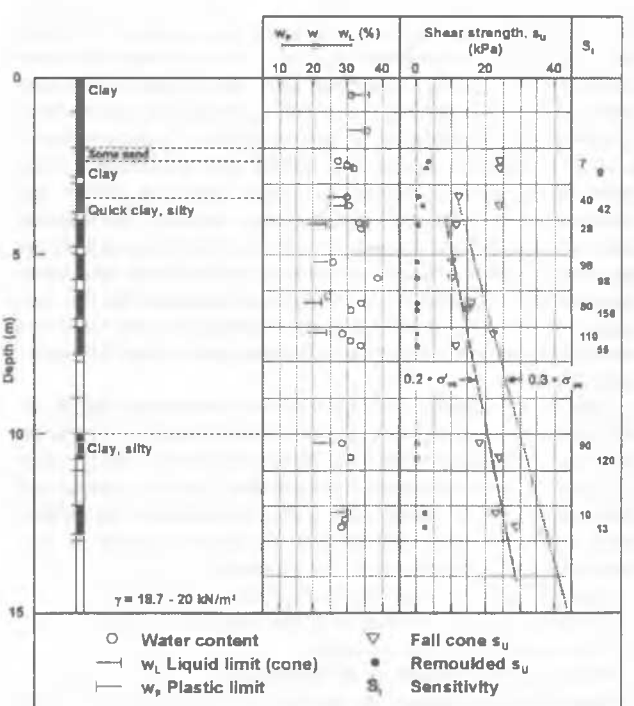
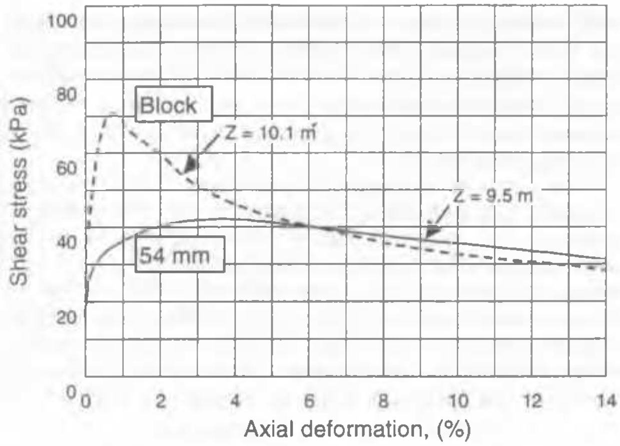


Figure 2. Soil profile, initial soil investigations, Nykirke railway link (Jernbaneverket, 2000).



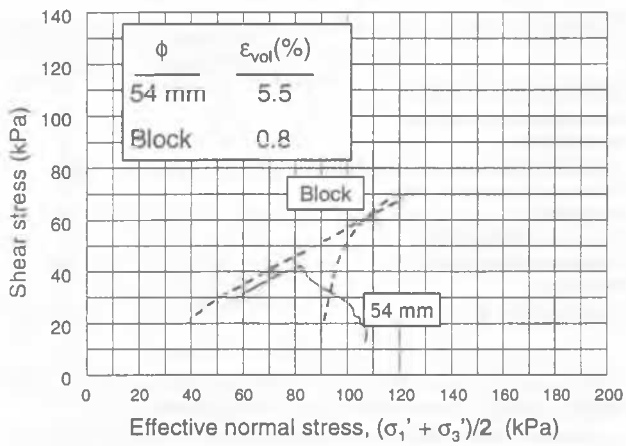


Figure 3. Comparison of triaxial compression test results on 54-mm and 250-mm samples, Nykirke railway link (NGI, 2000).

The 54-mm samples suffered greatly due to sampling disturbance, and the shear strength was too low. The volume of water pressed out during consolidation in the 54-mm specimen (5.5%) is 7 times higher than for the block specimen (Fig. 3). It is possible to correct for sampling disturbance based on recent research tests where disturbed samples were compared to block samples (Lunne *et al*, 1997). In this case, the shear strengths for a vertical stress path and a stress path at 1:3 were considered. The correction approach, still tentative, is illustrated in Figure 6 for the sample at depth 11.5 m. The initially measured disturbed shear strength of 42 kPa increased to corrected values of 56 and 66 kPa. The block sample gave a shear strength of 70 kPa at 10 m depth. The piezocone tests gave a triaxial compression undrained shear strength of 72 kPa at the same depth. Since the clay is overconsolidated (Figs 3 and 7), the correction along the 1:3 stress path is probably reasonable.

Oedometer test on specimens recovered with the block sampler suggested an OCR of 4.5 at 6-m and 3.5 at 10 m-depth. Figure 7 illustrates the normalised undrained shear strength of the block specimens as a function of overconsolidation ratio. The data suggest a normally consolidated triaxial compression strength of 0.28 (α), and the OCR-function increases with an exponent of 0.71. Both α- and β- factors are reasonable and agree with earlier published data.

The new profile, combining high quality sampling and newer developments with the piezocone, demonstrated that the shear strength of the clay was significantly higher than originally believed. The higher shear strength was caused by pre-consolidation under an overburden that has since been eroded away.

The initial solution proposed to build fills founded on piles down to bedrock. The new design profile enabled the contractor to use preloading and vertical drains to accelerate the settlements

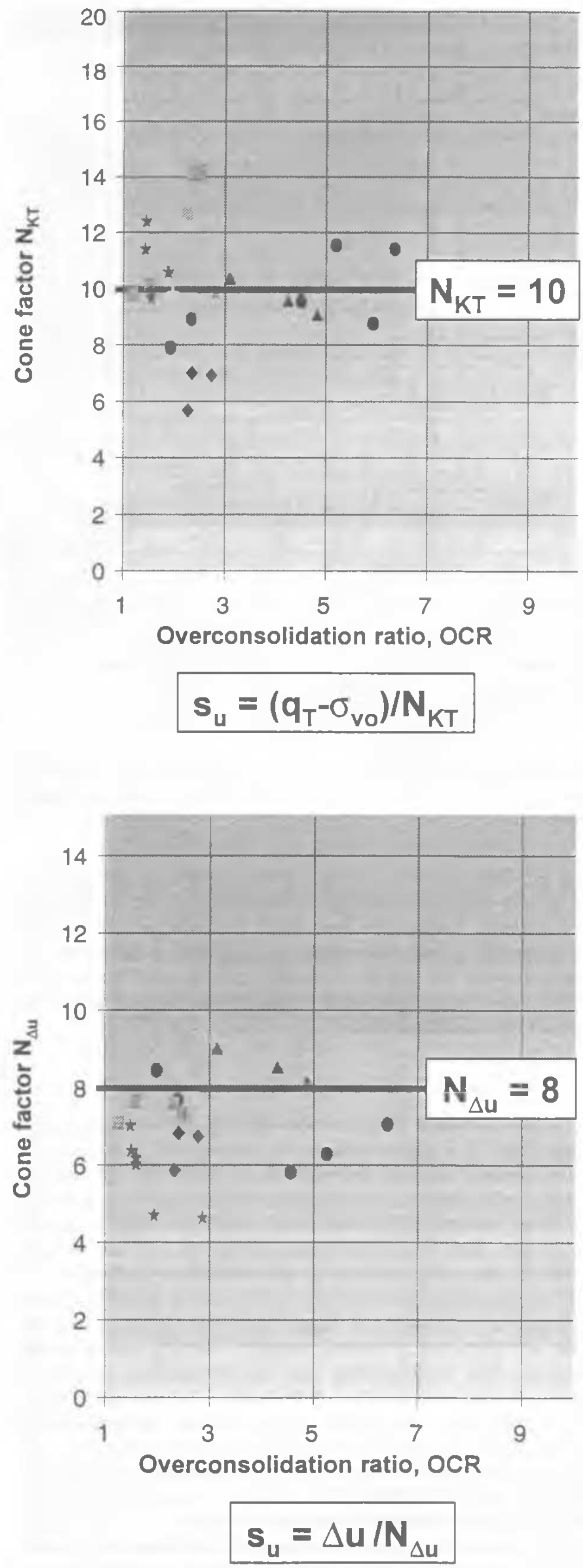


Figure 4. Reference cone factors on six soft Norwegian clays (NGI, 2000).

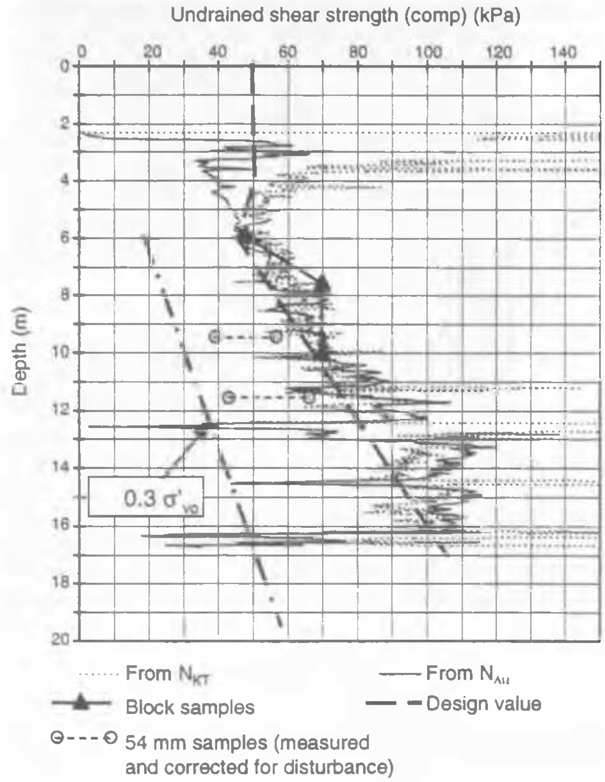


Figure 5. Undrained shear strength derived from cone penetration tests and compared with laboratory test results, Nykirke railway link (NGI, 2000).

(Fig. 8). Over the entire 1.5-km crossing, the new strengths enabled cost reductions of USD 1.5 million, or 20% of the total project costs. The savings were made possible because the contractor agreed to run three piezocone tests and to have these interpreted with the results of recent research, and the fact that higher shear strength parameters than used in the preliminary design could be demonstrated.

3.2 *Profitable soil and rock investigations*

For cities in coastal areas or close to large rivers, underground construction is a major challenge to geotechnical engineers. Often the tunnels and deep excavations are planned for ground that is marginally stable unless supported. Stability during construction must be assured. In urban areas, excavation-induced ground movements must be predicted and controlled so that overlying buildings, structures and services are not adversely affected.

The planning of underground constructions should be based on a good understanding of the geology. Soil and rock investigations are often not addressed properly, causing cost and time overruns. The consequences can be far-reaching, sometimes greatly detrimental to the environment. For example, when groundwater leaks into a rock tunnel overlain by compressible sediments, it can cause significant pore pressure reduction and consolidation settlements (Fig. 9). Subsidence due to leakage into rock tunnels becomes a major issue. A "good" safety factor has little significance when settlement governs.

To illustrate the cost-effectiveness of additional soil investigations, an example is taken from a 1.2-km long subway tunnel section in rock between Bergslia and Nydalen in Oslo. The section is part of the subway in Oslo ("T-baneringen"). The alternative was to either design and build the tunnel based on traditional investigations or to expand the investigations to reduce some of the uncertainties. With the first option, the site investigations were inexpensive. There was also a risk of considerable leakage of groundwater through the tunnel, construction delays, unbudgeted sealing operations, compensations for damage to dwellings and other buildings, environmental damage and public complaints, as well as general discontent with the engineering profession. With the second option, the question was whether the increased site investigation costs would decrease sufficiently the risks and associated costs.

Table 1 lists the investigations carried out. Classification and oedometer tests were run in the laboratory on the recovered soil specimens. The additional testing gave an improved knowledge base relative to what has been done earlier in the area and where leakage and damages due to settlements had been experienced. The new investigation covered a 500 to 600-m wide corridor along the tunnel alignment (Fig. 10). They revealed that the formation overlying the tunnel included permeable soil layers along most of the alignment, sometimes as much as 30-m thick.

Table 1. Bergslia-Nydalen Tunnel: traditional investigation and extended program

Test method	Traditional investigation	Additional testing
Refraction seismic profiles	3	8
Rotary pressure soundings	3	0
Rock drilling	12	0
Combined rotary and rock soundings	35	32
Piezocone penetration test	0	15
Piezometers	1	23
54-mm sampling profiles	1	4
95-mm sampling profiles	0	3
Field vane	1	0
Simple soundings	13	0

With the additional samples, *in situ* tests and experience from existing tunnels in the Oslo region, it was possible to:

- calculate settlements as a function of pore pressure reduction,
- estimate settlements as a function of leakage,
- identify the most critical location of the buildings and installations in each bedrock trench,
- establish maximum leakage criteria in the different tunnel sections to present excessive settlement on critical buildings and installations.

The maximum leakage criteria varied from 7 to 14 litres per minute per 100 m tunnel.

Figure 11 summarizes the pore pressure reduction measured in deep trenches at bedrock as a function of the distance from the tunnel centerline for eight tunnels in the Oslo area. Figure 12 presents the expected leakage as a function of the pore pressure reduction, as measured in 19 tunnels around Oslo. Lower and upper bounds are suggested. The scatter is due to:

- groundwater supply
- topography
- depth, width and length of observation trenches
- presence of layers more permeable than clay overlying rock
- presence and orientation of faults and fractures in rock
- sealing of tunnel
- depth of tunnel
- measured values of pore water pressure reduction
- spatial variability over distance considered

Results so far, when about 14 of the Bergslia-Nydalen tunnel has been excavated, shows that the maximum leakage criteria are met. An extensive pre-grouting effort was necessary in a 50-m long tunnel section that had very poor rock conditions (Q-values in the range of 0.01-0.7).

3.3 *Innovation and interaction in contracting*

To achieve more economical solutions, the challenges facing us include:

- We need to use existing projects with foresight, i.e. take every opportunity to develop new solutions and to test and monitor new technology

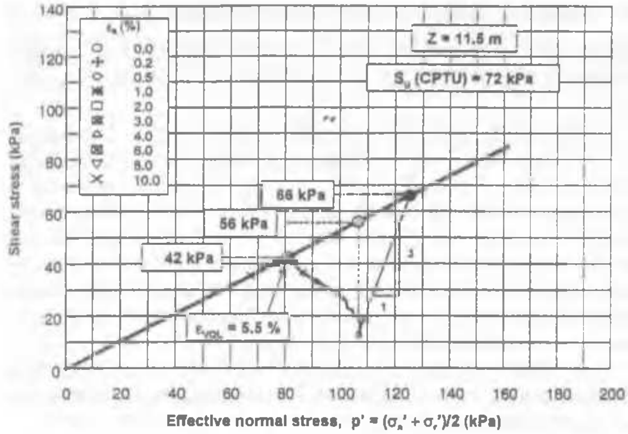


Figure 6. Correction for sampling disturbance of 54-mm sample of over-consolidated clay at 11.6 m, Nykirke railway link.

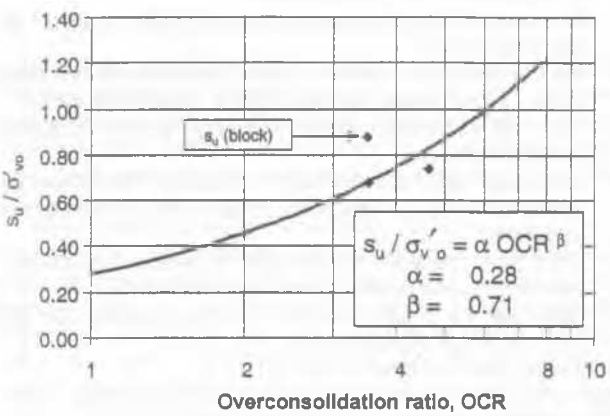


Figure 7. Normalized undrained shear strength, Nykirke railway link (NGI, 2000).

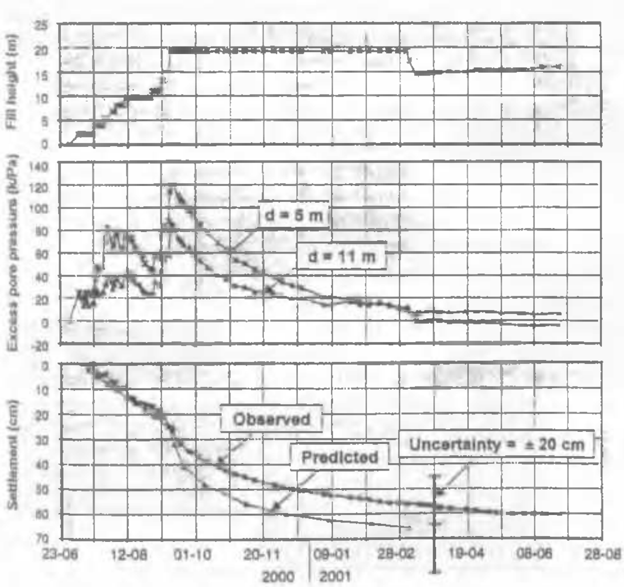


Figure 8. Fill height, pore pressures and settlements, Station 340, 7.5 m off centerline, Nykirke railway link (Hermann & Jensen, 2000; NGI files).

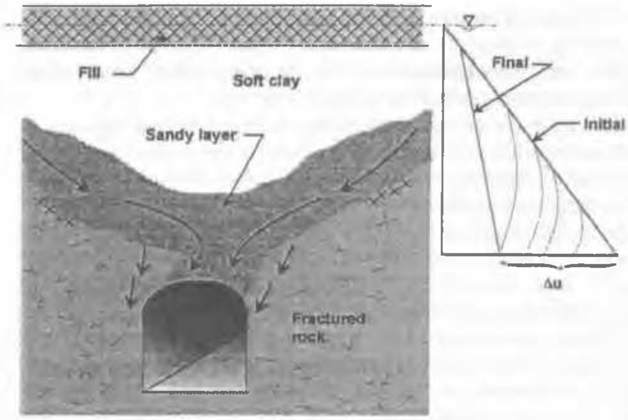


Figure 9. Pore pressure reduction and settlement due to tunnel leakage.

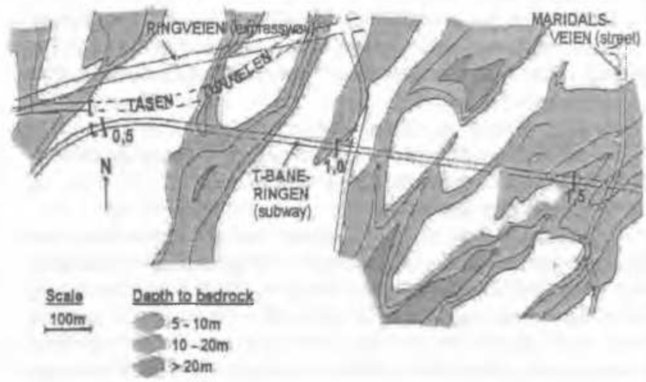


Figure 10. Thickness of soil deposits, Bergslia-Nydalen Tunnel, Oslo.

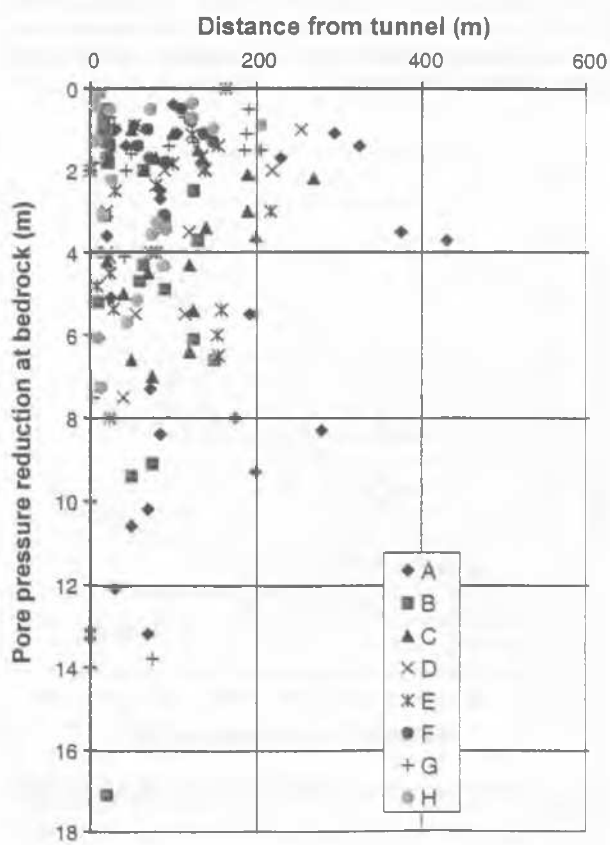


Figure 11. Pore pressure reduction at bedrock due to tunnel leakage, measured in deep trenches (NGI, 1998).

- We need to increase interaction among owner, designer, contractor, consultant and user, e.g. with new forms of contracting and the application of value engineering, encouraging brainstorming towards optimum solutions.

A national study in the building and construction industry in Norway was carried out to discern the reasons for the lack of successful collaboration in building and construction projects. The study concluded that five factors were the main culprits: lack of ability and lack of an arena for collaboration; lack of interest in changing the "way of doing things"; lack of competence; weak leadership and poor planning; and different, and even conflicting, goals and success criteria.

Value engineering's first objective is to enhance value by providing a framework of systematic procedures for conceptualisation, definition, implementation and operation of a project (Fig. 13). With appropriately structured contracts, value engineering creates opportunities to manage risk and achieve positive results for owner, designer, consultant and contractor. Key elements, in addition to planning and teamwork, include (ICE, 1996; Powderham & Rutty, 1994):

- increased value to customer by elimination of unnecessary cost or improved achievement of e.g. time and quality
- evaluation of options based on required function rather than simple cost cutting
- new idea creation as formal step in project
- life cycle costing (total costs of owning and operation of a facility) as input when evaluating alternatives
- integrated team approach

There is a strong synergy between value engineering, risk management and the observational method. Risk assessment adds value by listing and quantifying options, thus minimising the impact of all risks in the project. The observational method (Peck, 1969; 2001; Powderham, 1998) focuses on cost and time savings during construction and encourages a system to manage risk. Quoting Peck (2001), the observational method can pay-off handsomely, without more than the most elemental theory and with only qualitative predictions. In Peck's examples, there were few refinements, and no elaborate computer modelling to be "validated" by exotic remote-reading sensors. Refinements have their place, but they should not deflect attention and resources from the essence of the method.

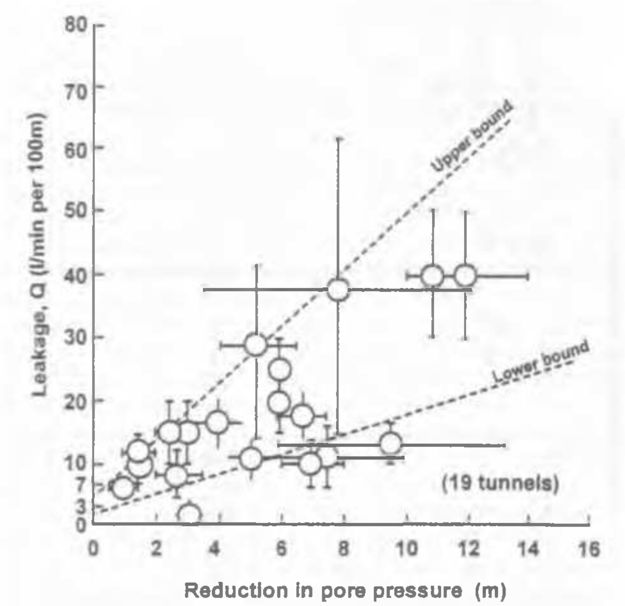


Figure 12. Observations of tunnel leakage and pore pressure reduction (NGI, 1998).

3.4 *Quality assurance to satisfy customer needs*

Quality assurance can be done in a time-consuming and costly manner. It can also be done as a profitable complement to a project.

Good quality assurance should merely confirm the natural way of doing things and be directed towards satisfying customer needs (Sørum, 1999). The goal of a good quality assurance is high quality work with satisfaction of all parties involved; client, supplier and supplier's team. The client is assured that he will receive the right product at the right price. The supplier is assured that the project will be completed on time, within budget and to a satisfactory level of accuracy. The supplier's team is assured the satisfaction of a job well done.

The quality assurance approach is in four acts: Plan, Do, Check and Act. Sørum suggested 10 commandments to help focus quality assurance work:

1. Think long-term: quality assurance is a strategic commitment, benefits will be long-term.
2. Keep the customer in mind: think through tasks from customer's viewpoint; ask customer for feedback.
3. Ensure good communication: contract review ensures a common understanding of deliverables and rewards, both with client and within project team.
4. Be pragmatic about documentation: keep it on a need to know only basis.
5. Keep it simple and relevant: quality assurance system must be easy to understand and perceived as relevant by users.
6. Plan work and quality checks: checking should be a natural part of the process.
7. Encourage participation: quality assurance system must be firmly anchored in management, project and throughout organization.
8. Learn from mistakes: while corrective action is important, preventive action is what gives long-term benefit.
9. Take time to reflect: evaluate projects, looking for improvements and simplifications.
10. Revise quality assurance system.

When used properly and positively, the quality assurance system will contribute to more economical solutions.

4 IMPROVED AND SAFER TRANSPORTATION

The public largely underestimates the importance of geotechnics for transportation infrastructure. Our profession influences planning, alignment and design of all arteries (Brandl, 1999). Geo-

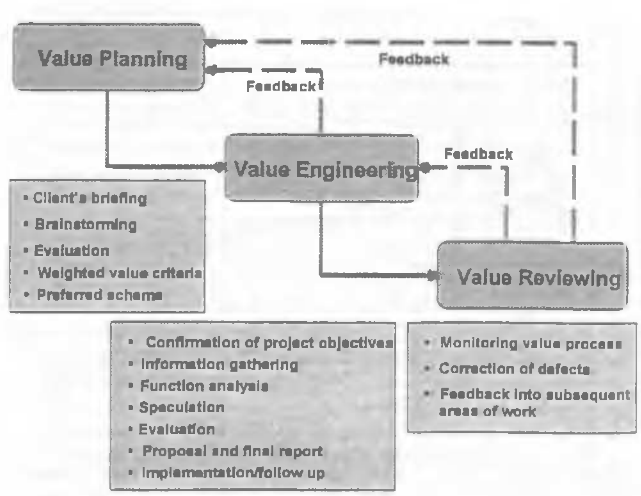


Figure 13. Value engineering (ICE, 1996)

technical engineers intervene in the feasibility study, risk and safety analysis, construction, operation and maintenance. Calculated risks need to be considered, highways and railways need to be placed along unstable slopes, cost-effective solutions need to be selected. The development of transportation infrastructure represents a major market and challenge for the geotechnical profession worldwide. There is need for:

- innovative solutions reducing costs and achieving required safety
- solutions for design on very soft ground, including road and railway embankments, airfields and harbour structures
- ground improvement techniques, such as cement/lime mixtures, jet-grouting, vertical drains and pre-loading
- improved construction methods limiting displacements and damage to neighbouring structures/utilities, e.g. deep excavations, tunnelling, leakage of groundwater into tunnels
- appreciation of allowable levels for noise and vibrations during construction and lifetime of infrastructure
- assessment of ground and groundwater pollution due to infrastructure
- remediation of contaminated ground and groundwater
- focus on sustainable solutions rather than costs alone.

4.1 *Effect of vibrations and high speed traffic*

Geodynamics and vibrations represent an old science enjoying renewed interest and research because of increased transportation needs in densely populated areas. The application of geodynamics ranges widely, from explosives to earthquake engineering, high-speed traffic to dynamic behaviour of offshore structures.

High-speed train traffic is developing rapidly in Europe, Asia, Australia and America. Transportation by rail is attractive because of the benefits it offers energy-wise, pollution-wise, the reduced needs for land and their longevity. Speeds exceeding 200 km/hr are common and some lines already operate at speeds above 300 km/hr. The speed record on ordinary railed track exceeds 500 km/hr. Demands for high-speed trains and short travel time call for straight alignments, which make crossing of soft soil zones unavoidable.

It is interesting to note that already in the 30's and 40's the Dutch railway engineers de Nie (1948) and Cuperus & de Nie (1948) were involved in the measurements of rail deflections and in the improvement of railway lines on poor ground conditions, in particular between Oudewater and Gouda. De Nie (undated, approx. 1949b) stated that rail deflections are a function of:

- axle load
- thickness of embankment fill
- elastic properties of sub-soil and damping in system
- train speed

De Nie also discussed that at certain speeds, "resonance" phenomena can cause rail deflections that are far larger than the static values. He also calculated that "resonance" would occur if a passenger train configuration travelled at a speed of 270 km/hr and if a freight train configuration approached the speed of 217 km/hr. De Nie's and his colleagues' work is still highly relevant and shows considerable foresight and engineering skills.

A railway embankment on soft ground must be designed to properly distribute the loads from passing train axles to avoid intolerable stress in the underlying soil and to provide sufficient support for the rail system. Soft soils pose challenges with respect to static bearing capacity, settlements and dynamic embankment performance. Inadequate dynamic design may lead to excessive dynamic displacements in the rail-sleeper-ballast-system and unacceptable vibrations in neighbouring buildings:

- At low and moderate speeds, the vibration of embankment and surrounding ground is mainly controlled by excitation from train response to track- and wheel unevenness, excitation from the passing over sleepers and loads passing over track, embankment and supporting soil non-homogeneity. Such vibration may annoy people in nearby buildings. This is an environmental issue.
- At higher speeds, the axle load induced deformations will be subject to dynamic amplification, and reach excessive values as a certain speed, termed the "critical speed", is approached. High deformations will pose at threat of train derailment, rail fatigue, ballast distortion, excessive embankment and ground settlements, and even degradation of the bearing capacity of the supporting soil. This is an embankment design issue.

4.1.1 *The environmental issue*

On soft soils, high-speed trains may cause high vibrations that can be transmitted to neighbouring buildings over substantial distances from the railway lines. People may be annoyed. Increased train speed in general and increased axle load on freight trains in particular will add to the problem. As population increases, railway lines through urban areas encounter more frequently this problem.

There is an increased awareness of environmental vibration issues. Vibration, rather than noise, is often the major cause of complaints. Annoying vibrations will also be detrimental for the image of the railway company wishing to promote an "environmentally-friendly" means of transportation. Official regulations started recently to focus on limiting vibrations by setting up criteria for acceptable levels.

There is a need to develop national standards for the effects and remediation to ground vibrations from rail and road traffic. Such standards should give criteria on how vibrations affect people, how vibrations should be classified. The standards should set requirements for measurement of the vibrations (Madshus & Hårvik, 1999). A Norwegian standard, setting criteria on building vibrations through limiting vibrating classes was issued in 1999. Table 2 presents the vibration classes used in Norway for buildings exposed to traffic (NBR, 1999). The maximum vibration velocity is taken as the maximum one-second root-mean square value of the frequency-weighted velocity during a train passage. It should have a probability of 95% of not being exceeded.

Table 2. Vibration classes according to Norwegian standard

Class	Degree of annoyance	Max.vel. mm/s
A	Population expects not to be disturbed by vibration	0.10
B	Population can expect to be disturbed by vibration to some limited extent	0.15
C	15% of population can expect to be disturbed by vibration	0.30
D	25% of population can expect to be disturbed by vibration	0.60

4.1.2 *The embankment design issue*

Soft soils, like clay and peat, have surface wave velocities so low that they may be lower than the train speed. Theoretical studies predict excessive vibrations of the railway track and embankment due to dynamic amplification as the train speed approaches a critical value function of the ground surface velocity and the embankment properties. Such problems have been encountered recently for railway lines being upgraded for higher speeds.

The problems of critical train speed and excessive vibrations are studied in several countries, and in particular in Sweden, United Kingdom and the Netherlands. In Sweden, extremely high vibration levels were detected along the West Coast line at several locations where the line passes over soft clay. There, the peat and organic clay layers had shear wave velocities as low as 40-50 m/s. Figure 14 presents the shear wave velocity profile at the test site. Ground improvement techniques are now being tested out to overcome the problem.

Madshus & Kaynia (1999; 2001) developed a numerical model "VibTrain" that can reproduce most of the significant features of the dynamic response of a railway embankment on soft ground subjected to train loads. Figure 15 presents results from the use of the VibTrain model to simulate an actual site, the Ledsgård site in Sweden (Adolfsson *et al*, 1999; Madshus & Kaynia, 2000). Vertical embankment displacements are plotted for passages with an X-2000 train at speeds of 70, 185, 235 and 250 km/h. Plot (a) shows the axle load pattern of the train. Plots (b) and (c) give the measured and simulated displacements. Plots (d) and (e) present predictions for speeds of 235 and 250 km/h.

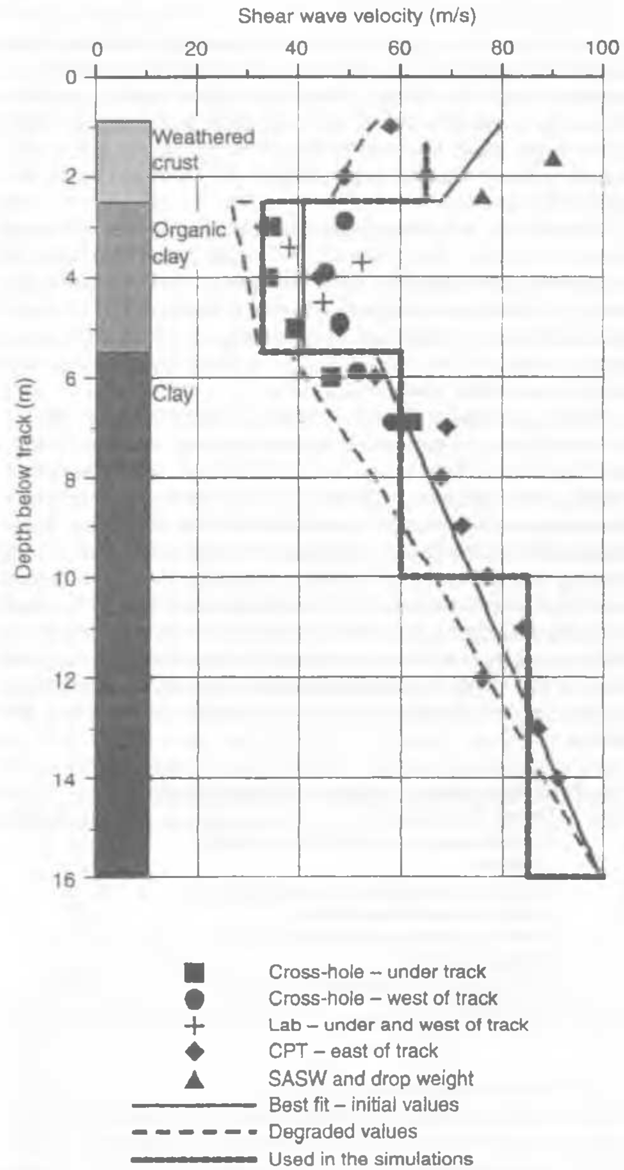


Figure 14. Shear wave velocity profile of the Ledsgård test site (Madshus & Kaynia, 2001).

The simulation is based on sub-structuring, where the soil is represented by discrete Green's functions for a layered half-space, and the rail-embankment system is represented as a beam by finite elements. Through an interactive process, nonlinearity in the soil and embankment materials is accounted for.

The simulations suggest that the critical speed at this site is about 235 km/hr (65 m/s). This threshold is related to a Rayleigh-like wave in the ground coupled to bending motions in the embankment. The extremely soft organic clay layer close to the ground surface, with a shear wave velocity as low as 40 to 50 m/s (Fig. 14), controls the amplitude of the critical speed. As the mode of the wave is such that it involves deformations in the much stiffer railway embankment-track system, its resulting natural propagation velocity ends up at about 65 m/s, with wavelength matching the overall bogie spacing of the train. The critical speed is a match of speed and wavelength between train and ground at the site (Madshus, 2001).

Figure 15 illustrates the features of the embankment response. At low train speeds, the displacement is quasi-static. It contains only downward motion and is a "foot-print" pattern of the axle loads, following the train motion, symmetrical about the loads. As the speed increases and approaches critical speed, a dynami-

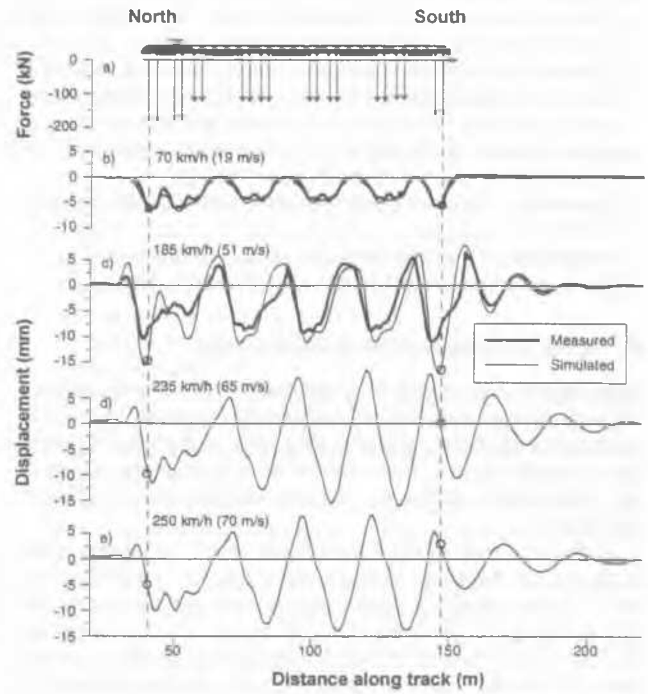


Figure 15. Vertical displacement of embankment at Ledsgård, Sweden for four train speeds below and above critical speed. Measured traces and traces simulated with VibTrain. (Kaynia *et al* 2000).

cally amplified displacement, in the form of a propagating wave, is added to the static displacement. The displacement pattern is still stationary with respect to the train, but the motions are both upward and downward, and the amplification builds up towards the end of the train. There is also a tail of diminishing oscillations following behind the train. This tail has the properties of the "natural wave" of the site.

Below critical speed, the axle loads are in phase with the displacement. At critical speed, there is phase-shift between load and displacement, and the loads ride about halfway between the trough and crest of the displacement. For speeds above critical, the load rides near the crest of the displacement. This phase shift resembles the dynamic response of a single degree of freedom system, when excited below, at and above its natural frequency. It also explains how energy is transferred from the train into the dynamically amplified wave motion close to critical speed. The wheels will keep running even in a slight uphill, pushed by the moving displacement pattern.

Figure 16 presents upward and downward displacement peak values and displacement amplitudes as a function of train speed for the range of speeds tested. The measured and computed displacements are for the central part of the train. The observations and predictions agree very well. The dynamic amplification as critical speed is approached is highly noticeable, both on the measured data and on the traces from simulations with the VibTrain model.

Figure 17 (Woldringh & New, 1999) compares displacement as a function of train speed at sites in the Netherlands, the U.K. and in Sweden (NS-RIB, 1997; Madshus & Kaynia, 2000;

Kaynia *et al*, 2000). The vertical peak dynamic displacement is normalised with respect to the static displacement at low train speed and the train speed is normalised with respect to the estimated critical speed at each site. The similarity and consistency of the observations at the three sites is very convincing.

4.1.3 *Summary*

Measurements and numerical simulations of trains with different speeds passing over a layered profile with soft clay, demonstrated the existence of a critical speed, function of the clay soil, the axle load and railway embankment.

For train speeds below about 70 km/hr, the displacement field appears to be mostly "quasi-static", following the pattern of the axle loads and resulting in mainly downward motion.

For higher train speeds, the displacement amplitude increases drastically as the speed increases, until it reaches a maximum as the train reaches the surface wave velocity of the ground-embankment system. Dynamic effects will significantly amplify the deformations of the track, embankment and supporting soil.

Railway embankments on soft soil may have a critical speed as low as about 200 km/hr. The critical speed depends on the shear wave velocity in the ground and the mass and bending rigidity of the track-embankment structure. Two issues need to be solved in relation to the effect of vibrations and high-speed traffic: the environmental issue and the embankment design issue. The two need to be solved hand in hand.

There is a need to further improve prediction methods, design tools and countermeasures, both to avoid track vibration problem and the environmental discomfort at critical speed. To model the several factors entering into the nonlinear behaviour and to simulate countermeasures, numerical approaches are needed. Numerical methods, both in the time and frequency domain are available, and they can simulate observed behaviour. To reduce required computational time, the modelling should be restricted to low frequencies and fine detail modelling should be avoided. A good modelling of the dynamic behaviour of the soil and embankment materials, including non-linearity, and of the infinite nature of the problem is essential to yield realistic results.

Monitoring is important for surveillance of the infrastructure and for validation of the numerical methods.

Ground improvements by the use of lime-cement columns can solve the critical speed problem at soft soil sites.

The determination of the dynamic properties of the soil need to be an integrated part of the planning, whether one is looking at upgrading existing infrastructure or a new transportation facility. Adequate soil investigations, including sampling and resonant column tests, *in situ* testing with both traditional and seismic methods (seismic cone, piezocone, surface wave methods) represents one of the necessary steps for solving both the environmental and the embankment design issues.

4.2 *Applications of GIS*

Geographical information systems (GIS) can find extensive applications for geotechnical engineers.

The environmental impact of high-speed traffic on the everyday life of dwellers is now part of integrated GIS mapping of a geotechnical investigation. For example, by combining a map of the vibration levels, expressed as a speed, and the possible alternative locations of a railway for example, it is possible to determine the degree of annoyance in a neighbourhood. Figure 18 illustrates the result of such an environmental impact study, where the number of dwellings affected by vibration velocities superior to 0.3 and 0.6 mm/s was quantified for different alignment alternatives.

In addition to serving as a support project and documentation database, GIS applications can for example:

- organise data from geotechnical investigations and extent of soil contamination due to, for example, spilling of diesel, spread of de-icing fluid, etc.
- be used to calculate on-line run-out distance of landslides or propagation of vibrations due to high-speed traffic. GIS facilitates, in the calculation, the utilisation of the information contained on digital maps, such as slope/inclination of the ground, shape/curvature of railway line and characteristics of existing buildings, installations and land property.
- systemise and present the results of analyses, landslide hazard zonation and environmental impact studies.

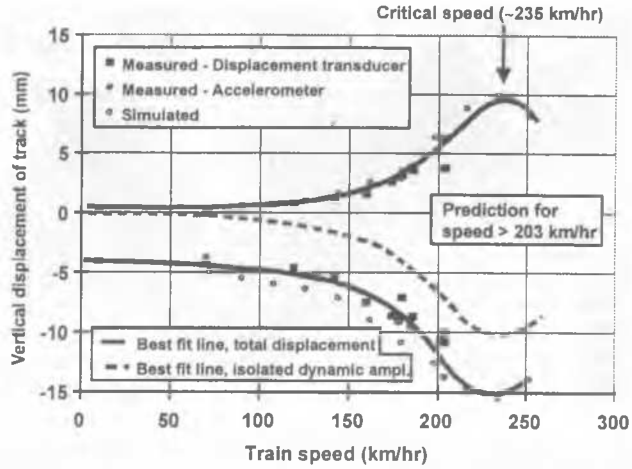


Figure 16. Peak upward and downward displacement of embankment at Ledsgård, Sweden, versus train speed. Measured values measured and traces simulated by VibTrain. (Madshus & Kaynia 2001).

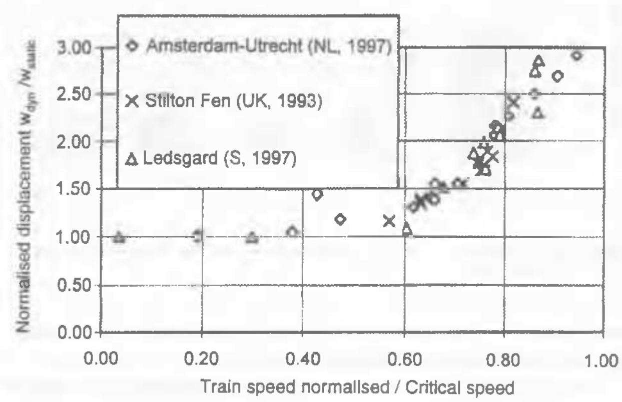


Figure 17. Normalised vertical dynamic displacement of embankment versus normalised train speed at three sites.(Woldringh & New 1999).

4.3 *Risk assessment*

Society has become less tolerant of failures of engineered structures, including disasters brought about by natural hazards in populated areas, and expects increasingly that risk be quantified. Our profession needs to be prepared to answer questions about risk and be able to quantify risk and probability of failure. It is increasingly important today to adopt rational, consistent, and "documentable" design approaches that inform of and account for the uncertainties in the analysis parameters. Only reliability and risk approaches can provide the designer with insight in the inherent risk level of a design.

Statistics, reliability analyses and risk estimates can be very useful decision-making tools in geotechnical problems. Yet the methods have been little used in practice, at least on land. Duncan (2000) presented an excellent discussion of factor of safety and reliability in geotechnical engineering that triggered considerable interest ASCE, 20001). This witnesses a keener interest

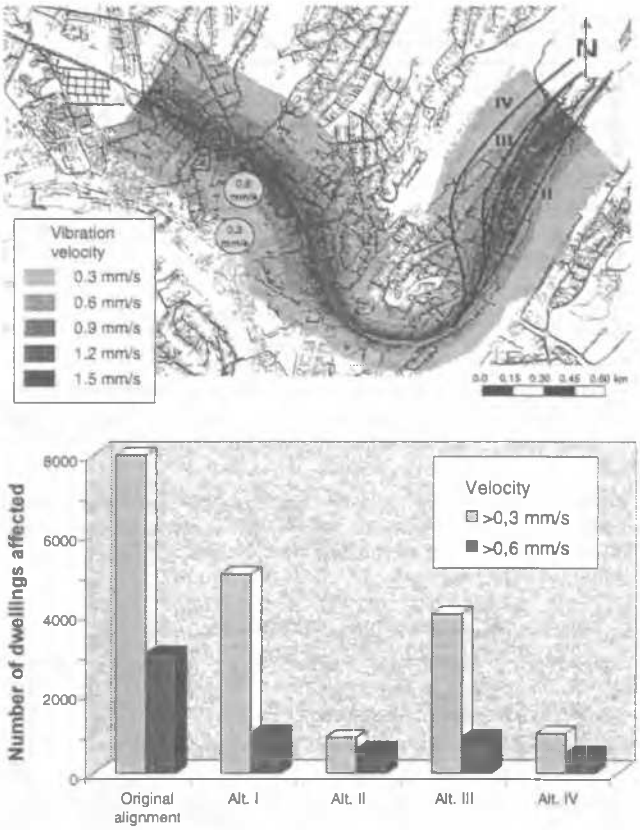


Figure 18. Vibrations from high speed train traffic. Results of environmental impact study.

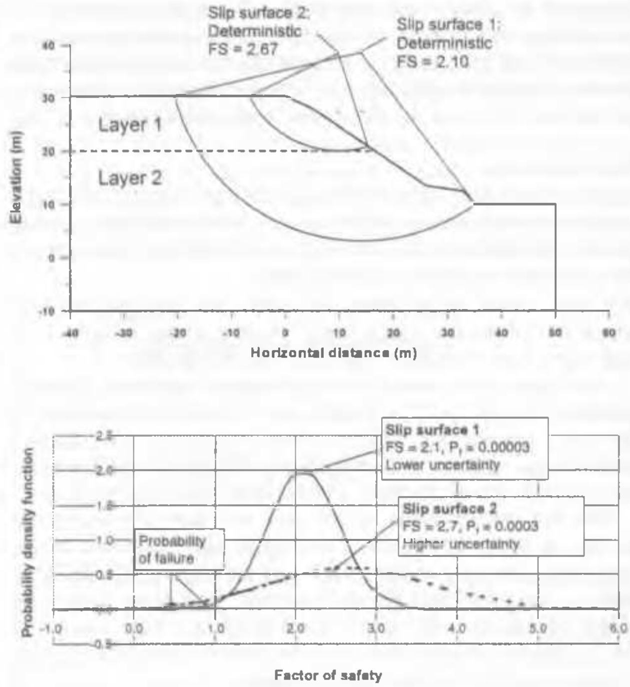


Figure 19. Safety factor (FS) and probability of failure of a slope.

than earlier in the topic, and is the prerequisite for the approaches having lasting value in the profession.

Reliability analyses are needed because geotechnics is not an exact science. Predictions of foundation behaviour cannot be made with certainty due to spatial variation of soil and load properties, limited site exploration, limited calculation models, and uncertainties in the soil parameters. Reliability-based analyses enable one to map and evaluate the uncertainties that enter in the formulation of a geotechnical problem. If a deterministic model for the analysis of a geotechnical problem exists, a probabilistic analysis model can always be easily established with the tools available today. That one finds difficult the quantifying of the uncertainties is not a good reason to avoid defining the uncertainties or establishing their significance in design.

The offshore industry, dam builders and the mining industry have been at the forefront in applying risk assessment and uncertainty-based analysis to assist in decision-making. This has contributed to the documentation of case studies where reliability and risk concepts have been used. Risk analysis is extremely important in the assessment of slopes highways slopes and protection against natural disasters (Section 5.3). Ho et al (2000) made an excellent review of the context of risk management, tools available including examples of slopes in Hong Kong, and major issues that slow the progress of the approach in practice. They concluded that qualitative and quantitative risk assessment in geotechnical engineering is here to stay.

A number of approaches exist, from simple judgement calls to advances system analyses. A single risk analysis format is not universally applicable to all issues in geotechnical engineering. There lies one of the strong points of the approach. Methods and procedures can be varied according to the type of the problem, failure modes and the nature and uncertainty of the conventional (deterministic) analysis, the purpose of the analysis and the needs the analysis is meant to fill. Differences in methods can be associated with differences in response, consequences or safety issues (Lacasse and Nadim, 1998).

The usefulness of the concept is illustrated with the case study of a slope where conventional and probabilistic analyses were done. The slope in Figure 19 consists of two distinct, saturated clay layers. The clay in the two layers has natural water content between 40 and 50% and plasticity index of about 12%. The sensitivity, from *in situ* vane tests, is between 4 and 5. The top layer is 10 m thick. It has a mean undrained shear strength in triaxial compression of 75 kPa and a mean total unit weight of 17.5 kN/m^3. The bottom layer, with same total unit weight, has a mean undrained shear strength in triaxial compression of 150 kPa.

The analysis parameters were treated as random variables and used in a probabilistic analyses of the slope stability (Nadim and Lacasse, 1999). The analyses used the first- and second-order reliability methods. The uncertainty in the undrained shear strength was obtained from the results of triaxial compression laboratory tests. Strength index tests were also considered for Layer 1 to increase the database of results. The strength anisotropy was based on data available for similar clays. The uncertainty in the undrained shear strength is larger in Layer 1 than in Layer 2 due to three factors: larger scatter in the triaxial test results, fewer tests available and probably a larger inherent variability at the top of the clay mass.

The model uncertainty was set to have a bias of unity with a coefficient of variation of 10%, based on model tests and experience. Since the main purpose of this analysis was to demonstrate the usefulness of the method, a small uncertainty was selected. A very large uncertainty in the model would tend to mask the effect of the other uncertain variables on the analysis.

Figure 19 shows the deterministic critical slip surface, cutting through both soil layers. The slip surface with the minimum safety factor cutting through only Layer 1 is also shown. Table 3 gives deterministic safety factor and probability of failure. The deterministic analysis gave a safety factor of 2.1 for slip surface 1 and 2.7 for slip surface 2. However, the probability of failure is 10 times higher for slip surface 2 than for slip surface 1. In other words, the analysis indicates that the slip surface with the lowest safety factor is 10 times <u>less likely</u> to fail than the surface cutting through Layer 1 only.

Taking into account the uncertainties, as perceived, indicates that the critical slip surface, even with a lower safety factor, may have higher safety margin than the slip surface with higher safety factor. Factor of safety is therefore not a sufficient indicator of safety margin because the uncertainties in the analysis parameters affect probability of failure and safety. The flatter distribution of the factor of safety (Fig. 19) reflects greater uncertainty and will result in a greater area under the curve where the factor of safety can be less than unity and will therefore result in a higher probability of failure.

The essential component of the probability of failure estimate was geotechnical expertise and engineering judgement. The geotechnical engineer may worry that engineering judgement might disappear if one puts emphasis on risk analysis. It is thus important to calibrate the results of risk analysis with experience. Risk assessment is really only complementary to the traditional deterministic approach. One shall not forfeit engineering judgement in favour of elegant mathematical solutions.

The approach should not be oversold, but it will provide additional information to the designer, which otherwise stays hidden in the deterministic analysis. The more critical this information is to the design, the more important it is to include them in the analysis with the appropriate degree of attention such that the consequences connected to each critical aspect are included in the analysis. There are some types of problems where doing reliability-based evaluations will not give adequate assistance: when the uncertainties are very large, when the mechanisms of the problem are not well understood, or when the parameters of analysis model are not well defined.

The most important contribution of uncertainty-based concepts and risk to geotechnical engineering is increasing awareness of the uncertainties and of their consequences. The methods used to evaluate uncertainty, probability of failure and risk level are tools, just like any other calculation model or computer program. The risk assessment should be an opportunity to look at the bigger picture and seek out designs that meet not just some arbitrary idea of acceptable risk but an unknown risk. For the geotechnical engineer, the message is to explore the opportunity that come from new ideas, to try to see the problem as a whole, and avoid getting lost in the detail. The obvious is to exploit the good features of the approach.

The risk approach still has major development needs, including reducing uncertainty in the calculation models by obtaining and analysing performance data of high quality, quantifying acceptable risk level and convincing the designer to view the value-added in uncertainty-based analyses. Just like selecting a target safety factor was difficult before there were codes of practice, establishing an allowable risk is a new challenge. It is both difficult and controversial. Nevertheless, society requires increasingly that analyses be done to determine the risk imposed on the public. The geo-engineer is the one with most insight in the technical aspect, so he needs to get familiar with the technique to be able to contribute his experience to the selection of allowable values. The selection of an acceptable risk has several dimensions: technical, social, political, economic and legal, and engineers alone cannot select it, but they definitely must be a part of it.

5 INNOVATIVE SOLUTIONS

5.1 *Adapting offshore geotechnical solutions to design on land*

Geotechnical progress, in particular the understanding and modelling of soil behaviour under cyclic loading, enabled the offshore industry to move towards increasingly optimum solutions. On the other hand, the needs and requirements of the offshore industry have contributed significantly to advance geotechnical knowledge, and this should be recognised.

The foundation of a typical offshore structure is exposed to a combination of permanent static loads due to gravity and buoyancy, pseudo-static loads due to currents and wind, and dynamic (cyclic) loads due to wave action. Dynamic loads may also be induced by earthquake, wind or iceberg impact. The foundation design aspects include evaluation of bearing capacity, cyclic displacements, equivalent soil spring stiffness for dynamic structural analyses, soil stresses against the structure, and settlements due to cyclic loads. Analysis approaches for each of these problems have been developed (Andersen, 1991; Andersen *et al*, 1993; 1994; Andersen and Jostad, 1999).

Table 3. Safety factor and failure probability in slope stability analysis (Nadim & Lacasse, 1999).

Slip surface	Factor of safety, FS	Probability of failure, P_f*
1	2.1	0.00003
2	2.7	0.0003

* P_f = area below distribution curve where FS < 1 (Fig. 19)

It is paradoxical for geotechnical firms to have played a key role in the development of new and cheaper foundation solutions involving skirts and anchors (Section 5.1.4). By making the small and lightweight skirted foundations a dependable solution, the firms reduced the demand for in situ and laboratory testing. Although the volume of work has greatly decreased, by doing so the geotechnical profession gained credibility for encouraging more optimum designs, and established a close, and necessary, link in the design of the foundation.

Engineering designs on land also benefit from the knowledge acquired on the behaviour of soils under repeated (cyclic) loading. These include:
- breakwaters, storm surge barriers and bridge piers subject to wave loading;
- high-speed trains, highway traffic embankments and machine foundations subject to vibrations;
- tall buildings, towers and bridge pylons subject to wind loading;
- buildings, structures, and slopes subject to earthquake loading;
- structures that can be founded on skirted foundations and anchors, such as elevated pipelines, towers, etc.;
- foundation techniques that can make use of an under-pressure to enhance consolidation or penetration, such as vacuum consolidation in harbours (e.g. Tang and Shang, 2000; NGI files), near-shore windmills and pipelines (NGI files), etc.

Figure 20 presents examples of foundation design for structures on land and offshore.

5.1.1 *Soil investigations*

Equipment, laboratory and in situ testing methods, model testing, interpretation and parameter determination are some of the aspects that have greatly benefited from enhanced research and attention brought on by the offshore work. For adequate design of foundations, soil parameters need to be determined through a combination of interpretation of the local geology, in situ testing and laboratory testing.

The development of the piezocone penetration test and new sampling devices for increasingly greater depths has been most important (Kolk & Campbell, 1997; Lunne *et al*, 1997). Without these methods and the reliability they have gained, the design today would be much more conservative. The uncertainties surrounding soil profile and soil parameters would have been significantly larger. These improvements would probably not have been possible without the offshore industry supporting research and demanding improved results.

Laboratory testing techniques have greatly improved, and the way of setting up testing programs has become a rational, cost-benefit oriented process. The rationale has also influenced practice on land. The necessity of reproducing as closely as possible the in situ conditions and the stress path under extreme loading is common practice today. The effects of sampling disturbance, although not easy to quantify, are a factor routinely considered when assessing soil parameters. The problem has now renewed interest as samples are recovered from greater water depths.

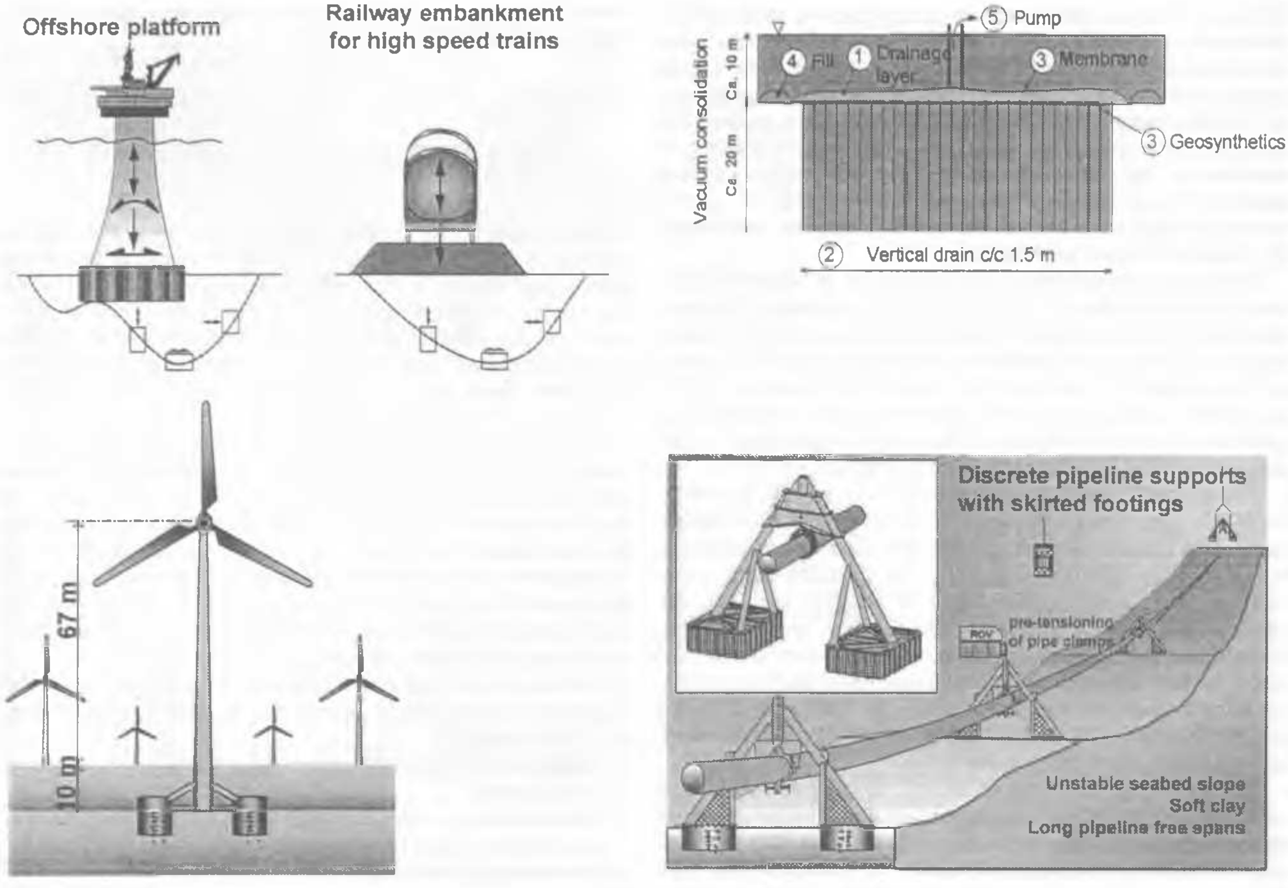
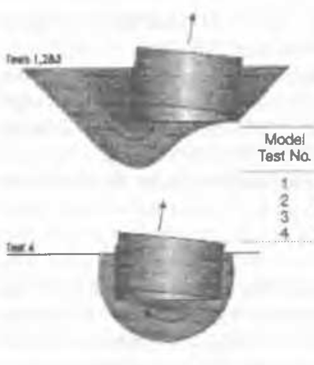


Figure 20. Foundations on land using methods developed for offshore foundations.



Model Test No.	Test Type	Failure Load (kN) Predicted	Measured	Pred./Meas.
1	Static	138	137.7	1.0
2	Cyclic	118	112.9	1.05
3	Cyclic	105	99.5	1.06
4	Cyclic	92	90.5	1.01

Figure 21. Results from pull-out capacity analyses (Andersen *et al*, 1993).

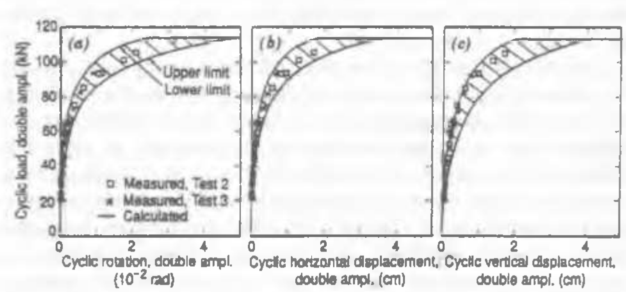


Figure 22. Predicted and measured cyclic displacements in clay at ground surface level (Andersen *et al*, 1993).

Model testing (1-g or in the centrifuge) is one of the best geotechnical tools to document the mechanism of failure, the deformation pattern, the soundness of a design method and the reliability of a calculation model. Figures 21 and 22 show the results of predicted and measured failure loads and cyclic displacements for a tension leg platform. These were 1-g model tests run to in situ to evaluate the calculation models (Andersen *et al*, 1993). The calculation of failure loads was done before the model tests were run, thus providing an unbiased calibration of the calculated values to the measured values in the model tests. Model tests, although expensive, should reduce considerably the uncertainty in a calculation model when they are carefully planned and run. However, model tests should normally not be used to extrapolate directly the results from a small model to a prototype.

5.1.2 *Modelling of soil response*

Concepts from the theory of elasticity may often prove satisfactory for practical design of foundations exposed to monotonic loading and/or very low amplitude vibration. This is found adequate although soils undergo irrecoverable deformations even at very low strain levels, and the directions of strain increments do not in general coincide with the directions of stress increments as assumed in the isotropic elasticity theory.

For situations with repetitive loading-unloading-reloading, cyclic strains as well as accumulation of permanent (irrecoverable, plastic) strains occur, and it is sometimes more important to be able to predict the latter than the former. By definition, the theory of elasticity alone, even if applied in non-linear incremental form, cannot provide estimates of these permanent deformations. One may resort to either plasticity theory or a numerical analysis utilizing experimental results from laboratory tests on soil samples exposed to approximately the same static and cyclic combinations as corresponding representative elements experience in the field. Practical design of offshore foundations is almost exclusively based on the latter approach.

The stress conditions in the soil beneath a structure subjected to cyclic loading could be quite complex. A simplified picture of the shear stresses in a few typical elements along a potential failure surface underneath a gravity structure is shown on Figure 23. The elements follow various stress paths and they are subjected to various combinations of average shear stresses τ_a, and cyclic shear stresses τ_{cy}. Herein, τ denotes the shear stress on the horizontal plane in the direct simple shear (DSS) test and on the 45° plane in the triaxial test. The average stress is caused by the initial shear stress in the soil prior to platform installation τ_0, and the additional static shear stress due to the weight of the structure. The cyclic shear stress is caused by the cyclic loads. In a storm, the wave height and period vary continuously from one wave to another and the cyclic shear stress will also vary from cycle to cycle.

To determine the soil properties needed in the foundation design analyses, it is necessary to run laboratory tests where the stress conditions for the various soil elements are followed as closely as possible.

The behaviour of a soil element subjected to a combination of static and cyclic loads under undrained conditions (relevant for foundations on clay) is shown schematically on Figure 24. When the static shear stress is increased by $\Delta\tau_a$ from τ_0 to τ_a, the soil will experience a pore pressure change Δu_a. The repeated cyclic shear stresses will cause a pore pressure development with cyclic and average components u_{cy} and u_a, which both increase with number of cycles. The pore pressure at the end of the cycle is called the "permanent pore pressure" u_p.

The shear strain varies in much the same manner as the pore pressure. When the shear stress is increased by $\Delta\tau_a$, the shear strain increases by $\Delta\gamma_a$. The cyclic shear stress causes a shear strain development with cyclic and average components which both increase with number of cycles.

Under cyclic loading, the bearing capacity of the soil may decrease relative to the static capacity (Fig. 25), and settlements will occur (Fig. 26). The results in Figure 25 are from model tests of a skirted foundation in a soft, lightly overconsolidated marine lay in southern Norway.

The soil parameters needed for design include: cyclic shear strength, cyclic shear modulus, damping, permanent shear strain due to cyclic loading, pore pressure generation and recompression modulus.

Andersen and his co-workers have developed and refined a procedure for design of shallow offshore foundations on clay where these parameters are established from cyclic triaxial and DSS laboratory tests consolidated to the in situ effective stresses (Andersen, 1991). Since the cyclic behaviour depends on both cyclic and average shear stresses and type of loading, the cyclic shear strain, average shear strain, and permanent or average pore pressures are determined from laboratory tests and plotted as functions of average and cyclic shear stresses. Examples for

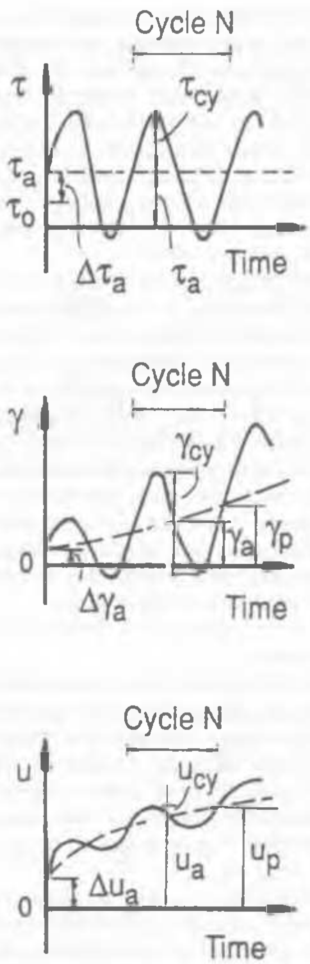


Figure 24. Shear stress, shear strain, and pore pressure during undrained cyclic loading (Andersen, 1991).

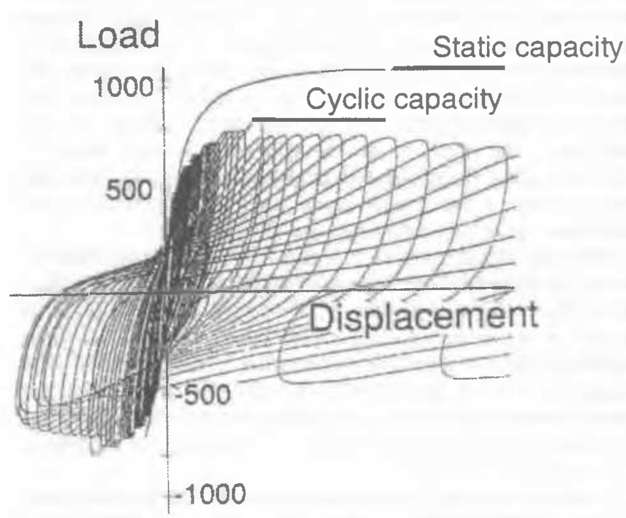


Figure 25. Static and cyclic capacity, soft Norwegian clay (Andersen, 1991)

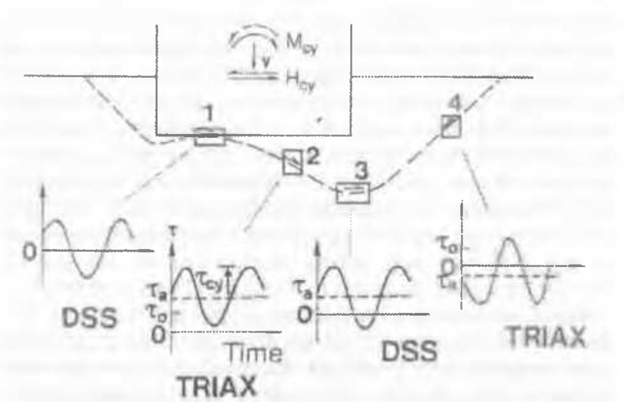


Figure 23. Simplified stress conditions for elements along a potential failure surface (Andersen, 1991).

Drammen clay are presented on Figures 27 and 28. The shear stresses are normalized with respect to the reference static undrained shear strength for the relevant mode of shearing and with respect to the effective vertical consolidation stress.

In the strain contour networks, the solid curves represent the cyclic shear strain and the dashed curves represent the average shear strain. The strain contours for $\gamma_{cy} = 15\%$ and $\gamma_a = 15\%$ give the outer bounds in the diagrams. These strain levels are very large and may be defined as failure conditions. The term "cyclic shear strength" is defined as the sum of the ordinate τ_{cy} and the abscissa τ_a for points on the bounding strain contours. It is this cyclic shear strength which is used in the bearing capacity calculations for suction anchors and foundations of offshore gravity structures on clay (Andersen & Lauritzsen, 1988).

Analysis of response of sand foundations under cyclic loading is more complicated because the soil can no longer be assumed to remain undrained throughout the design storm. To predict the cyclic and average foundation displacements, it is essential to evaluate the pore pressure generation and dissipation during the storm. Andersen *et al* (1994) described an extension of the procedure developed for foundation design on clay to sand. The basic assumption is that pore pressure generation and dissipation occur simultaneously during the storm, but the soil is essentially undrained during a single load cycle. The pore pressure change in the sand is caused by the pore pressure build-up generated by cyclic loading, the cyclic pore pressure due to dilatancy, and cyclic changes in the octahedral effective stress.

5.1.3 *Modelling of repeated loading*

The diagrams on Figures 27 and 28 give the cyclic shear strains and strengths for elements where the shear stresses are constant during the cyclic load history. In a storm, however, τ_{cy} will vary from cycle to cycle. The equivalent number of cycles of the maximum shear stress, N_{eqv} that gives the same effect as the actual cyclic load history must therefore be determined. This 'strain accumulation' procedure to determine N_{eqv} is presented by Andersen (1991).

For clays (i.e. undrained conditions), N_{eqv} may be computed by keeping track of the cyclic shear strain during the cyclic load history. For sands, N_{eqv} may be computed by accumulating the permanent pore pressure generated during the cyclic load history. The reason for using the accumulated pore pressure for sands is that drainage is likely to occur during the design storm in sands. To account for the drainage, it is necessary to keep track of the pore pressure in the computations. Drainage will have a positive effect in the sense that some of the permanent excess pore pressures generated by cyclic loading may dissipate during the storm. Cyclic loading accompanied by dissipation of permanent pore pressures ('precycling') may also change the structure of the sand and increase the resistance to excess pore pressure generation during subsequent cyclic loading. On the other hand, one needs to be cautious about relying upon the beneficial effect from reduced pore pressures which may develop in dense dilating sand deposits during individual cycles, since these cyclic pore pressures may also dissipate.

The irregular loading in a storm is taken into account by keeping track of the development of the permanent pore pressure during the cyclic load history. The pore pressure accumulation calculation is performed using a pore pressure contour diagram established from cyclic stress-controlled laboratory tests. The dissipation of the permanent pore pressure, due to both drainage towards free drainage boundaries and redistribution, may be determined by finite element analysis or, for idealized situations, by closed-form solutions.

In addition to the drainage and redistribution of the permanent pore pressure during the storm, the pore pressure variations within individual cycles may also be influenced by drainage and redistribution. For dense sands that tend to dilate during shear, this may mean that a part of the pore pressure reduction that prevents the sand from developing large shear strains may be lost. The cyclic shear strength may then be less than with fully undrained conditions. The redistribution of the pore pressure within individual cycles may be determined by finite element analyses or from closed-form solutions.

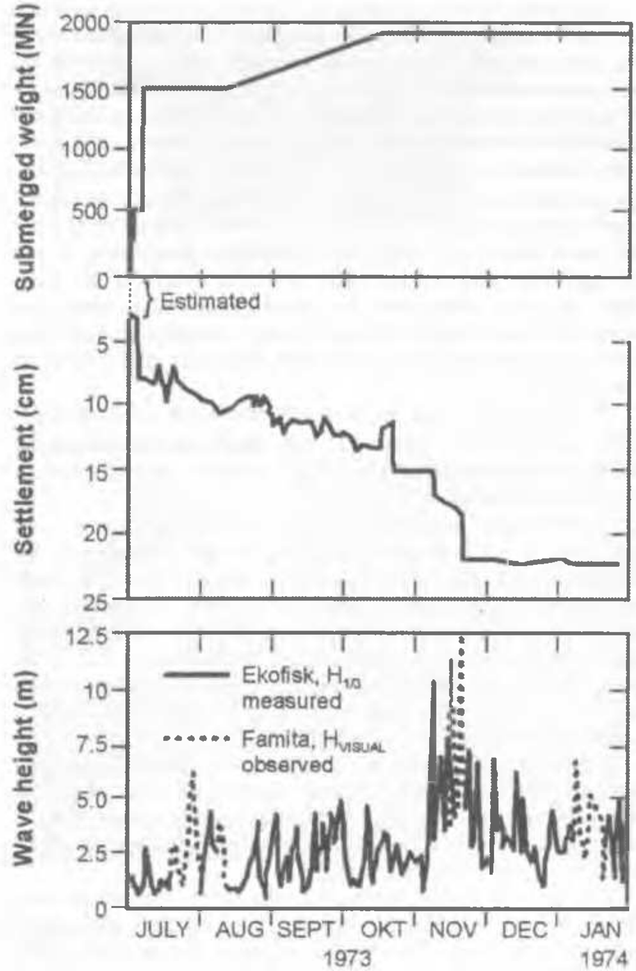


Figure 26. Observed settlement below Ekofisk tank.

In principle, the cyclic shear strength could also be computed for clays by accumulating the permanent pore pressure. In practice, however, laboratory pore pressure measurements are more difficult to perform with good accuracy in clays than in sands. Since drainage will not take place in clays, it is therefore preferable to use the shear strain to determine the cyclic shear strength for clays. For situations where the cyclic shear strength and the cyclic shear moduli under undrained conditions are of primary interest, the shear strain will also be a more direct parameter than the pore pressure.

5.1.4 *Skirted foundations and anchors*

Skirted foundations and anchors have become competitive alternatives to other foundation solutions. One of the reasons for the success of skirted foundations is that they offer important cost savings compared to more traditional foundations and anchors. The savings are related to fabrication, offshore installation (equipment and time), ease of accurate positioning, small size thus limited extent of soil investigation, simple geotechnical and structural designs, and potential re-usability of the structure. Skirted foundations and anchors can be used in most soil types and for both fixed and floating platforms, including floaters, tension leg platforms, steel jackets, jack-up rigs, sub-sea systems and other protection structures (Andersen and Jostad, 1999).

Skirted anchors have significant uplift load capacity. The possibility of relocation of the structures at different sites may render marginal fields profitable. Removal of the structure also provides a clean site after exploitation, thus meeting environmental concerns.

Figure 29 explains the principles of the suction installation and holding capacity of skirted foundations and anchors, and

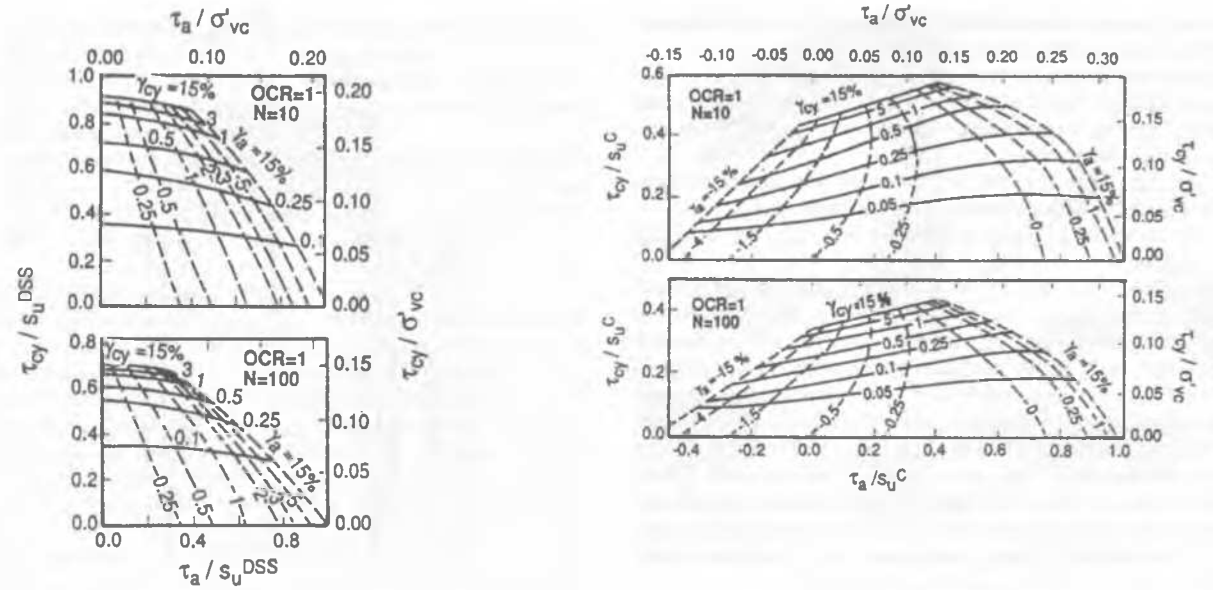


Figure 27. Average and cyclic shear strains after 10 and 100 cycles in DSS and triaxial tests on Drammen clay with OCR = 1 (Andersen *et al*, 1988).

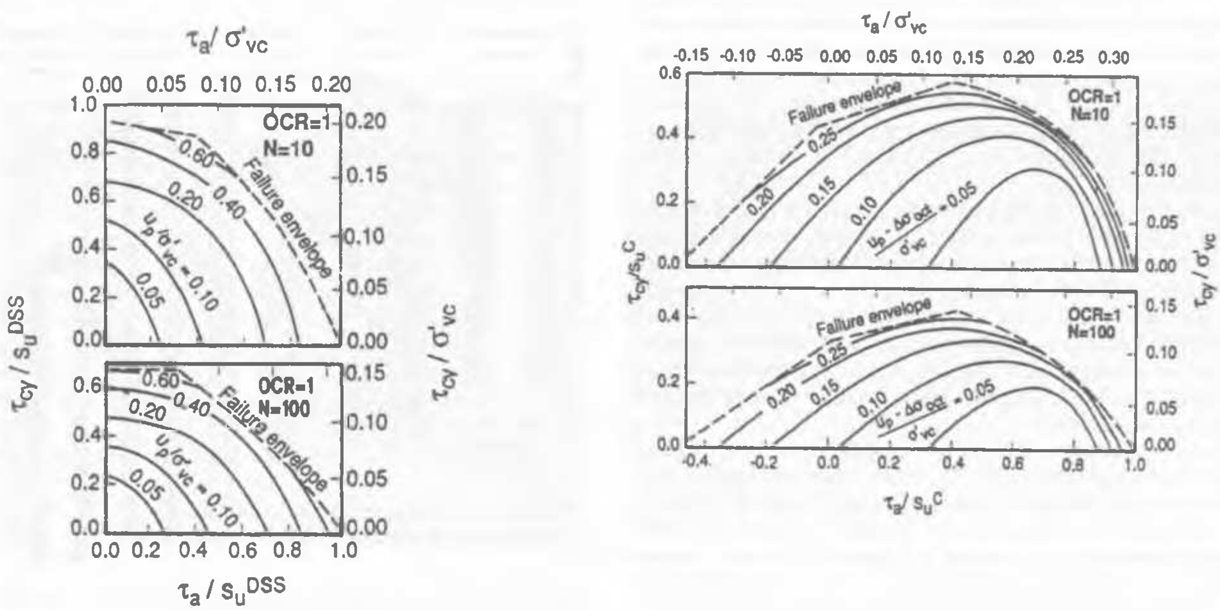


Figure 28. Average pore pressure after 10 and 100 cycles in DSS and triaxial tests on Drammen clay with OCR = 1 (Andersen *et al*, 1988).

Figure 30 gives examples of the failure modes for skirted foundations. Design includes analysis of skirt penetration, capacity, displacements (consolidation, cyclic displacements and permanent displacements due to cyclic loads), soil spring stiffness and soil reactions and soil structure interaction for structural design. Geotechnical calculation procedures are now well developed and have been verified. The skirted foundation concept has now been developed for other applications, e.g. for support of near-shore submarine pipelines, near-shore windmills, etc. This type of foundation works also well in the presence of uneven seabed and unstable slopes (Fig. 20).

5.1.5 *Breakwaters*

An extensive European Union project focused on the design of caisson breakwaters, both caisson breakwaters and rubble mound breakwaters (de Groot *et al*, 1995). The study concluded that:

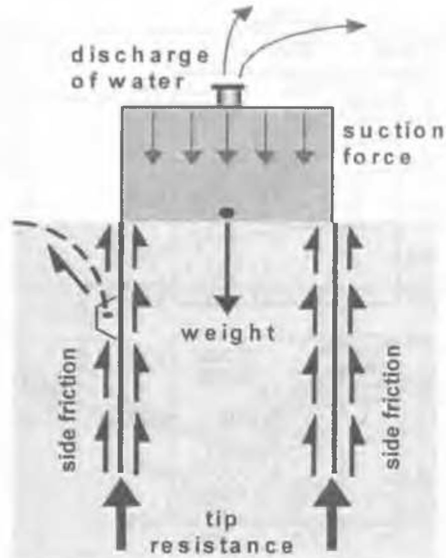
- the bearing capacity of the subsoil is often decisive for the dimensions of the caissons when the subsoil is clay or loose to medium dense sand;
- extensive soil investigations are needed;
- wave impact of relatively long duration, even with low amplitude, are often the most critical with respect to stability;
- stiffer soil seemed to yield the highest sensitivity to wave impact;
- instantaneous pore pressure build-up influences strongly the stability against sliding and rotational failure;
- residual pore pressures may also influence strongly the bearing capacity in sand.

5.1.6 *Summary*

The offshore industry has been a major driving force in the advancement of geotechnical knowledge in the past decades. Offshore solutions developed for harsh, even extreme, environmental conditions now present attractive options for infrastructure on land, including bridges and towers, embankments and buildings subjected to cyclic loading and the foundation of near-shore installations. An important opportunity is the application of the knowledge acquired in offshore practice to problems on land, for example:

- use of vacuum consolidation to improve the shear resistance of the soil in e.g. harbour facilities;
- skirted foundations for near-shore installations;
- application of knowledge from the behaviour of soils under cyclic loading to problems with dynamic amplification and cyclic displacements;
- use of the large and well-documented soil parameter databases established for offshore design in land applications;
- re-use of offshore structures for other purposes, e.g. as bridge foundations.

The impetus provided by the offshore industry is expected to continue in the future. As oil and gas exploitation moves at greater and greater water depths, new solutions will be needed. On the short term, major advances are expected in the areas of behaviour of gassy and unsaturated soils, modelling of geological processes, analysis of underwater slope instability and new soil models to understand the response of deepwater marine clays to external loads such as earthquakes (Pestana *et al*, 2000). Improvements of equipment and testing techniques are also expected, as well as the development of new foundation concepts and of increasingly remote installation and monitoring techniques.



5.2 *Crossing waterways*

Underground and underwater construction offers existing opportunities for young geotechnical engineering researchers and practitioners as it grows in importance around the world. There is room for innovation, and for reducing uncertainty, by increasing understanding of the geotechnical aspects of underground construction. For example, immersed tunnels represent an elegant and versatile solution.

Increasing road and rail transportation has drawbacks because it uses much coveted land, causes congestion, consumes energy and is the source of noise and pollution. The main portion of the population in Norway is located along the coast. The numerous islands, deep fjords and high mountains result in a transportation network where tunnels, bridges and ferries are needed to connect people. An important aspect of fixed crossings over waterways is the freedom to travel at any time, a freedom fully appreciated only by the islanders.

There are several options for crossing waterways: ferries, fixed and floating bridges (Melby, 2000), immersed tunnels, sub-sea tunnels and immersed floating tunnels (Flaate & DiBiagio, 2001). To ensure communication, bridges or tunnels are often the only alternative, as illustrated in Figure 31. Close to Ålesund in Norway, three tunnels, each 3.5- to 4.2-km long and maximum depth below sea level between 140 and 190 m, link the insular populations. Sub-sea tunnels have become a special feature of the Norwegian transportation network. In twenty years 23 of these have been built, most of them for connecting islands to the mainland. The longest Norwegian sub-sea tunnel has a length of 8 km and the deepest has a maximum depth of 260 meters below sea level. One tunnel is currently under construction and three more will be built in the near future.

A new tunnel concept extending the possibilities for fixed crossing of wide and deep fjords is the submerged floating tunnel. The technique has considerable merit in urban and densely populated areas since it permits flexible location and alignment thereby saving land and preserving the environment. Several projects are in an advanced stage of design. Studies are underway in Japan, Italy, Switzerland, China, USA and Norway.

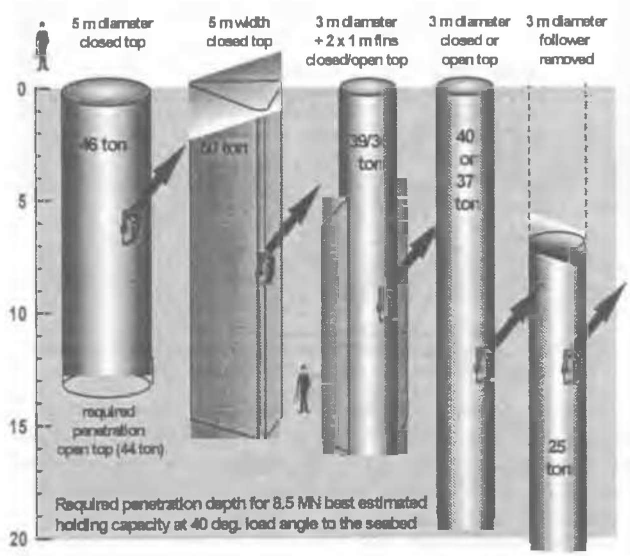


Figure 29. Principles of skirted foundations and anchors - penetration and holding capacities for different geometries.

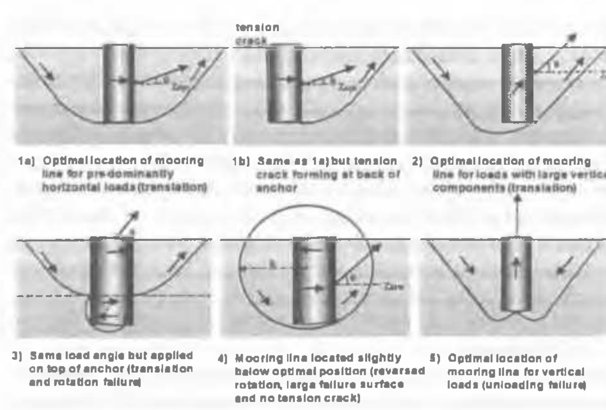


Figure 30. Failure modes for a skirted foundation.

5.2.1 *Sub-sea tunnels in rock*

A sub-sea tunnel in rock makes a fixed crossing technically feasible even when the crossing is fairly wide and the water is deep. The alternative could in some cases be a suspension bridge, but with the lengths in question the costs would be prohibitive. The advantage of a tunnel can also be low initial cost if the rock is competent. Important aspects to be consider include:

- excessive water inflow if stability is not satisfactory;

- need for thorough geological mapping and acoustic and seismic investigations;
- need for mapping and probe drilling during construction to gain information on rock cover and position and properties of weak zones:
- added maintenance due to leakage of saltwater affecting durability of materials. Leakage tends to decrease with time (Melby and Øvstedal, 1999), but maintenance costs have been significantly higher than expected.

5.2.2 *Submerged floating tunnels*

The submerged floating tunnel is a tube-like structure made of steel or concrete, floating at some depth in the water and held in place by tethers, pontoons or columns (Fig. 32). Detailed studies have verified that the concept is technically feasible. The initial area of application was for crossing fjords and sounds that were too wide and too deep for bridge construction. Whereas the cost per meter of a suspension bridge increases with length, the unit cost for a submerged floating tunnel is essentially constant with length.

The Høgsfjord tunnel (Fig. 33) will have a length of 1.4 km with a gentle grade. A suspension bridge would have had total length of 1.5 km. A sub-sea tunnel in rock would have had to go down to a record depth of 400 meters (rock surface is at 350 m depth). With maximum water depth of 155m, the tunnel in rock would have been about 11-km long, even with steep grades (Flaate & DiBiagio, 2001).

The Lake Lugano crossing in Switzerland is for a high-speed railway. An elevated bridge solution was not acceptable because of the tourist industry. The alignment flexibility of a submerged floating tunnel presented definite advantages for a railroad line. The length of the Lake Lugano crossing is 900 m and the maximum water depth about 70 m. Whereas crossing deep fjords requires an anchoring by tethers or pontoons, the technical solution for the Lake Lugano crossing was to put the tunnel on pillars.

The submerged floating tunnel has considerable merits from the environmental point of view: in urban areas where part of the solution is bringing traffic underground, with alignment of roads and railways possible in the vertical and horizontal directions, and minimum traffic and pollution. The concept has considerably lower energy consumption and exhaust emission for fjord crossings compared to ferry connections or sub-sea tunnels in rock.

The design conditions can be handled, including resonance vibrations of the tube and the anchoring system. Adaptation to local conditions is necessary as for any foundation. The capacity and deformations of supports and anchoring systems need to be evaluated, as well as, in the case of deep fjords, the risk of underwater sliding and rockfall. The main challenge is to get the first submerged floating tunnel built.

5.3 *The challenge of geological risks and natural hazards*

"Geo-hazards" are events due to geological features and processes that present threats to humans, property and the environment. The site and soil conditions have the potential of developing into a failure event causing loss of life or investments. The assessment of geological risks, or geohazards, requires the identification and analysis of the relevant failure scenarios that can contribute significantly to increasing overall risk, including failure modes, triggering factors and failure consequences.

Landslides are the most common "geohazards" on land. Floods cause sliding to occur. Earthquakes can trigger slides. Geological features offshore like gas hydrates and mud volcanoes are hazards that can trigger large mass flows.

There is an urgent need to improve the profession's understanding and ability to deal with the risks associated with "geohazards". The need was accentuated recently by increased sliding and flooding in many regions, increased earthquake vulnerability, and increased concern for hazards in production and transport of oil and gas. Facts supporting this urgency include:

Figure 31. Transportation needs between islands in Norway.

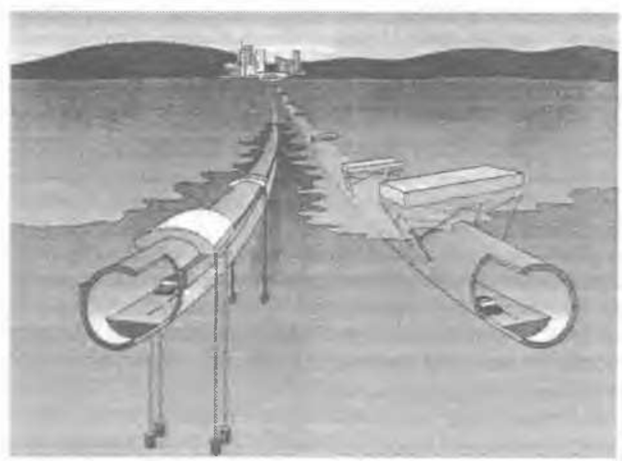


Figure 32. Recent submerged floating tunnel concepts (Flaate & DiBiagio, 2001).

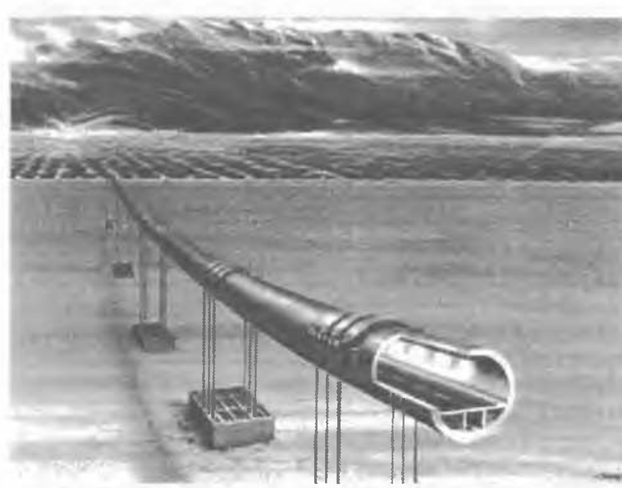


Figure 33. Submerged floating tunnel concept at Hogsfjord (Flaate & DiBiagio, 2001)

- The 1999 World Disaster Report estimated that in the period 1988-1997 landslides alone caused 9,000 deaths and total damages of about USD 450 million.
- The extreme rainfall that hit Venezuela in 1999 triggering severe flooding and landslides caused 20,000 deaths and made several 100,000s homeless. Total damages can amount to USD 1.2 billion.
- Statistically, 10 or more large slides are expected to occur in Norway in the next 50-100 years, each with possibly 20-100 deaths or more. As urbanisation increases, exposure grows. The number of deaths caused by all types of slides in Norway over the past 150 years exceeds 2000.
- Tsunamis (large flood waves formed by rapid mass movements or earthquakes) present extreme threats to coastal areas. Tsunamis caused the loss of 174 lives in Norway in Loen and Tafjord (1905, 1934, 1936). Between 1992-1998, four tsunamis ravaged the coasts of Nicaragua, Indonesia, Japan, Papua New Guinea. Over 4,000 lives were lost.
- Recent devastating earthquakes (Turkey, 1999; El Salvador, 2001; India, 2001) caused the loss of 40,000 lives and made many more homeless.
- Earthquake-triggered landslides have caused immense tragedies. Yungay in Peru was buried in 1970 by an ice fall-triggered mudslide following a magnitude 7.8 earthquake; 70,000 were reported dead or missing and 1 million people were made homeless.
- The Munich Re reinsurance company assess the losses due to earthquakes for the last 5 decades to be respectively USD 1, 19, 53, 80 and 209 billions (1999 equivalents). Further increases are likely, due to increasing urbanisation and vulnerability, in particular in developing countries.
- Seven of the 10 largest oil companies define reduction of risk due to geohazards in deep water as one of their top research priorities. The consequences of a geohazards-triggered event offshore in terms of loss of life and damage to the environment would be catastrophic.

The human, environmental and economical consequences of geohazards can be reduced by improved assessment, mitigation and prevention, and management of geological risks and natural hazards. New developments are critical from a societal point of view, for optimal land use, and for safe and cost-effective exploitation of natural resources.

Assessment of the in situ effective stress conditions is essential for evaluation of soil strength and stiffness and requires assessment of the in situ pore pressure conditions. Unsaturated or gassy soils bring in complicating factors into the material behaviour. The uncertainties in site and soil conditions are amplified by the areal extent and depth of sediments involved and the practical and economical limitation of the site investigations.

Field development activities on the continental slopes require special attention. Large slides (historic and ancient) have been observed on slopes with a very low inclination. The slides seem to develop retrogressively upwards and sideways and the run-out distance can be several hundred kilometres. Slope instability may thus not only affect a local the field development project locally, but also have a potential impact on third parties in a much wider area. Important challenges are the basic understanding and the modelling of:
- triggering mechanisms of submarine slides on very gentle slopes,
- retrogressive slide development up-slope and laterally,
- evolution of the slide masses into down-slope "mass wasting" processes (mud flows, turbulent current).

To solve these aspects, improved material models and mechanical analysis tools are needed.

5.3.1 *Slides in soils and rock on land*
Landslides in soft marine clays, including quick clays, occur often rapidly, and can have devastating consequences. They occur regularly in Norway, Sweden and Canada. Natural processes, e.g. erosion in brooks and rivers, heavy rainfall and flooding, and human activities trigger such landslides.

Coastal slides occur in soft sediments, with main body of the slide in the sea. Most often the sliding also comprises sediments on land. Triggering factors, other than human coastline activities are high sedimentation rates, wave action, erosion, heavy rainfall and flooding.

Slides in steep hills occur most often as a result of heavy precipitation or snowmelt and can cause devastating debris and mudflows. Debris and mudflows travel considerable distances, involving a mixture of water, earth material and debris. Deforestation, road building, and land development can also trigger such slides. These slides can in turn cause tsunamis.

Rock falls, up to a few thousands m^3 in volume, can occur due to long term natural processes such as weathering and freeze-thaw action, or due to heavy rainfall. Mountain slides, larger than rock slides, occur less frequently but can cause enormous damage and trigger tsunamis.

5.3.2 *Earthquake geohazards*
Hazards due to earthquake represent perhaps the most important direct threats to life and property worldwide because of their frequency and the direct threat to life due to damage to building and infrastructure. The profession needs to focus on earthquakes as triggers of soil liquefaction, slides on land, coastal slides, underwater slides and tsunamis.

5.3.3 *Offshore geohazards, including tsunamis*
Offshore geohazards can cause considerable damage to offshore installations and pipelines, with loss of life and grave environmental and economical consequences. The main concern today is for geohazards in deep water, where mass flows may travel very long distances on very gentle slopes. One example is the gigantic Storegga slide offshore Norway about 8,000 years ago, extending over 30,000 km^2 and generating 5-25 m flood waves (tsunamis) that hit Norway, Scotland and other North Atlantic coasts (Bryn *et al*, 1998).

As oil and gas exploitation moves at greater and greater water depths, geohazards have become major issues, mainly because the nature, extent and effects of geohazards are not well known. Geohazard failure events are mainly related to gradual or sudden development of unacceptable submarine soil mass displacements causing forces against installations or loss of foundation support. Geohazards include for example, submarine slides, gas hydrates and free gas, over-pressured sand zones, and very soft, brittle soils such as oozes.

The areal extent and volumes involved in a geohazard failure scenario can range from local slumping or creep displacements to enormous submarine slides with thousands of km^3 soil mass involved (thus with potential for tsunami generation). The associated damage can be limited to local overstressing and damage to a subsea installation or pipeline or can lead to total loss of field installations and a high number of fatalities in coastal areas hit by tsunamis.

Slope instability and mass flows might damage the installations located in the instability zone and downslope in the track of the slide blocks, debris flow material and turbidity currents.

Damage to structures caused by overstressing under earthquake shaking and fault displacements is a common problem on land as well as offshore.

Mud volcano eruptions and mudflows, fluid (water and gas) seeps and expulsions, seabed erosion, etc., will affect structural integrity and operability of subsea installations.

5.3.3.1 Triggers for submarine slides. The triggers for failure are either natural, including on-going geological processes, or human activities. The natural triggering sources that may cause failure include (Kvalstad *et al*, 2001):
- rapid deposition leading to excess pore pressure conditions, underconsolidation and increased shear stress level in a slope;

- toe erosion or top deposition giving higher slope inclination and increased gravity forces and shear stress along potential failure surfaces;
- melting of gas hydrate caused by temperature increase or pressure reduction leading to increased pore pressure and reduced soil strength;
- active fluid /gas flow and expulsion;
- mud volcano eruptions and diapirism giving rise to mass wasting and soil displacements;
- earthquake activity causing short term inertia forces and post-earthquake pore pressure increase and fault displacements in upper strata;
- sensitive (contractive) and collapsible soils may lead to retrogressive sliding and increased areal extent of failure zones;
- sea level lowering during glacial periods leading to lower pressure, free gas expansion and gas hydrate melting;
- increased sea water temperature at sea bed level caused by changes in current regime leading to temperature increase in the soil mass and melting of hydrates.

Human actions related to field exploration and development activities include:
- drilling of wells, creating blow outs to sea bed and cratering;
- underground blowouts changing the pore pressure regime in shallow layers becoming critical in sloping areas;
- oil production leading to heat flow and temperature increase around wells and well clusters leading to hydrate melting and strength loss of the adjacent soil;
- depletion of reservoir pressure giving reservoir subsidence and stress changes in overburden;
- installation activities; rock fills, equipment weights giving increase in gravity forces;
- mooring installations and anchoring forces imposing short term and long term lateral forces.

5.3.4 *Assessment of geological risks and natural hazards*
Essential tasks for the geo-engineers and geo-scientists are slope stability analysis, modelling of *in situ* stress conditions, modelling of sliding and consequences of sliding, including loss of foundation support, impact forces on structures and pipelines, and modelling of generation and impact of tsunamis. The assessment of geological risks and hazards should include:
- Understanding of geohazards generation and sliding processes: the past and present geological and physical processes are the key to the occurrence of hazards. Triggering mechanisms for different types of slides and the link between triggers and other factors causing major failures are poorly known, even though there exist a number of case studies.
- Geological, geophysical and soil engineering investigations: *in situ* and laboratory testing techniques should be used to improve the profession's ability to identify potential hazards on a local and regional basis.
- Understanding of the effects of mineralogy and geo-chemistry, in particular for gas-charged and unsaturated soils.
- Database of slides: the database should include geology, soil type, meteorological data, slide events, mechanism and type of failure, etc. International alliances should be formed for sharing of data, correlations and experience. Monitoring stations should be installed and shared, where possible.
- Development of analysis models: models for analysing slope stability, rockslides and debris flows, run-out distance, impact forces and tsunamis need to be improved or developed. Material models need to be improved for unsaturated soils, gas-charged sediments and gas hydrates, weathered and residual soils, and strain-softening soils. Analytic procedures are needed to model the geo-hydrological regime and predict pore pressure response to rainfall and flooding events and slope stability for different geological settings and for different triggers. Analysis methods to predict soil liquefaction and slide development due to earthquakes; including impact of dynamic and static stresses and long-term instability effects over a large region, should be improved.
- Model testing and calibration of analysis methods: the reliability of analytical models needs to be verified and quantified. The best approach to do this is to make predictions with the models, and to verify these with model tests or prototype measurements.
- Risk analysis and slide hazard and risk mapping: procedures for risk assessment and for mapping slide hazard and risk need to be developed, including selecting criteria for different courses of action.

5.3.5 *Prevention, mitigation and management*
There is a need to improve or develop new protection measures and to evaluate their cost-effectiveness for different slide types, different geological settings and different geographical regions. Especially in developing countries, it is vital to establish and promote proper land-use planning to stop human activities that increase risk of landslides and to prevent settlement of communities in high-risk areas.

To reduce risk, systems need to be developed to provide means to monitor long term slide evolution and to forewarn of an impending hazard. Criteria for parameters to be monitored, optimum location and threshold values for different ground conditions should be established. Early warning systems, monitoring equipment and monitoring programmes for high-risk areas should be developed.

The geotechnical profession has also an important role to play in public awareness programmes, development of standards and guidelines and transfer of knowledge to third world countries. The exchange of scientists with organisations from developing countries is an important contribution to an enhanced service to society. Practical guidelines and public awareness programmes, also teaching the public to be able to warn of telltale signs of possible imminent failure, are the key to reducing risk.

5.3.6 *Summary*
The assessment of geological risk due to natural hazards (also man-made hazards with similar consequences) covers a wide range of activities and needs to involve most geoscience disciplines. The understanding of geological, geophysical and geochemical processes that have formed the regional and local site conditions, and which still may be on-going, is essential for an assessment of in situ soil conditions.

Thorough understanding of the natural and human induced changes and how they affect soil stresses and displacements is required to identify relevant potential failure scenarios. Quantification of the associated risk must be based on observations and analysis techniques applying adequate material and mechanical models.

The areal extent of observed slide occurrences on continental slopes and their regional consequences are of special concern. Risk assessment cannot be limited to failure scenarios focused only on the actual development project, but have to take third-party interests into account. The geotechnical discipline faces a series of challenges related to deep-water conditions on the continental slopes, including (Kvalstad *et al*, 2001):
- material models for gassy soils, unsaturated soils and gas hydrates;
- assessment of in situ pore pressure and effective stress conditions to considerable depth below seabed and large areal extent through site investigations, monitoring and analysis techniques;
- techniques for evaluation of slope failures that are capable of explaining observed sliding activity on gentle slopes and establishing reliable methods for predicting retrogressive slide activity, areal extent and involved volumes;
- accuracy and uncertainties related to techniques and analysis methods for assessment of direct and indirect slide consequences: run-out distances, flow velocity, flow impact and tsunami generation and impact.

Extensive research on geohazards, in particular on slope instability and effects of gas on soil response, is currently being performed. The work is so complex, it needs to involve a close collaboration of geologists, geophysicists, geodynamicists and geotechnical engineers.

6 PRESERVING THE ENVIRONMENT

6.1 *Environmental geotechnics*

Geo-environmental engineering evolved from geotechnical engineering and found its rightful place in our profession. While traditionally the geotechnical engineer's main interest has been the physical properties of soil, in the environmental field chemistry and (micro)biology became part of the geotechnical engineer's baggage. Before the development of geo-environmental engineering, a geotechnical engineer's main interest in organic soils was to ensure that they had all been removed before work started. Only the physical properties of soils mattered.

Many major construction works have been delayed by hidden "surprises" of soil and groundwater contamination. To solve these problems, the chemical and process engineering may in many cases dominate the geotechnical content. Soil science, as taught in agricultural colleges and universities, is needed to solve "geotechnical" problems.

The New York Times wrote in an editorial this year (2001): "The environment is not a competing interest, it is the playing field on which all other interests intersect". Civil engineering is in addition at the intersection of society and natural environment. The profession is ideally placed to reconcile these interests. The strength of the geo-engineer is to solve complex projects where the foundation dimension and the environmental content converge towards an optimal solution.

Site investigation for geotechnical purposes can be extended to cover soil contaminants, taking in consideration their chemical properties. Physically undisturbed sampling is not identical with chemically undisturbed sampling. Non-destructive geophysical techniques have proven to be valuable for delineation of contaminated areas and source zones (Westerdahl & Kong, 2000).

In the field of site remediation, the geotechnical engineer plays a dominant role. With intelligently contrived solutions, construction work, site remediation and risk reduction can be integrated. These aspects are of primordial interest in handling brown-field sites. Old industrial sites have become valuable locations for business development in ever-expanding urban areas. Redevelopment is hampered by the enormous costs involved in environmental clean-up.

Site assessment for land use and regional planning are therefore important tasks for the environmentally conscious geotechnical engineer.

Risk-based remediation strategies involving *in situ* remediation and isolation can be integrated in the foundation design for new infrastructure (Doelman & Breedveld, 1999). This type of integrated solution is profitable for both past and new owners of a site. This was the case for the re-development of the Oslo municipal gas plant site. The early integration of environmental engineers in the design of the building resulted in an integrated solution of partial contaminant removal, isolation and risk reduction allowing historic buildings to be rehabilitated without foundation damage.

Similar solutions are required when historic disposal sites on the outskirts of cities become prime building sites.

Harbours present a new challenge for the engineering profession. Sedimentation processes have collected contaminants in the near shore environments over many decades. Construction work in these areas requires handling of large amounts of contaminated sediments. The integration of offshore geotechnology and environmental technology is required to find technically feasible and environmentally sustainable solutions for contaminated materials (Hauge *et al*, 1998). Figure 34 illustrates options for disposal of contaminated sediments: (1) separation technology, (2) disposal on land, or (3) disposal in deep water and capping. The consequences of disposal on land and in deep water are given. The benefits of deepwater disposal are important.

The increased focus on the environmental consequences of infrastructure works, including providing freshwater resources, provides new challenges for our industry. The geotechnical engineer should be willing to expand its vision towards the chemical and microbial aspects of the geo-environment. Still much remains to be done, in a highly competitive business.

6.2 *The Arctic*

Permafrost underlies about 20% of the world's surface on land. Construction of facilities in these regions presents unique engineering challenges associated with the change in the thermal regime in the ground. The fine thermal balance needs to be accounted for in the design of Arctic infrastructure at the same time as the solutions need to be both cost-effective and environmentally stable.

Experience from oil and gas field development in the Beaufort Sea and the Barents Sea and the growing infrastructure in the Arctic have clearly shown that one of the challenges in the near future is providing infrastructure and operating at sub-zero temperatures. At the same time, the solutions should be caring for the fragile environment.

Mapping of permafrost and improved understanding of the physical properties and properties of soils in the Arctic regions are required. Instanes *et al* (1998) presented definition, classification and genesis of offshore permafrost. The presence and formation of permafrost can be estimated by seismic methods, electrical methods, in situ measurements and sampling, and with thermodynamic models. These models use geological and climatic history, geotechnical properties (soil and rock), seawater and air temperature and geothermal gradient in profile. Such models should not be used alone, but in combination with site-specific soil sampling and in situ measurements.

Permanently frozen ground in Arctic regions has a large impact on the structural characteristics and transport of contaminants in soils underlying man-made infrastructure. The maintenance of soil conditions for adequate load support and/or low contaminant transport is often directly connected to maintaining frozen conditions in the soils. Otherwise settlements and contaminant mobility would occur. New problems occur in the Arctic:

- uneven thaw settlement and overstraining of warm oil pipelines
- differential settlements, perhaps failure of foundation
- freeze-back and subsidence of well bores
- complex behaviour of material found in partially or fully frozen areas

There exist solutions to alleviate or solve some of these problems, such as elevating pipelines, insulation/refrigeration of pipelines or chilling of transported fluid, using heavy-walled pipelines to tolerate higher stresses. Each solution needs to be

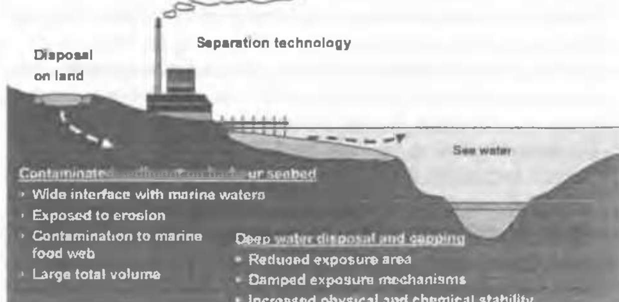


Figure 34. Disposal of contaminated shore sediments - an engineered solution.

evaluated together with its potential impact on the foundation and the environment.

Permafrost thaw can be prevented by techniques that generate a passive cooling effect. Goering (2000 a; b) studied the thermal characteristics of embankments constructed of highly porous materials. With these materials, a passive cooling effect can be achieved due to the unstable density stratification and resulting natural convection that occur during the winter months. The convection enhances transport of heat out of the embankment, thus cooling the lower portions of the embankment and foundation soil and preserving the frozen soil layer. Goering made numerical simulations with an unsteady 2D finite element model and compared them to full-scale field measurements. Both the experimental and the numerical results show a strong passive cooling influence.

The technique has direct applications to heat transfer considerations for railway embankment ballast material in Northern regions (Goering *et al*, 2000). Natural convection of the ballast pore air can have a large impact on heat transfer rates during periods when unstable pore-air density gradients exist within the material. This may lead to enhanced frost penetration and frost heave in foundation soils beneath the embankment and have an adverse effect on the performance of high-speed railway lines in the winter.

Foundation design of pipelines in areas with discontinuous permafrost represents a particular challenge, as the environment is very sensitive, and the consequences of leakage are not well known. In particular, models for the diffusion and transport of hydrocarbons through permafrost and/or partially frozen soils should be developed. Pipeline installations in the Arctic require critical planning and careful and continuous follow-up if responsible solutions are to be achieved.

7 RESEARCH AND DEVELOPMENT

Industrial research is important to maintain technical competence and readiness for design, to bring breakthrough technologies to practice, and to promote future growth.

Good research does not usually happen in closed rooms but rather through the interaction of several persons with different ways of thinking, different backgrounds and diverse qualifications. The exchange of ideas and the combination of multidisciplinary competence will be the recipe of future successful research because the problems are no longer one-dimensional. Solutions need to be found for global problems. The days of "free" basic research without anchoring it to definite targets are more or less over for our profession. One should do research to develop new solutions that are attractive enough to be later used by industry.

Techniques for successful research exist and should be used. Important principles include:
- understanding the subject
- knowing the sources of information
- getting organised
- collaborating with your peers
- planning and targeting the research
- verifying all data
- distinguishing facts from opinions
- being careful with old information
- budgeting the steps in the research
- making notes and having a trace of information sources

Worldwide, research and development funding is going to fields other than civil engineering. Funding is concentrated on fields such as biotechnology, information and communication technology. The technology drive is not with civil engineering. Our response should be to draw from these fields that are advancing faster than ours do, and use the technology as a springboard for our own development.

For geotechnical engineers, good experimental facilities are important to enhance research results, and are absolutely necessary to model and understand complex situations in practice. Experimental education should be integrated in the curriculum at universities, so that the geo-engineer has a feel for the material he is working with rather than a drawing or words on his PC. The reliability of theoretical methods can only be quantified with experimental results and/or comparisons with prototype measurements.

8 OUR CHALLENGING PROFESSION

Karl Terzaghi described engineering a "noble sport" calling for good sportsmanship. Occasional blundering is part of the game. The challenge is to discover our blunders in time and to admit them. Karl Terzaghi promoted that one should be critical of one's own work and profession. Perhaps it is time to be critical of how we are ensuring the future of our profession.

8.1 *Communication*

In his description of "Soil mechanics and the history of civil engineering", Sir Alec Skempton (1950) described the three sciences contributing to the practice of civil engineering: theory of structures, hydraulics and soil mechanics. The science of soil mechanics turned out to be unique because soil mechanics is the least exact among the three, because the properties of soils are more troublesome than those of steel, concrete or water, and because of the fact that the "experience to science ratio" is preponderant for soil mechanics competence.

With unique perceptiveness and foresight, Skempton remarked how important people skills (he called it "personality") are in soil mechanics. He also noted the need to place the "intractable problems of soil mechanics" on a sound scientific basis and in a form useful to engineers and the ones using "soil mechanics" services.

In light of Skempton's observations: it is one thing to be an outstanding engineer, but to combine that with an understanding of the human values and to practice both together is a combination everyone should aspire to. It is necessary to bridge the past and the future of our profession: "Sharing the past, shaping the dreams" may be an appropriate focus for our profession. Both mature engineers and those starting their career, can shape their future while remembering the legacy of those who preceded them. Experienced engineers have in addition the obligation to train and encourage their younger colleagues.

A most urgent development in our thinking is the increasing importance of the interplay among geotechnical engineer, geologist/geomorphologist, geophysicist and geodynamicist. These and other associated geo-professions need to move away from closeted solutions to part of a problem, and rather opt to solve global problems through enhanced communication and recognition of each other's contribution.

8.2 *Adaptability to change*

The final years of the last millennium have been years of change in the construction industry and in particular in the relationships between clients, general contractors and specialists. The new millennium offers a crossroads. If we take correct action, we have the opportunity to develop more sustainable technology. The technological challenges are looking for engineered solutions. The pressure for these changes started in the early 1990s and quickly encompassed the whole industry, its clients and government. We need to refurbish the lacklustre of our profession to ensure its survival and growth.

At a practical level the process has, however, really just begun and the next decade is going to be one of change and improvement in all aspects of how we work together (Sherwood, 2000). There are dangers in some of the trends of our profession:
- designers or contractors compete primarily on price and optimum alternatives do not receive the attention deserved.

There should be incentives to encourage the elaboration of alternate optimum solution.

- design and construction are required, more than before, to be completed in short times, often unrealistically short.

Such pitfalls should be avoided through dialogue among client, designer and contractor. The intervention of professional societies should also be useful, as they will provide a forum for debate.

Contractors, interested in forming teams for complex projects, will increasingly solicit competent geo-specialists. Geo-engineers should be part of an attractive package offered to increasingly discerning clients.

8.3 *The younger generation*

Geotechnical engineers have blossomed at all levels. Dealing with the uncertainty inherent in natural ground conditions, together with the experience of expecting the unexpected, are great assets. It produced a class of engineers unparalleled elsewhere in the construction industry in their ability to adapt to and manage uncertainty, to solve problems and to lead teams of doers (Sherwood, 2000). The geo-engineer has ingenuity, flexibility and enthusiasm.

Engineers make a major contribution to the economic activity and infrastructure of everyday life. We need to be proud of our profession. We need to also adapt our actions to the changing world. We should offer bright and varied career prospects to geo-engineers (Sherwood, 2000):

- a career full of challenges on both the technical and human level,
- a profession where ingenuity and experimentation are strongly encouraged,
- a career path where responsibility is given early to anyone who can bear it reasonably,
- a branch of engineering where experience and judgement are more valued than in other fields of engineering,
- an industry undergoing substantial changes for the better, creating new professional opportunities,
- a friendly and welcoming community of engineers with a substantial international dimension.

8.4 *Opportunities*

The next few years will bring a time of great opportunity for civil engineers. In the late 90's, civil engineering was losing its attractiveness to fields like biotechnology and information technology. However, as demand for optimum use of the natural environment, fresh water, energy, waste disposal, transportation, protection against natural hazards increases, the trends will change.

Our profession will not be able to meet its challenges if it clings to old practices. The challenge is everyone's task: private industry, government and educational institutions. Information and communication technology should be the catalysts of change, both for practice and in education. More and more of geotechnical design is done with computerised tools, with automatic generation of input data, results and graphs. Still, the potential and efficiency of ready-made, popular computer codes to solve complex problems should not overshadow the dangers of misuse. The computer codes offer extensive possibilities, but "hands-on" experience is needed to ensure proper use and interpretation.

The profession needs to deal with the ethic issues lying in the squeeze between cheap, "quick-and-dirty" solutions and the optimum solution serving society on the short and long term. The challenge is difficult because it is often at the middle of conflicting objectives. Often the role of the science and technology profession in organisations is weaker than that of economists, business management and lawyers. This we can partly remedy to by taking a more active and more diplomatic part at the level of decision in these organisations. Our profession needs to also contribute to increased collaboration among client – designer – consultant – contractor,

Challenges on the technology side include:

- increase our efforts to evaluate the risk of natural hazards and develop mitigating measures;
- develop improved methods for the analysis of slopes;
- improve methods for the analysis of and countermeasures against the effect of vibrations, e.g. due to high speed trains;
- include automatically the environmental component to our foundation solutions;
- develop innovative solutions for the Arctic environment;
- revitalise the use of in situ measurements and performance monitoring, and the careful interpretations of the observations;
- do consequence analysis of alternatives and gradually move towards a quantification of the risks involved;
- achieve a more effective dialogue and cooperation among the geosciences.

To recruit our successors and to ensure our profession's place in society, we also have the following unique challenges:

- adapt and provide excitement in our profession to recruit among the best;
- be the champions and premise-givers of sustainable development; we need safe, reliable solutions that serve society and to recognise our social responsibility;
- speak a language that is adapted to the ones listening;
- ensure a strong recognition of the geotechnical contribution by society, by the universities and by the building and construction industry;
- remember our history and tell the future generations about the heroes of geo-engineering;
- focus on the art of engineering and engineering art; we must adopt "engineering for life" as motto.

The profession must gradually change, but there is a unique role for geo-engineers to play in the development of society, not as technologists alone, but as well-rounded professionals working in a well-defined environment.

9 CONCLUSIONS

Today's society experiences greater than ever vulnerability connected to infrastructure: water supply, electricity, energy and heat supply, transportation, protection against natural hazards and information and communication systems. Landslides, a dam failure, subsidence and settlements offshore, uncomfortable vibrations, to name only a few examples, will interfere with expected comfort and safety. The good function of infrastructure systems requires the expertise of the geotechnical engineer.

Our profession, however, does not excel at telling society and policy- and decision-makers of its contributions. We have a proud profession with many accomplishments to boast about. We must "show up" to be heard and create an atmosphere that will cause the brightest students to want to go into geo-engineering. The engineers' voices need to be heard by politicians, policy-makers, society and the younger generation.

Geotechnical engineers should be more aware of the omnipresent influence of geology. Geology can not be ignored or discounted by the successful geotechnical engineer. In fact, the boundaries among engineering geology, geophysics, rock mechanics, soil mechanics, hydrogeology, seismology, and a host of other disciplines are meaningless. Contribution to the solution of geotechnical problems may come from any or all of these sources. The practitioner who keeps too narrowly to one specialty is likely to overlook knowledge that could be of the greatest benefit in reaching a proper judgement.

On the other side, the geotechnical engineer must also be increasingly aware of the influence of societal needs on the goodness of the solutions provided.

The importance of interweaving good practice and research was illustrated with a few examples in this Theme Lecture. It is possible to use the results of recent research and to offer increasingly cost-effective solutions. We need to be aware of promoting innovative solutions, even for traditional consulting projects. We need to convince our clients to consider alternative solutions. Innovation is the key. Innovation results in new, cheaper and safer methods of construction, but we should be aware that it is costly to develop new approaches.

Technically, we need to increase our efforts to evaluate the risk due tonatural hazards and to develop mitigating measures. We need to improve analysis methods for safer transportation infrastructure and to develop countermeasures against the effects of vibrations, for example due to high-speed trains. The profession should get comfortable with doing consequence analysis of alternatives and quantifying the risks involved. More than before, exploit the solutions developed for offshore problems for design on land. And, not the least, we need to include automatically the environmental component in our foundation solutions.

Earlier work is an important source of ideas and solutions. The profession does not read enough. The foresight and ingenuity of our predecessors even in the 40's, 50's and 60's is remarkable. This source of knowledge should not be left untapped.

Geotechnical engineering adds value by saving lives, preserving the environment, improving performance, reducing costs and exploiting natural resources in a responsible manner. Perhaps it is time to be critical of how we are ensuring the future of our profession. Communication needs to be improved, we need to thrive on change, we must offer attractive and varied career prospects, and we need to focus on both the art of engineering and engineering art.

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