Newsletter

Spring/summer 2009

Geophysics edition

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Colophon

Ingeokring, founded in 1974, is the Dutch association of engineering geologists. It is the largest section of KNGMG (Royal Geological and Mining Society of The Netherlands). Ingeokring also forms the Netherlands National Group of the International Association for Engineering Geology and the environment (IAEG).

With over 200 members working in different organizations, ranging from universities and research institutes to contractors, from consultancy firms to various governmental organizations, Ingeokring plays a vital role in the communication between engineering geologists in The Netherlands.

The objective of the Newsletter is to inform the members of the Ingeokring, and other interested parties, on topics related to engineering geology, varying from detailed articles, book reviews and student affairs to announcements of the Ingeokring and current developments in the field of engineering geology. The Newsletter wants to make engineering geology better known by improving the understanding of the different aspects of engineering geology.

All correspondence concerning the Ingeokring should be addressed to:

Ingeokring

TU Delft, Faculty CEG, Section of Geo-engineering

P.O. Box 5048

2600 GA Delft

Fax: +31 (0)15 2783328

E-mail: ingeokring@hotmail.com

Correspondence about the Newsletter should be addressed to the editorial team via the address above, or:

E-mail: erikschoute@hotmail.com

Tel.: +31 (0)6 27565538

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Cover photo

Sediment in the North Sea

Clouds of brown and green sediment swirl through the North Sea in this true-color Aqua MODIS image acquired on December 18th, 2004. The sediments are most concentrated in river outlets, most notably the Thames and the Mouth of the Humber on England's southeastern coast. Within the larger body of the North Sea, the sediment is likely being pulled up from the sea floor, which lies no more than 50 meters below the surface. Large storms often stir up such sediment.

Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC

Owner: NASA/Visible Earth

Source: http://visibleearth.nasa.gov/view_rec.php?id=6217

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Editorial

Erik Schoute

Dear reader,

It is my pleasure to introduce to you, on behalf of the entire editorial board, this issue of the Ingeokring Newsletter: the geophysics edition. Since publication of the last official Newsletter (dam edition), there have been many interesting Ingeokring and Ondergrondse activities of which some reports will be given in this issue. A summary of activities organised by De Ondergrondse is given in a contribution by a former and present member of the Ondergrondse board, Paulien Kouwenberg and Paul Spruit. Reports of two of the excursions organised by De Ondergrondse are presented in this Newsletter: Werner van Hemert writes about an interesting excursion that took place to the Hambach lignite mines in Germany, where Robrecht Schmitz explained many aspects of the surface mining of lignite. In a separate article in this Newsletter, Robrecht reports on the use of geophysical logging tools in the Hambach mining district in order to constantly enhance the geological model, which is used for dewatering-, geotechnical- and mine planning. The second excursion report, which was written by Johan Haan, deals with the continuous threat of earthquakes in Istanbul, and what kind of techniques are used to measure seismic activity and how this information is used to predict and respond.

Two articles that focus on theoretical aspects of geophysics are written by members of the section of Applied Geophysics and Petrophysics of TU Delft: Christiaan Schoemaker, on the use of electrokinetics in geophysical research, and Joost van der Neut, whose contribution deals with the repositioning of sources with seismic interferometry. Christian Hérisson and Sophie Minard of Fugro France have written an interesting article about the application of seismic refraction surveys on dredging projects. The cover photo of this Newsletter can be seen in line with the contribution of Ad Stolk and Cees Laban, on the Dutch sector of the North Sea. Guido Spanjaard and Mara van Eck van der Sluijs of Grontmij Geogroep explain several tools and techniques that can be used to solve geophysical problems. Some applications of such techniques on actual projects are illustrated in the article by Bjorn Vink of Grontmij, who writes about the integration of various geophysical and geotechnical techniques on the A2 tunnel project in Maastricht; in the article by Michiel Maurenbrecher on geophysical research in the harbour of Gothenburg; and in William Munsterman's contribution, which deals with the application of the 'total engineering geological approach' to construction of highways on soft soils.

An interesting paper by the winner of the Ingeokring Student Award 2006-2007 for best thesis in the field of Engineering Geology, Richard de Jager, and co-written by François Mathijssen, Professor Frans Molenkamp and Art Nooy van der Kolff, elaborates on a static liquefaction analysis applied to dredged sludge depot Hollandsch Diep. Professor Jacob Fokkema and Professor Kees Wapenaar have written the professor's column for this edition, on the misinterpretation of the commonly used term *Measuring is Knowing*. That life is great when working as an engineering geologist abroad, is shown by Sabine Backx in her contribution to the section 'Engineering geologist abroad' of this Newsletter. She works as a geotechnical engineer for Rio Tinto in Queensland, Australia, and describes the pros and cons of living in a relatively remote mining community. Peter Verhoef has written a review of the book *Engineering Geology, Principles and Practice*, which can be seen as the magnum opus of David Price's professional life of 40 years in engineering geology, in which he and his colleagues at Wimpey's are credited to have 'invented' the profession of engineering geology as we know it now.

There have been and will be a few changes in the composition of the editorial board of the Newsletter. Since publication of the dam edition of the Newsletter in 2008, Jacco Haasnoot and Wiebke Tegtmeier have stopped their activities for the editorial board. Paulien Kouwenberg, as representative for De Ondergrondse, was replaced by Werner van Hemert. After publication of this issue, current member Gerhard Wibbens will step down as an editor as well. From this place, I would like to take the opportunity to thank all for their great efforts that were put in the time consuming work of putting the Newsletter together and getting it published!

Many thanks to all the authors for their interesting contributions to this Newsletter and to the companies who made publishing possible by sponsoring the Newsletter with many colourful advertisements.

Expanding geophysical research methods using electrokinetics

Ir. F.C. Schoemaker *(Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Applied Geophysics and Petrophysics)*

Abstract

In this article an overview is given of the possible applications of electrokinetic models for geophysics and related subsurface disciplines (geotechnology, hydrology). The processes that occur in association with electrokinetics involve a lot of physical phenomena which are difficult to control. It is therefore necessary to understand these processes, so that methods and procedures can be optimised in the future. A historical perspective, focussing on developments within chemistry, will be given, followed by a theoretical discussion of the physics involved.

Introduction

Electrokinetics is the phenomenon where a surface charge is created, by hydraulic, electrical, chemical and/or thermal interaction on a solid phase which is in contact with a fluid. In the past decade this research area has gained importance as an effective manipulation- and observation technique in the micro- and nano domain. It is being used in an ever increasing variety of research disciplines, ranging from the microsystem processor industry, pharmaceutical industry, earthquake prediction & geotechnical engineering. The success however depends on certain conditions which are controlled by many parameters. Fundamental knowledge of the associated physical process is a requirement.

Reuss (1809) already noticed the influence which an electrical current has on soil, causing water transport. He defined this phenomenon as electro-osmosis. The first theoretical development of electrokinetic transport equations is attributed to Helmholtz (1879) and Smoluchowski (1903). In the 1930's, electro-osmosis was for the first time utilised for drainage (manipulation) and stabilization of low permeable soil (Casagandre, 1941) and also for geophysical exploration (detection and characterization) (Thompson, 1936). During this decade and the following ones, chemists realised that electrokinetics does not only consist of electro-osmosis, but also of a variety of phenomena within non-equilibrium thermodynamics. Geo-hydrology is also one of the areas which benefits from these developments. By combining Darcy's law and Fick's law using transport (coupling) coefficients such as chemical osmosis, it is now possible to model, observe and manipulate underground pollution. These developments didn't occur overnight, progress was rather slow, consider geophysics for example. Due to insensitive technical equipment, the lack of computing power, the lack of accurate models but also the success of conventional seismic and EM methods, it took more than 50 years before electrokinetics came into focus of the geophysical community.

In 1944, the Russian physicist Frenkel developed an early model which already incorporated electrokinetic coupling (Frenkel, 1944). Mainly due to the fact that Frenkel lived in the Soviet Union, his model was hardly known by Western scientists. In the following decades only some scattered publications on this research topic where revealed, until 1994 when Pride (1994) derived the now used governing electrokinetic equations. This set of equations is essentially a coupling between the so-called Biot theory (Biot, 1956) (which is the dynamic theory of fluid-infiltrated porous materials) and Maxwell theory. In this article, it will become clear that this was just an initial step towards a much broader soil model. Notwithstanding important theoretical advances, laboratory and field tests to validate the theory are scarce.

Physics

When a saturated porous material is subjected to hydraulic, potential, chemical or thermal gradients, it gets out of equilibrium. Classical thermodynamics is capable of describing the initial and final states of the process. However, if we want to describe the time-dependent behaviour of the system we need non-equilibrium (also known as irreversible) thermodynamics. The power of classical thermodynamics is its capability to determine the properties of a uniform equilibrium system with only a small set of state variables. When we deal with irreversible thermodynamics, in systems not too far from equilibrium, it is possible to divide the system into small subsystems, thereby assuming that each of these

Table 1 Direct and indirect Onsager-type coupled processes (Mitchell, 1991).

Gradient X / Flow J	Hydraulic	Electrical	Chemical	Thermal
Fluid	Darcy's law (Biot eqn's)	Electro-osmosis	Chemical-osmosis	Thermo-osmosis
Current	Streaming potential	Ohm's law (Maxwell eqn's)	Diffusion potential	Seebeck effect
Ion	Streaming current	Electrophoresis	Fick's law (Convection diffusion eqn)	Soret effect
Heat	Isothermal heat transfer	Peltier effect	Dufour effect	Fourier's law (Conservation of energy)

subsystems is in a local equilibrium. For that condition of local equilibrium, it is possible to treat the subsystem as an individual thermodynamic system which can be characterised by only a small number of equilibrium variables.

$$J_i = \sum_j L_{ij} \nabla X_j$$

The fluxes J_i are a linear function of driving forces X_j and L_{ij}, the phenomenological (Onsager, transport or coupling) coefficients. Onsager found that there is an underlying symmetry for the phenomenological coefficients, also known as the Onsager reciprocal relation:

$$L_{ij} = L_{ji}$$

Linear non-equilibrium thermodynamics is based on all laws of classical thermodynamics and expanded by the hypothesis of local equilibrium in combination with the following assumptions:

- Local equilibrium: the system can be considered as if it were in local equilibrium, making it possible to describe thermodynamics using reversible processes.
- Linear relationship between driving forces and flows.
- Onsager's symmetry of the phenomenological coefficients.

In Table 1 Onsager's coupled processes are shown. The coloured diagonal elements contain the well known first order (direct processes) phenomena while the off diagonal effects contain the second order (indirect) effects (Molina et al., 1999).

The mechanism that drives all electro-osmotic and streaming potential processes is the development of a surface charge on a solid phase which is in contact with a liquid (Figure 1). This surface charge is created by chemical interaction between the solid and liquid phase. This interaction of the mineral (surface) mainly occurs when the liquid phase is an electrolyte.

Electrokinetic phenomena will occur when the 2 phases are moving with respect to each other. Due to an excess of ions or electrons in one or both phases, there will be a tendency for the electric charge to distribute itself in a non-uniform way at the interface. The surface charge will be opposite in sign of the charge in the liquid, creating a diffuse layer of counter-ions next to the surface of the solid. This phenomenon of redistribution of the charge along the solid-liquid interface is defined as the *electric double layer*. During equi-

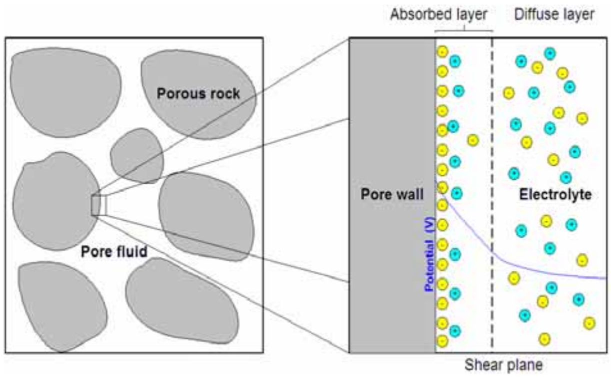


Fig. 1 The electric double layer.

librium (liquid and solid are not moving with respect to each other) the porous medium will be neutral.

If we take a close look at Table 1, it can be noticed that Darcy's law, which is a principal physical phenomenon, is only part of the physics. It is limited to viscous flow while inertial flow effects are not included. To incorporate these effects and the surrounding porous medium, Biot developed the *Biot equations* which are effectively conservation of mass and momentum for the solid as well as for the fluid. Conservation of mass combined with the constitutive equations form the Biot-Gassmann constants. Having these equations in mind, combined with the knowledge of the Onsager relationships, Neev & Yeats (1989) and Pride (1994) started to expand the Biot equations to include electro-magnetic effects. Therefore the Biot equations and Maxwell equations where combined with the seismo-electric/electroseismic coupling term. This way seismic and ground-penetrating

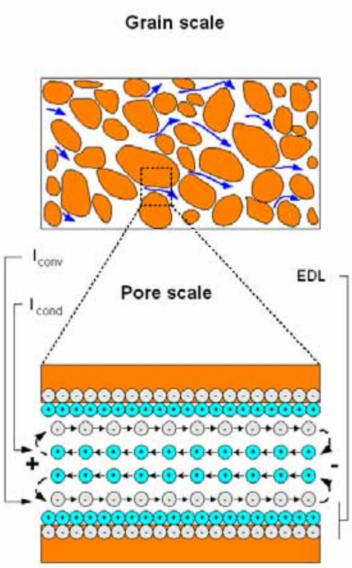


Fig. 2 Seismo-electric phenomena.

radar are effectively combined in one method. Reconsidering Table 1, it can be noticed that this was just step number 2, as in the future, thermal gradients and chemical gradients also will be included. This system will contain conservation of energy and the convection diffusion equation to describe chemical changes. Also, these conservation laws will describe the fluid as well as the solid. However, as is well known, the devil hides in the detail. To get the set of equations complete, the right set of constitutive equations needs to be found. The coupling coefficients on the other hand, at least the frequency independent part, can more easily be found in chemistry literature.

If we focus our attention to the electroseismic/seismoelectric effect, a variety of physical effects can be recognised. Within electro-osmosis and streaming-potential phenomena, 3 different observations can be made: first of all the source of a seismo-electric signal (sledgehammer impact), creates an enhanced fluid pressure on one side of the impact point (for a few milliseconds). When the fluid distribution equilibrates, a charge separation will occur due to the electrokinetic mechanism. The charge separation at a vertical impact point will have a strong vertical dipole component, creating a strong electric wave also known as the *direct field* which propagates with the speed of light in a poroelastic medium (Figure 4a). This disturbance is measured almost immediately by nearby electrodes (Figure 4d).

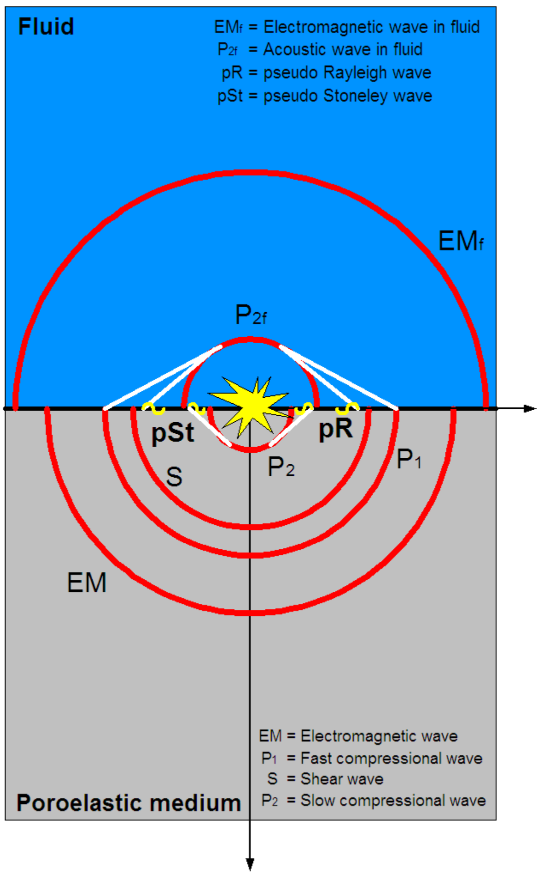


Fig. 3 Characteristic waves in half space at fluid/poro-elastic medium boundary. The 4 characteristic waves and some surface waves (Rayleigh and Stoneley) are shown.

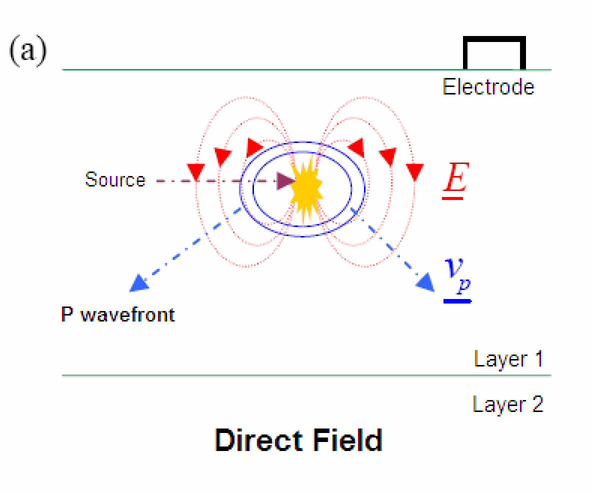


Fig. 4a Seismo-electric effects: direct field (Haines, 2004).

When a metal plate is used as impact point for the hammer, the Lorentz force can create an electric field. Both effects are not being used for interpretation purposes (Packard, 1953). There are four kinds of waves, the electro-magnetic wave, the shear wave and two sorts of compressional waves which travel through a fluid saturated porous medium (Figure 3). There is the fast compressional wave which travels through the porous material and slow compressional wave (also known as the Biot wave) which travels through the fluid. The fast compressional wave travelling through the porous medium creates a fluid gradient that induces pore fluid flow. Due to pore fluid movement within the electric double layer a small amount of electric charge relative to the fixed charge (on the pore wall) is transported (Figure 2). The pressure gradient causes a convection current I_{conv}, which has to be balanced by the conduction current I_{cond} (Packard, 1953). The

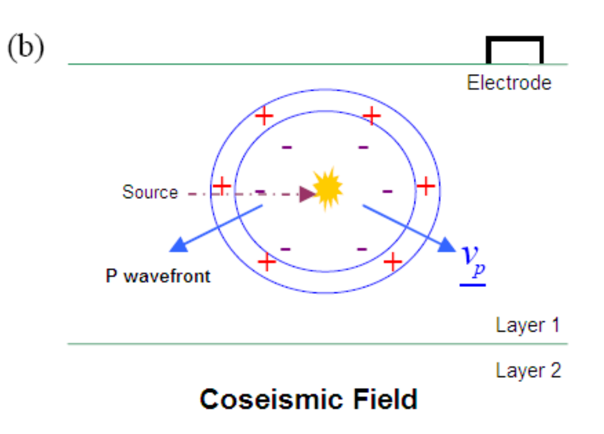


Fig. 4b Seismo-electric effects: coseismic field (Haines, 2004).

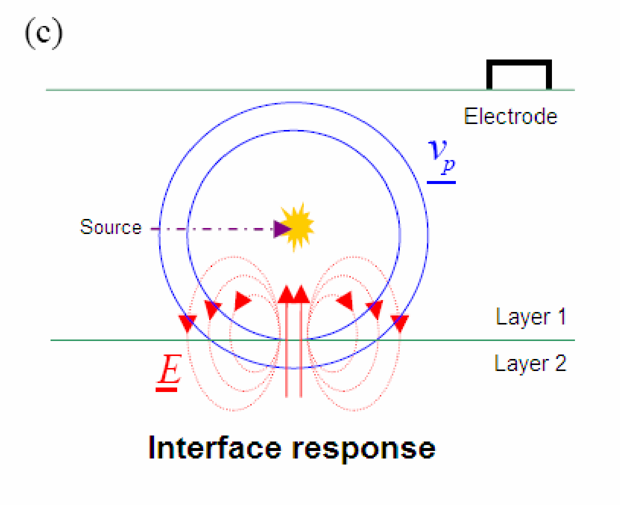


Fig. 4c Seismo-electric effects: interface response (Haines, 2004).

occurring electric field is known as the coseismic field (Figure 4b). The coseismic field travels along with the fast compressional wave and is therefore slower than the direct field and the hereafter discussed interface response. Also surface waves can create a coseismic field. Similarly, an array of magnetometers will record the magnetic field inside the shear and surface waves as they pass the magnetic sensor. The coseismic wave is ideal for obtaining petrophysical properties of the near surface layers in terms of fluid content (Garambois & Dietrich, 2001).

The third phenomenon occurs when the fast compressional wave hits an interface in material properties. Charge separation in the wave will be disturbed at the interface causing asymmetry in the charge distribution. This will result in an oscillating electric dipole with its dominant contribution coming from the first Fresnel zone. The associated electromagnetic field will travel almost immediately to the receivers (Figure 4d). This seismo-electric conversion is known as interface response (Figure 4c) (Packard, 1953).

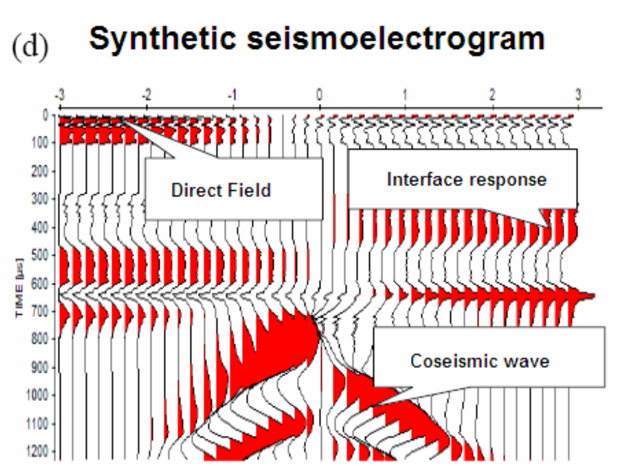


Fig. 4d Seismo-electric effects: seismo-electrogram (Haines, 2004).

In Figure 4d a synthetic seismo-electrogram is given as modelled by Haines (2004).

Benefits of EK for geophysics

Why should we make use of electrokinetic research? This can be seen by looking at the benefits of electrokinetic methods. For geophysics one of the main benefits, compared to seismic methods, is that seismo-electric and electroseismic methods are capable of detecting much thinner layers than the principle wavelength (Haines & Pride, 2006). The small amount of field tests that have been performed with the electroseismic method (detecting zones of high fluid mobility and fluid chemistry contrasts), indicate that gas, sand and oil reservoirs could be visualised to at least 1,500 m (much deeper than ground penetrating radar). In the future, deeper penetration should be possible by using better sources and analysis methods. Current signals are weak because of limits in driving large currents into the ground. Thompson et al. (2007) suggest that electroseismic measurements are possible in lithologies where seismic hydrocarbon indicators are weak. Hydrocarbon reservoirs are better visible than non-hydrocarbon reservoirs of the same lithology, due to the resistivity of the hydrocarbons which is higher than water. It is also possible to visualise hydraulic permeability which is invisible for conventional geophysical methods (Packard, 1953).

Using electrokinetic techniques, one is capable of determining hydrological parameters such as saturation, fluid type, permeability and porosity with better resolution than with conventional methods. With such techniques one is capable of obtaining a much more detailed picture of a reservoir without performing destructive research (like core measurements).

Obstacles during measurements

A distinction can be made between electroseismic (Figure 5) and seismo-electric measurements. The electroseismic approach is better implementable than the other method. This can be seen by looking at ways to obtain large amplitude conversion between seismic and electromagnetic energies. There are three methods, good contrast in acoustic impedance, permeable pore space and high resistivity pore fluids to obtain good amplitude conversion values. For the seismo-electric approach, the contrast in acoustic impedance can be the weakest contributor, the seismic reflections are small (most of the seismic energy propagates through the target interface unperturbed). Another reason to prefer electroseismic measurements is that a clearer source signal can be created than during seismo-electric measurements.

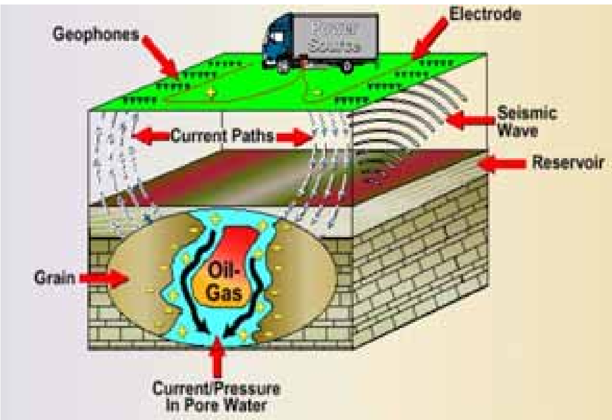


Fig. 5 Electroseismic prospecting in the field.

The electroseismic approach also may give different information than the seismo-electric approach (Thompson et al., 2007).

In laboratories and in field equipment, power lines cause difficulties for interpreting transient electric signals (to minimise this noise, optical cable systems can be used) (Garambois & Dietrich, 2001). The main energy of the electroseismic signal is contained in the low frequency range, 10-150 Hz (Mikhailov et al., 1997). To improve the signal quality, reference measurements need to be performed to remove noise, in combination with averaging the measured signal. Only by collecting enough information, seismo-electric data may be interpreted unambiguously.

It is important to take the most useful sources and use a sufficiently dense source spacing. If during geophysical prospecting the investigated object is not illuminated adequately, no unambiguous result can be obtained. The receivers and sources are not optimal for these kinds of measurements and lots of improvement can be reached on this aspect. Real progress in this area will require an increase in complexity and an associated increase in expenses (Haines & Pride, 2006). To prevent electrochemical reactions on the electrodes (corrosion, oxidation) use should be made of electrodes from sintered Ag-AgCl or Monel plates which are ideal for these circumstances (Packard, 1953).

Current measurement techniques are not capable of reaching deeper than 1,500 m below surface (Thompson et al., 2007). Especially for geophysical observations deeper penetration will be necessary in the future.

Due to the fact that a large number of physical effects are interacting, scientists and engineers are required to have at least basic knowledge of theory of elasticity (mechanics), hydrology for fluid flow, physical chemistry, thermodynamics and electromagnetics. Therefore it takes quite some time to go deeply into this subject.

Possibilities for the future

Looking at the applications of electrokinetics, we see that it is also used within hydrology and geo-engineering as a tool for soil treatment. Electro-osmosis can be used to prevent undesired flow and to manipulate underground flow. It increases the water flow velocity by up to 10,000 times more than achievable under typical hydraulic flow conditions. It allows for recycling of waste materials (such as salt-water intrusion and waste containment (Masliyah & Bhattacharjee, 2006)), saving time and money whereby the environmental impact is also reduced. Also hydrogeological evolution studies of sedimentary basins, paleohydrogeological research and long-term radioactive waste, repository monitoring belong to the possibilities. It is also used in other areas for many industrial processes such as in biological, physiological and micro- and nanofluidic applications (Masliyah & Bhattacharjee, 2006).

In petroleum engineering use can be made of electrokinetic phenomena for bitumen extraction in oil sands and for oil extraction from shales. Oil sands are unconsolidated sand deposits that are impregnated with high molar viscous petroleum (commonly known as bitumen). Bitumen embedded within quartz sand, clay and connate water (together with the associated salts) have a very high viscosity at room temperature and therefore need to be upgraded before it can be refined. The oil should be clearly visible with geophysical exploration techniques, a.o. due to its relatively high zeta-potential in comparison to the surrounding materials. The electrokinetic properties of bitumen and silica have also been investigated extensively for possibilities to separate the bitumen easier from the sand (thereby reducing the power consumption used in standard techniques) (Masliyah & Bhattacharjee, 2006). Steam injection is also one of the techniques that is used by petroleum engineers. It is used as an enhanced oil recovery technique and uses electrokinetic effects (Butler & Knight, 1995).

In other areas like chemistry, the graphic industry and medicine, electrokinetic phenomena have an increased popularity. By miniaturization of complex procedures on small chips, we are now capable of analyzing biological and chemical substances much faster than a decade ago. These labs-on-chips can perform a wide array of fluid manipulations in these devices. Functions like pumping (without moving parts), screening, separation, mixing and diagnostics are possible. Printing equipment can also be revolutionised with these techniques. By removing moving parts, equipment is less sensitive to fatigue and other related causes of long term usage damage. Also here, a multidisciplinary approach is possible, printing techniques to construct biological organs belong to the possibilities with these techniques (Mironov et al., 2003).

Applications regarding membrane filtering also belong to the possibilities. Not only in the area of biology and chemistry but also for engineering purposes like fuel cell technology, knowledge of electrokinetics is a requirement.

By combining all of the above mentioned Onsager transport effects in one generalised set of governing equations which include conservation of mass, momentum (Biot theory), Maxwell equations, conservation of energy and convection diffusion equation (for changes in concentration), it is possible to physically describe different scientific areas in one set of equations. Effectively it is combined geophysics, geohydrology and geo-engineering (Neev & Yeats, 1989). Wapenaar & Fokkema (2004) show in their paper about reciprocity for diffusion, flow and waves, a general form in which the combined set of governing equations describing Onsager's relationships can be captured by a differential equation in matrix-vector form (in case the governing equations are linearised). A variety of processes are shown, like acoustic wave propagation, electromagnetic diffusion and wave propagation, as well as coupled elasto-dynamic and electromagnetic wave propagation in porous media. Although their matrices and vectors are different, the structure of the differential equations and the symmetry properties are the same for all cases. The total set of governing equations can find its applications in forward and inverse modelling for problems in diffusion, flow and wave theory.

In short, electrokinetics is a multidisciplinary research area, which keeps a great promise for future applications. Due to continued improvement of technical equipment, increased computer capabilities, and more accurate models we will be capable of measuring hydrological parameters in much more detail, thereby increasing our knowledge of the shallow subsurface, and deeper located reservoirs and other geological formations. Electrokinetics expands at the same time the amount of tools and brings different disciplines together.

References

Biot, M.A. (1956). Theory of propagation of elastic waves in a fluid-saturated porous solid. *Journal of the Acoustical Society of America,* **28**(2), 168-191.

Butler, D.B. & Knight, R.J. (1995). The effect of steam quality on the electrical behavior of steam-flooded sands: A laboratory study. *Geophysics,* **60**(4), 998-1006.

Casagrande, L. (1941). Die entwasserung feinkörniger Boden. *Die Strasse,* **8**(19-20), 324.

Frenkel, Y.I. (1944). On the theory of seismic and seismically generated electric phenomena in wet soils. *Trans. USSR Acad. Sci. (Izvestia) Ser. Geophysical Geograph.*, **8**, 134-149.

Garambois, S. & Dietrich, M. (2001). Seismoelectric wave conversions in porous media: Field measurements and transfer function analysis. *Geophysics,* **66**(5), 1447-1430.

Haines, S.S. (2004). *Seismoelectric imaging of shallow targets.* PhD-thesis, Stanford University.

Haines, S.S. & Pride, S.R. (2006). Seismo-electric numerical modeling on a grid. *Geophysics,* **71**(6), N57-N65.

Helmholtz, H.V. (1879). Studien über electrische grenschichten. *Annalen der Physik und Chimie,* **7**, 337-387.

Masliyah, J.H. & Bhattacharjee, S. (2006). *Electrokinetic and Colloid Transport Phenomena*. John Wiley & Sons, Inc.

Mikhailov, O.V., M.W. Haartsen & M.N. Toksöz (1997). Electroseismic investigation of the shallow subsurface: Field measurements and numerical modeling. *Geophysics,* **62**(1), 97-105.

Mironov, V., T. Boland, T. Trusk, G. Forgacs & R.R. Markwald (2003). Organ printing: computer-aided jet-based 3D tissue engineering. *Trends in Biotechnology,* **21**(4), 157-161.

Mitchell, J.K. (1991). Conduction phenomena: from theory to geotechnical practice. *Géotechnique,* **41**(3), 299-340.

Molina, C., L. Victoria, A. Arenas & A. Ibáñez (1999). Streaming potential and surface charge density of microporous membranes with pore diameter in the range of thickness. *Journal of Membrane Science,* **163**(2), 239-255.

Neev, J. & Yeats, F.R. (1989). Electrokinetic effects in fluid-saturated poroelastic media. *Physical Review B,* **40**(13), 9135-9141.

Packard, R.G. (1953). Streaming potentials across glass capillaries for sinusoidal pressure. *Journal of Chemical Physics,* **21**, 303-307.

Pride, S.R. (1994). Governing Equations for the Coupled Electromagnetics and Acoustics of Porous Media. *Physical Review B,* **40**(21), 15678-15696.

Reuss, F.F. (1809). *Mémoires de la Societé Impériale de Naturalistes de Moscou,* **2**, 327.

Smoluchowski, M. von (1903). Contribution a la theorie de l'endosmose electrique et de quelques phenomenes correlatifs. *Bulletin International de l'Academie des Sciences de Cracovie,* **8**, 182-200.

Thompson, A.H., Hornborstel, S., Burns, J. et al. (2007). Field tests of electroseismic hydrocarbon detection. *Geophysics,* **72**(1), N1-N9.

Thompson, R.R. (1936). The seismic electric effect. *Geophysics,* **1**, 327-335.

Wapenaar, C.P.A. & Fokkema, J. (2004). Reciprocity theorems for diffusion, flow and waves. *Journal of Applied Mechanics,* **71**(1), 145-150.

Marine seismic refraction for soil exploration in very shallow waters - Application to pre-dredging surveys

S. Minard *(Geophysicist, Fugro France, s.minard@fugro.com)*

C. Hérisson *(Manager of Marine Engineering Geophysics, Fugro France, c.herisson@fugro.com)*

Abstract

At the earliest stage of their bid process, dredging companies need to get as much information as possible about soil properties, especially to evaluate the dredgeability of sediments. Seismic refraction provides in short time continuous compressive velocity data which is in close relation with the mechanical properties of sediment. The correlation of geotechnical and geophysical data allows extending the local information provided by boreholes to the whole velocity profile. GIS software can interpolate velocities measured on a 2D network of seismic profiles into a volume of soil and then extract depth, velocity and thickness maps.

Introduction

Nearshore construction and development projects can be various and numerous, ranging from port development and harbour construction, wind farms or reclamation areas to cable and pipeline landings.

To achieve these projects, morphology and mechanical parameters of the soil have to be known. An accurate knowledge of the geology of the working area is a key element to evaluate the feasibility of a project, its costs, the choice of appropriate tools (for coring, trenching or dredging), the dimensions of foundations, etc.

Harbour extension, development of new port zones, LNG installations and access channels are activities involving extensive dredging work. The choice of the most suitable dredging technique, the realistic evaluation of the volumes to be extracted and the possible need for a pre-treatment of the rock by blasting are key factors controlling the costs.

Optimizing its experience in burial assessment of submarine cables and pipelines, and acting for the dredging companies at the earliest stage of their bid process, Fugro has been involved in recent years in marine seismic refraction surveys for evaluation of volumes and dredgeability.

Seismic refraction technique

The seismic refraction method is designed to measure the intrinsic compressive velocities (V_p) of the soil and its geometry by recording waves that propagate along pseudo horizontal layer limits. To collect refraction data, the standard spread is made up of a source that creates an acoustic wave and an array of hydrophones (streamer) which records pressure variations versus time. When the source is fired, a compressive wave (P-wave) is generated and then travels either by a direct path through the slow sediments near the surface, or by a refracted path via deeper, faster layers. Then the first arrival of the P-wave is measured and detected at each hydrophone. By building up the relationship of travel time versus distance along the array, the technique is then able to compute the velocity of wave propagation in the various horizons and their thickness. Unlike standard seismic reflection techniques, the investigation depth of seismic refraction is not dependant on the water depth, therefore the technique is efficient in very shallow water.

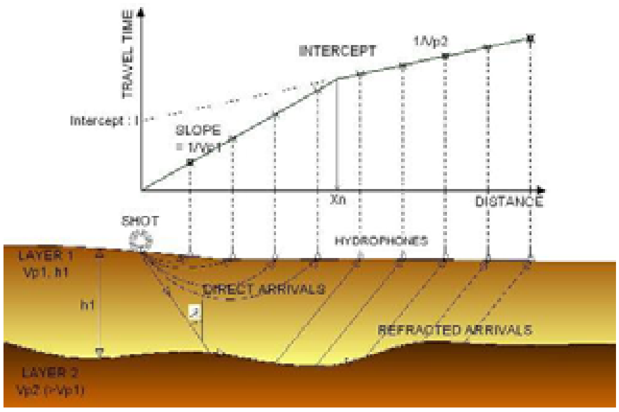


Fig. 1 Basic refraction principle.

Basically, the compressive wave velocity V_p is proportional to the degree of consolidation, stiffness and cementation of the material. Thus, loose sands and soft clays usually show velocities ranging between 1,500 and 1,600 m/s. Velocities in denser sand and stiff clays generally range up to 1,800 m/s. Slightly cemented sediments may exhibit velocities up to 2,100 m/s, whilst 'rock' can offer velocities in excess of 2,000 m/s to over 6,000 m/s, depending on its degree of cementation, weathering, fracturing and jointing.

GAMBAS®50 system

To investigate the first metres of sediment below the seabed, Fugro has developed a towed light high resolution marine seismic refraction system called GAMBAS®50. The equipment has been designed especially for investigations for shallow waters, from very shallow down to 40 m depth. It is a bottom dragged system made up of a sledge, carrying the seismic source, and a streamer towed behind the sledge. The geometry of the acquisition system (length of the streamer, number of hydrophones, energy of the source) can be tailored to the required penetration depth, usually from 6 to 15 m below seabed.

A key component of the GAMBAS®50 system is the *stop-and-go* motion device which enables the sledge to remain stationary while the vessel continues sailing at a 2 or 3 knot speed. Hereby, noises are avoided since the streamer keeps in close contact with the seabed during the shooting and recording sequences. This technique allows a production of about 5 to 15 km per day, on a daylight work basis, the production mainly depending on the survey specification (profiles length) and environment (existing infrastructure, geohazards, etc.).

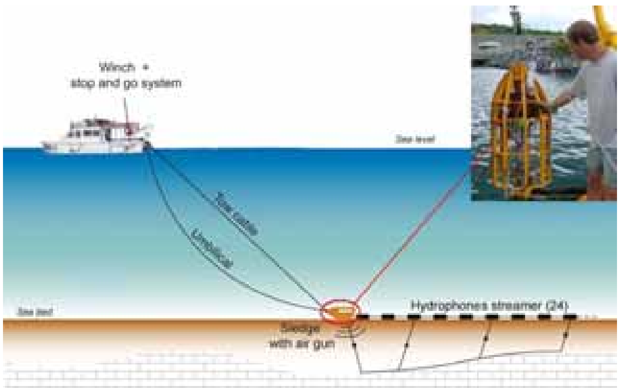


Fig. 2 GAMBAS®50 system.

The GAMBAS®50 end processing provides velocity profiles geo-referenced in terms of kp (kilometric point) and presented as coloured bar-charts where velocity classes are related to mechanical characteristics of the soil.

When geotechnical data is available, Fugro proposes full integrated studies, optimizing the correlations between results from boreholes or in-situ tests and the marine seismic refraction data. For such purposes, Fugro has developed a database, populated from the numerous shallow surveys performed, that correlates the seismic velocity V_p with cone resistance q_c. Integrated results could be directly used for the pre-engineering studies.

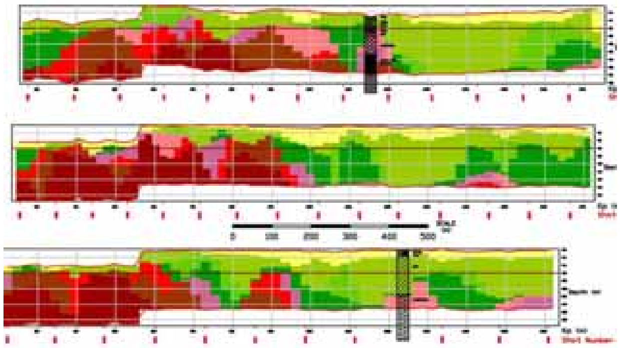


Fig. 3 Example of a velocity profile, correlated with geotechnical boreholes (computed with StarfixGambas®).

A powerful tool: GIS

A Geographic Information System (GIS) is a powerful tool for data management. The recent developments allow the integration of all kinds of data: bathymetry, geotechnical or geophysical data, aerial and satellite images, etc. Velocities computed on crossing profiles can be extended to a 3D volume and compared to borehole logs. Thus GIS is an efficient tool for quality control of data and qualitative as well as quantitative interpretation.

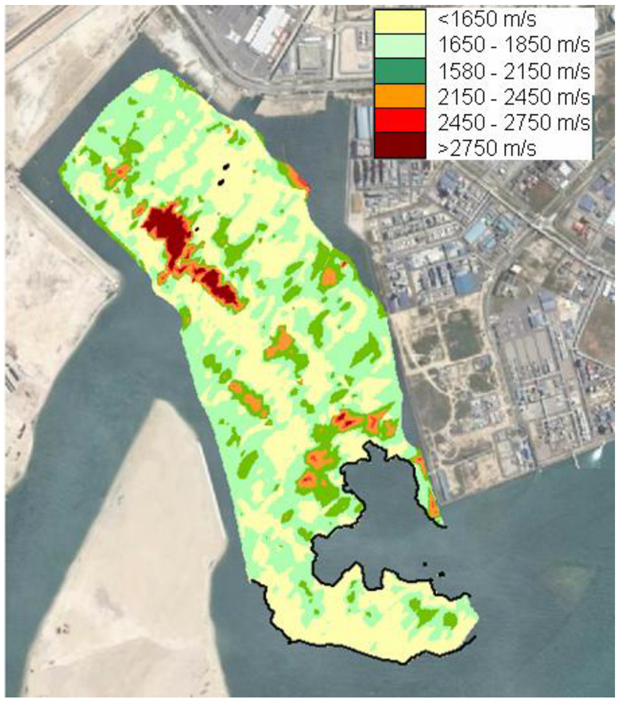


Fig. 4 Distribution of velocity classes at -18 m LAT (target depth) from a GAMBAS®50 survey at Banyan terminal (Singapore) (Map computed with ArcGIS® 9).

Using specific requests, results can be presented as:

- Distribution of velocity classes at target depth (see Figure 4)
- Thickness of dredgeable sediments (see Figure 5)
- Depth of seismic velocities (see Figure 6)

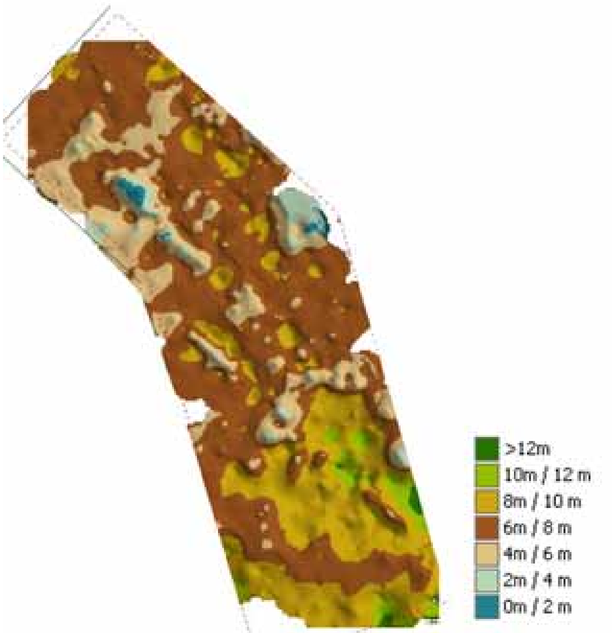


Fig. 5 Thickness of dredgeable sediments (V_p < 2,150 m/s) from a GAMBAS®50 survey at Banyan terminal (Singapore) (Map computed with ArcGIS® 9).

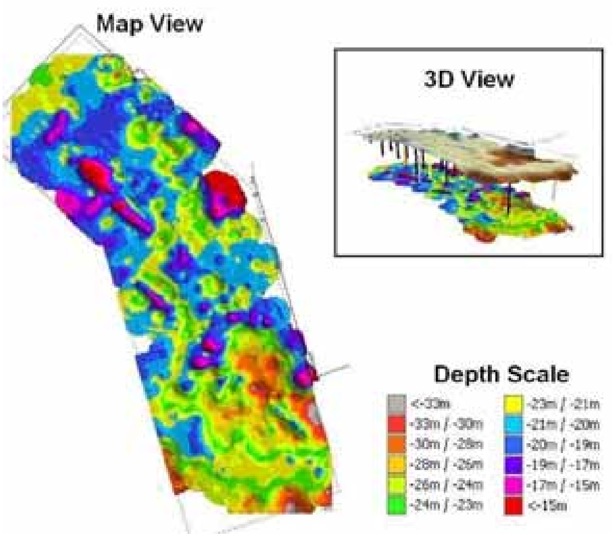


Fig. 6 Depth of substratum, i.e.: seismic velocities above 2,150 m/s from a GAMBAS®50 survey at Banyan terminal (Singapore) (Map and 3D view (sea bed, substratum and boreholes) computed with ArcGIS® 9).

Conclusion

At the earliest stage of their bid process, dredging companies need to get as much information as possible about soil properties, especially to evaluate the dredgeability of sediments.

Seismic refraction provides in short time continuous compressive velocity data which is in close relation with the mechanical properties of sediment. As a first geological assessment, refraction will highlight each area presenting specific velocity properties and also velocity anomalies. Then, a smart choice for borehole locations, based on seismic results, will optimise the cost of the geotechnical survey by reducing the number of boreholes dramatically. The correlation of geotechnical and geophysical data allows to extend the local information provided by boreholes to the whole seismic velocity profile.

GIS software, such as ArcGIS®, can interpolate velocities measured on a 2D network of seismic profiles into a volume of soil and then extract depth, velocity and thickness maps. For pre-dredging surveys, marine seismic refraction is the very appropriate method in addition to geotechnical surveys. Since 1998, GAMBAS®50 surveys have been performed in a challenging time schedule and with results provided to the dredging companies within a few days allowing an immediate evaluation of dredgeable volumes.

Repositioning sources with seismic interferometry

Joost van der Neut *(Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Applied Geophysics and Petrophysics)*

Introduction

Imaging below complicated structures in the subsurface is a major problem in modern exploration geophysics. In some cases we can bypass these complexities to some extent by deploying seismic receivers in a well, with sources laid out on the earth's surface. With seismic interferometry, source locations can be effectively repositioned from their actual locations to downhole receiver locations. In this way we create a virtual data set with both sources and receivers close to the target of interest, while bypassing the complexities. In this article, we derive the theory of interferometry on an intuitive level and discuss a few applications. For more information, we refer to Wapenaar et al. (2008a).

Theory

In a conventional seismic survey we would place sources and receivers at the earth's surface to image the subsurface reflectivity, as illustrated in Figure 1a. If the target is buried under complicated structures with strong contrasts in seismic velocity, internal scattering can complicate the waveforms and consequently the quality of the image. The situation would be simplified if the source and receiver could be placed in a well beneath the complexities (see Figure 1b). However, downhole sources can be expensive, destructive and their radiation characteristics are in many cases undesirable. Therefore, it is cheaper to keep the source locations at the earth's surface, while deploying downhole receivers, as depicted in Figure 1c. However, signals that reflected at the target location T in this configuration still have propagated through the complexities which we aim to avoid.

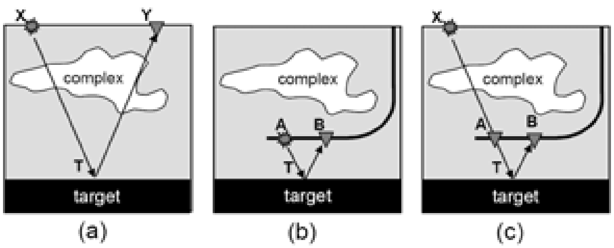


Fig. 1 Imaging below complex overburden: a) conventional acquisition design with sources and receivers at the earth's surface, located at X and Y, respectively; b) desired acquisition, with sources and receivers in a borehole, located at A and B, respectively; c) acquisition for seismic interferometry, with sources at earth's surface location X and receivers in the borehole at locations A and B, where location A corresponds to the virtual source location.

With seismic interferometry we can transform actual data obtained from an acquisition strategy as depicted in Figure 1c to virtual data with an acquisition strategy as depicted in Figure 1b. Key is to remove the segment XA from the propagation path XATB as it appears in Figure 1c, thus redatuming (or repositioning) the source from its actual location X to receiver location A. As we create a virtual source at location A, this method is also referred to as the virtual source method. The approach is fully data driven, meaning that no other information is required than the observed wavefields at locations A and B.

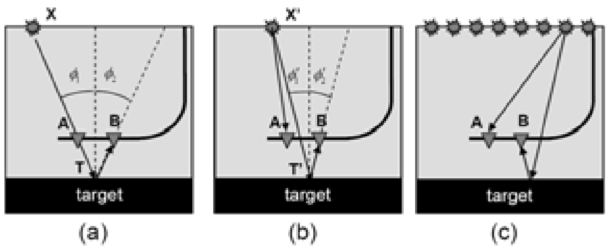


Fig. 2 Example to illustrate the concepts of seismic interferometry: a) source located at X; b) source located at X' (right of X); c) multiple source locations.

To explain this methodology at an intuitive level, we remove the complexities from the subsurface for a moment, leaving us with the configuration as depicted in Figure 2a. A wave is excited at X and propagates over the segment XA to arrive at receiver A at $t_{XA} \approx$ 0.19 s. The response is known as a seismic trace and shown in Figure 3a. The signature of the wave is referred to as the seismic wavelet. The journey of the wave continues from location A down to reflection point T. Next, it reflects to arrive at receiver B at $t_{XATB} \approx$ 0.39 s. The registration is shown in Figure 3b. Note that the wavelet is similar to the one we found in receiver A, shifted in time due to the extra propagation path ATB.

To remove the segment XA from the total path of propagation XATB, the travel time of the direct wave at A needs to be subtracted from the travel time of the scattered wave at B. In interferometry this is done by cross-correlation. On an intuitive level, cross-correlating the signals of receivers A and B, means shifting the signal in A over t_{shift} and multiplying it sample-by-sample with the signal in B. All multiplied time-samples are then added, yielding the cross-correlation function at $t = t_{shift}$. If the specific time shift is chosen such that the wavelets in trace A and B overlap, the cross-correlation function yields a strong (positive) response (see Figure 3c). In the example, this occurs exactly at $t_{shift} = t_{XATB} - t_{XA} \approx 0.20$ s which corresponds to the travel time t_{ATB} to propagate from A to B along the segment ATB. We have thus shown that cross-correlating the direct wave at A with the scattered wave at B eliminates the propagation time along XA, yielding a trace as if a virtual source was excited at A, reflected at T and recorded at B.

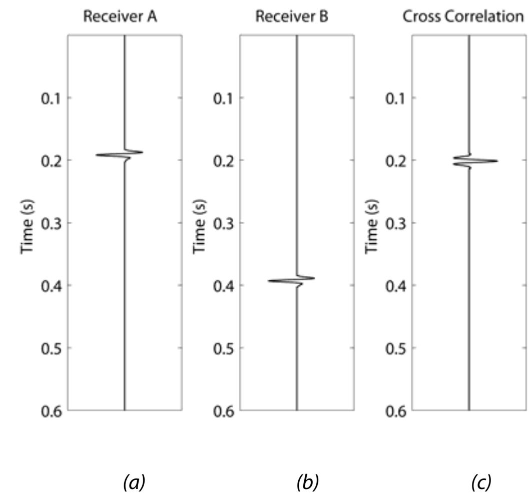


Fig. 3 Seismic traces: a) direct wave at A; b) scattered wave at B; c) cross-correlation function.

In the previous example, we silently assumed that the scattered wave reaches receiver B through the path XATB. In practice, waves propagate along the fastest path according to Fermat's principle. It can be shown easily that the angle of a reflected wave should equal the incidence angle. In other words: angles Φ_1 and Φ_2 as shown in Figure 2a should be equal. This poses restrictions on the source location X, in order for the cross-correlation function to yield the correct travel time of the segment ATB. In Figure 2a, location X is a so-called stationary point for the reflection ATB, meaning that the paths of the direct wave at A and the scattered wave at B overlap. If we shift the source to location X', angles Φ_1 and Φ_2 should once more be equal and the paths of the direct wave at A and scattered wave at B do no longer overlap (see Figure 2b). To obtain the correct travel time for segment ATB, a direct wave that propagated over X'A should be cross-correlated with a (non-physical) scattered wave that propagated over X'ATB. However, the observed scattered wave propagated along X'T'B. Fermat's principle dictates that the path of physical propagation is the path with the shortest travel time. Therefore the time we predict by cross-correlating the observed waves will always be smaller than the desired time t_{ATB} , if the source is not located at the stationary point X.

To overcome this problem, we place multiple sources on the earth's surface (see Figure 2c). Each source will produce a direct wave at A and a scattered wave at B, as shown in Figure 4a and 4b. We cross-correlate each source individually, yielding a so-called cross-correllogram as shown in Figure 4c. As predicted, an event is created at a travel time $t \leq t_{ATB} \approx 0.20$ s. If we add the cross-correlation functions of all sources, destructive interference will cancel the contributions at $t < t_{ATB}$, whereas constructive interference will enhance the signal at $t = t_{ATB}$ (see Figure 4d). All contributions of 'mispositioned' sources cancel, whereas the contribution at the stationary point remains. It can be shown that an infinitely long array of sources yields an exact response as if there was a source at A and a receiver at B. We laid out the theory for a direct wave at A and a reflected wave at B. It can be shown that a perfect response can be retrieved by the correlation of full waves if a closed boundary of sources surrounds the receivers (Wapenaar et al., 2005).

In practical applications however, sources can be placed at the earth's surface only, thus not fulfilling the requirement of a closed boundary of sources. Therefore we speak of one-sided illumination. Due to this problem, fake reflectors can emerge in the virtual gathers and amplitude information is generally not retrieved correctly. Intuitively speaking, the desired constructive and destructive interference as illustrated in Figure 4 requires 'isotropic illumination'. More scattering can improve this requirement, as shown by Wapenaar (2006). Therefore, interferometry is assumed to be blessed in strongly heterogeneous media. If sufficient receivers are available, anisotropic illumination can be corrected for by replacing cross-correlation by a more rigorous matrix inversion. First a set of forward equations is formulated that ex-

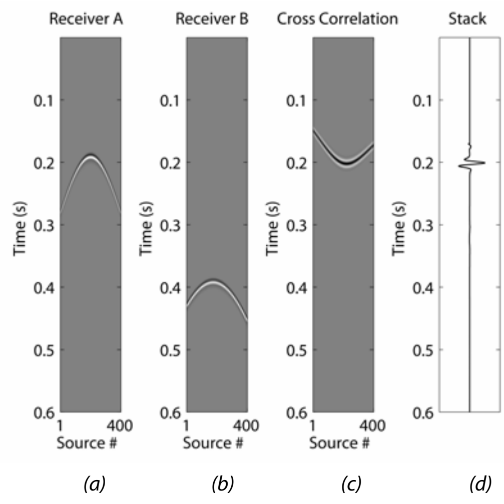
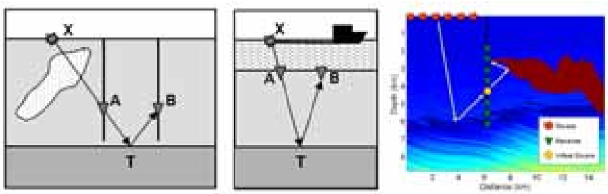


Fig. 4 400 shot positions: a) direct wave at A; b) scattered wave at B; c) cross-correlation functions; d) stack of cross-correlation functions.

tend the direct wave at A with the unknown virtual response of the segment ATB, yielding the scattered wave at B. These equations are based on convolution, a tool from signal processing that adds travel times, comparable to the subtraction of travel times in cross-correlation. This set of convolution equations can be inverted to retrieve the virtual source response. The inversion is referred to as multi-dimensional deconvolution (Wapenaar et al., 2008b).

Applications

In recent years, interferometric redatuming has been applied in a variety of cases. See Schuster (2009) for an overview. In Figure 5a we show how a transmission response between two wells can be extracted without having to deploy downhole sources. The direct wave at A is cross-correlated with the wave at B to remove the segment XA from the path XATB. An advantage of this technique over placing downhole sources is that radiation characteristics can be improved and manipulated (Mehta et al., 2008).



a) *b)* *c)*

Fig. 5 a) generating virtual crosswell data; b) ocean bottom cable redatuming; c) salt flank imaging.

Another idea is shown in Figure 5b. A source is towed behind a boat at location X. Receivers are located in an Ocean Bottom Cable (OBC) at seafloor locations A and B. In 4D (or time-lapse) seismics, we repeat experiments over time to observe changes in the subsurface. For this purpose, it is desirable to have repeatable source and receiver locations. By using permanent sensors at the seafloor, receiver repeatability will be acceptable. However, source repeatability at the sea surface generally is not. We can exploit interferometry to redatum the sources to a receiver location A. As both virtual source A and receiver B are permanently stationed, a highly repeatable data set can be obtained, even if the actual source locations X are varying from experiment to experiment (Bakulin & Calvert, 2006).

Interferometry can exploit seismic travel paths that are ignored in conventional processing. As an example we introduce Figure 5c. Shown is a seismic velocity profile. A major salt flank can be observed on the right of the figure, creating a seismic shadow zone where imaging is cumbersome.

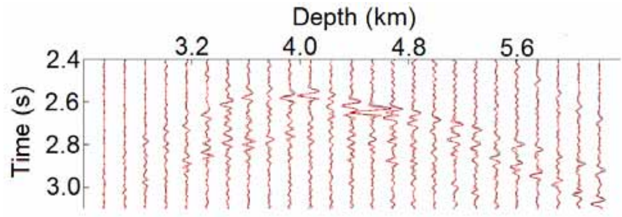


Fig. 6 Redatumed virtual shot record with seismic interferometry by multi-dimensional deconvolution (red) superimposed on a reference response, generated by placing an active source at the virtual source location (black).

Sources are located at the earth's surface. Receivers are located in a vertical well. To illuminate the salt, multiple reflections need to be exploited, as shown in the figure. By interferometry, a virtual source can be created at a downhole receiver location. In Figure 6 we show a shot record of a virtual source that is generated by multi-dimensional deconvolution, exploiting illumination from paths as shown in Figure 5c. We superimpose the results in red on those of a reference response, which is generated by positioning an active source in the well. Note that a perfect match is achieved.

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References

Bakulin, A., & Calvert, R. (2006). The virtual source method: Theory and case study. *Geophysics*, **71**(4), SI139-SI150.

Mehta, K., Bakulin, A., Kiyashchenko, D. & Lopez, J. (2008). Comparing virtual versus real crosswell surveys. *Expanded Abstracts SEG 78th Annual International Meeting*, 1372-1375.

Schuster, G.T. (2009) *Seismic interferometry*. Cambridge University Press.

Wapenaar, K., Fokkema, J., & Snieder, R. (2005). Retrieving the Green's function in an open system by cross-correlation: A comparison of approaches (L). *J. Acoust. Soc. Am.*, **118**(5), 2783-2786.

Wapenaar, K. (2006). Green's function retrieval by cross-correlation in case of one-sided illumination. *Geophysical Research Letters*, **33**(19), L19304.1-L19304.6.

Wapenaar, K., Draganov, D., & Robertsson, J., (Eds.) (2008a). Seismic Interferometry: History and Present Status. *SEG Geophysics Reprints Series No. 26*.

Wapenaar, K., Slob, E., & Snieder, R. (2008b). Seismic and electromagnetic controlled-source interferometry in dissipative media. *Geophysical Prospecting*, **56**, 419-434.

The Dutch sector of the North Sea - A geological introduction

Ad Stolk *(Ministry of Transport, Public Works and Water Management, North Sea Directorate, ad.stolk@rws.nl)*

Cees Laban *(Deltares, cees.laban@deltares.nl)*

Abstract

The North Sea directorate of the Ministry of Public Works and the Department of Geo-Marine & Coast of TNO (Since 2008: Deltares) jointly carried out a geological mapping programme and the assessment of industrial sand deposits in the Dutch sector of the North Sea. In this article, a brief outline of the geological history and features is given.

Introduction

The Dutch part of the North Sea (NCP) is with its 57,000 km^2 larger than the mainland of The Netherlands. A wide range of users is active in this shallow shelf area with a maximum water depth of approx. 50 m in the northern part. Besides traditional activities like fishery and shipping, new activities like oil and gas exploration, and exploitation and extraction of sand also take place since the sixties of the last century. Installation of offshore windmill parks and coastal extensions in the NCP are in progress. Besides the location for these activities, the NCP is part of a valuable marine ecosystem. Therefore, these activities must have a minimal effect on the ecosystem. The morphology of the seafloor and the sediment properties are important, both for the ecosystem and for the infrastructural activities.

Subsiding basin

During millions of years the North Sea basin has mainly been subsiding in a SE-NW direction. Its present form started during the Tertiary period about 60 million years ago. From the adjacent land area this basin has been filled by rivers, glaciers and wind, with gravel, sand and clay deposits that thicken in a NW direction. The last 2.6 million years are characterised by an alternation of cold (glacial) and relatively warm (interglacial) stages. During a number of glacial stages the sea level dropped because of the growth of glaciers which during their coldest phases covered large parts of the northern hemisphere. The Dutch part of the North Sea became dry land several times and the sediments deposited in the basin were of glacial and fluvial origin. During the interglacial stages high sea levels occurred and marine conditions prevailed. The marine processes reworked the older sediments and marine sediments were deposited.

After the last glacial stage, during the start of the Holocene about 10,000 years ago, sea level rose again and a rapid transgression took place, covering the entire southern North Sea within about 4,000 years. This transgression caused changes in the existing bed forms and sediments. Nevertheless, locally the pre-Holocene morphology and sediments are still recognisable at the present sea floor. Most striking is the influence of the former glaciations on the bed forms in the northern part of the NCP. Both glacial morphological features like moraines and (fluvio)glacial melt water valleys as well as glacial sediments like boulder clay are present. In the southern part of the NCP the morphology has a more marine induced character with sand waves and linear ridges consisting of reworked fluvial sediments.

Bathymetry

The NCP is one of the shallowest parts of the North Sea. The present bathymetry (Figure 1) clearly shows the relatively shallow area between the northwest of The Netherlands and the UK. This area formed a connection between England and the continent till about 9,000 years BP. It has depths of about 30 to 40 m. The northern part of the NCP has a rather flat seafloor and depths between 30 and 50 m below sea level. Exceptions are the Dogger Bank, with a depth of 20 m, and the Cleaver Bank (30 m). The Botney Cut is a NW-SE running depression with a depth of 60 m. It lies 20 to 30 m below the surrounding seafloor. The southern part of the NCP has depths of 20 to 30 m, only in the western parts depths of 40 m are reached.

Complexes of linear ridges are formed more or less parallel to the coast. In the south, the Zeeland Ridges reach heights of more than 10 m above the surrounding sea floor. The banks have lengths of 10 km or more and are about 3 km wide. A complex of north-south oriented ridges with a low amplitude (<10 m) lies around the northwestern part of the Dutch coast. Near the central Dutch coast so called shore face connected ridges occur. A remarkable feature is the Brown Bank. This linear ridge lies rather isolated from the other complexes and has an amplitude of more than 20 m. The shallowest part is 20 m below sea level. The banks seam to be stable features, many of them are visible on century old bathymetric charts.

Connected to the tidal inlets of the southern and northern coasts of The Netherlands are ebb tidal deltas. In the north

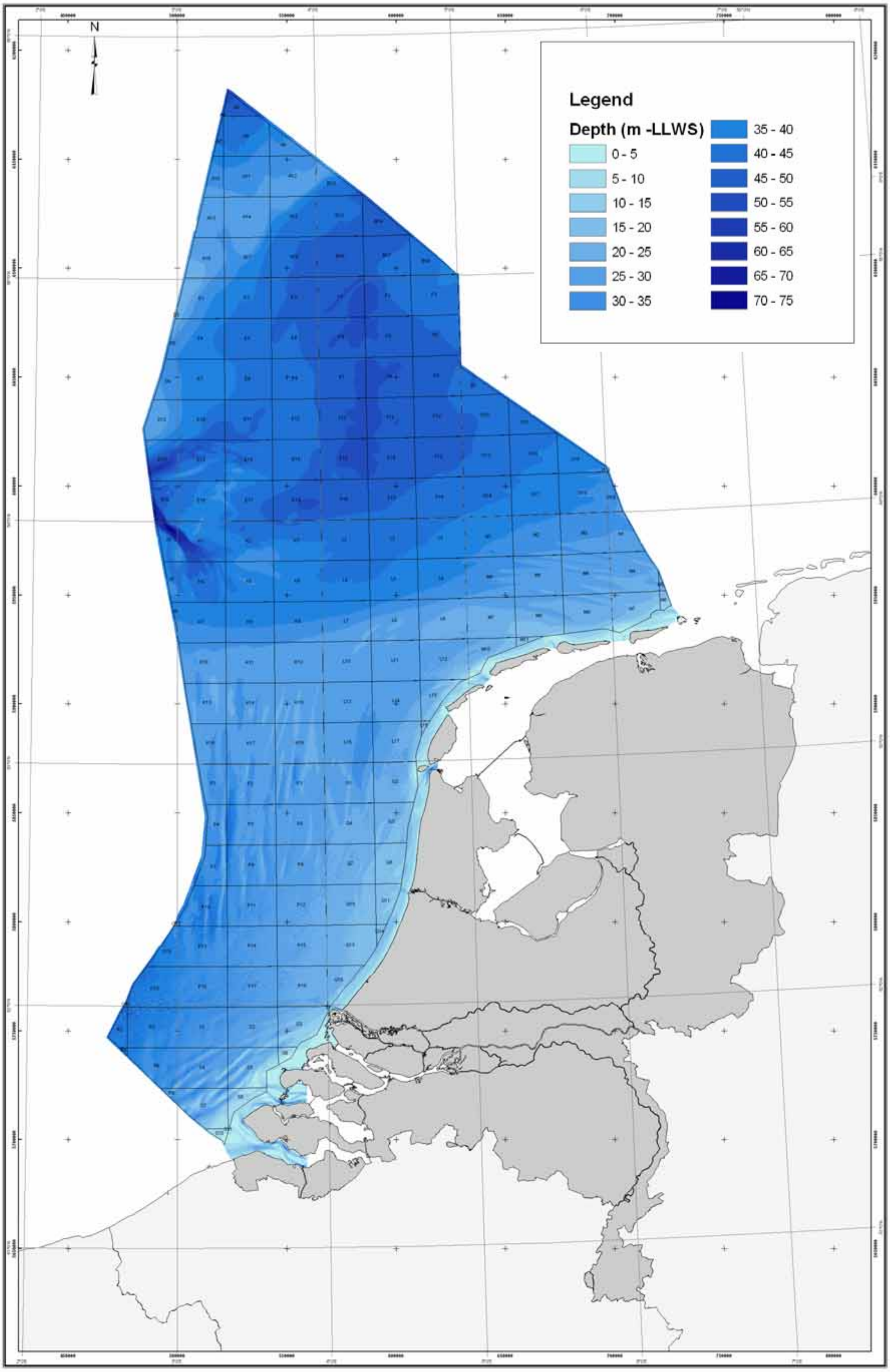


Fig. 1 Bathymetric map of the Dutch sector of the North Sea.

they have developed into isolated features between the barrier islands. Due to the small distance between the tidal inlets in the south they have merged into one large system of ebb tidal deltas. The shore face reaches to a depth of 20 m in the south and north and to 15 m in the central part of the Dutch coast.

Smaller morphological features are also present. In the south, sand waves occur from the southern border of the NCP to about 53˚ N, while isolated areas with sand waves exist north of the barrier island coast. The amplitude of the sand waves varies from 2 to 12 m, but is mainly between 4 and 6 m. Their wave length varies between 190 and 400 m. Sand waves are much more dynamic than sand banks. Although in some areas they seem to be stable, in other areas they migrate or vary in height with the seasons.

Surficial sediments

The sea floor of the NCP consists mainly of fine to median sand. Locally small gravelly areas occur in the northern part. In the central northern part, silt and clay is deposited. In general, the grain size of the surficial sands decreases from south to north. In the south, median sand with mean grain sizes between 250 and 500 μm dominates. More to the north, fine sand (125-250 μm) or even very fine sand (63-125 μm) occurs. In the areas with very fine sand, the silt and clay content is rather high (Figure 3). Gravel deposits are found in places were glacial features like moraines are near or at sea bed. The Cleaver Bank is the only area on the NCP with a vast amount of gravel and cobbles. Locally, gravel is found at the so called Vlieland Rough northwest of the island of Texel. Marine sands of the NCP are of good quality for coastal nourishment and landfill. There is enough marine sand to fulfil the needs for these purposes for decades or even centuries. More problematic is the use of marine sand for construction. For the manufacturing of concrete, coarser and less sorted sand is needed. These sands, mixed with gravel, are present at the surface near the Cleaver Bank. In the southern part of the NCP they are present in former fluvial deltas at a depth of 5 tot 10 m below the sea floor.

Special phenomena

Some areas on the NCP are special regarding their depth, morphology, and composition of the sediments. Other areas are of interest because of geological features below the sea floor. Areas can be of special interest for the ecological habitat formed by the morphology and the sediments, or for the geological features itself. For both an example will be given below. Furthermore, an example is given of the need to understand the geological structure of the sea bed for activities on the NCP.

Cleaver Bank

The Cleaver Bank is located at a distance of 160 km NW of the Dutch coast, near the median line with the British part of the North Sea, and has water depths between 30 and 40 m. It is a glacial moraine built from boulder clay with a cap of sand and gravel. Also coarser material as cobbles and stones are found at the sea floor south of this bank. Due to these coarse sediments the benthic fauna has a special character compared with the fauna at the NCP in general. Therefore it has a high ecological value. On the other hand it is one of the few areas on the NCP where sand for the concrete industry is found. A geological investigation on the amount and distribution of the useful layer of sand and gravel is the basis for the policy decision on extraction.

Natural heritage in the sea bed

Some features have an intrinsic geological or geomorphological value. They are a good example of a form produced by a specific geological process or are important as part of the geological archive in the sub bottom. These kinds of features are found on the NCP as visual elevations or depressions or as geological layers in boreholes or seismic profiles. A nice example is the occurrence of a pock mark due to the escape of gas from older gas containing layers in the sub bottom (Figure 2) in the northern part of the NCP.

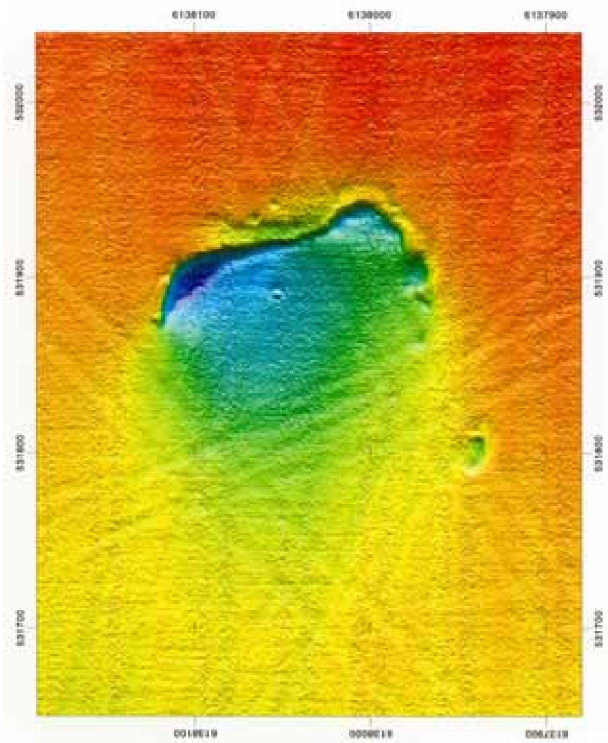


Fig. 2 Multibeam image of a pock mark in block A11 in the Dutch sector, with a diameter of about 150 m. The wall of sediment left behind after the explosion is still partly visible. Trawling scars have destroyed the pockmark partly.

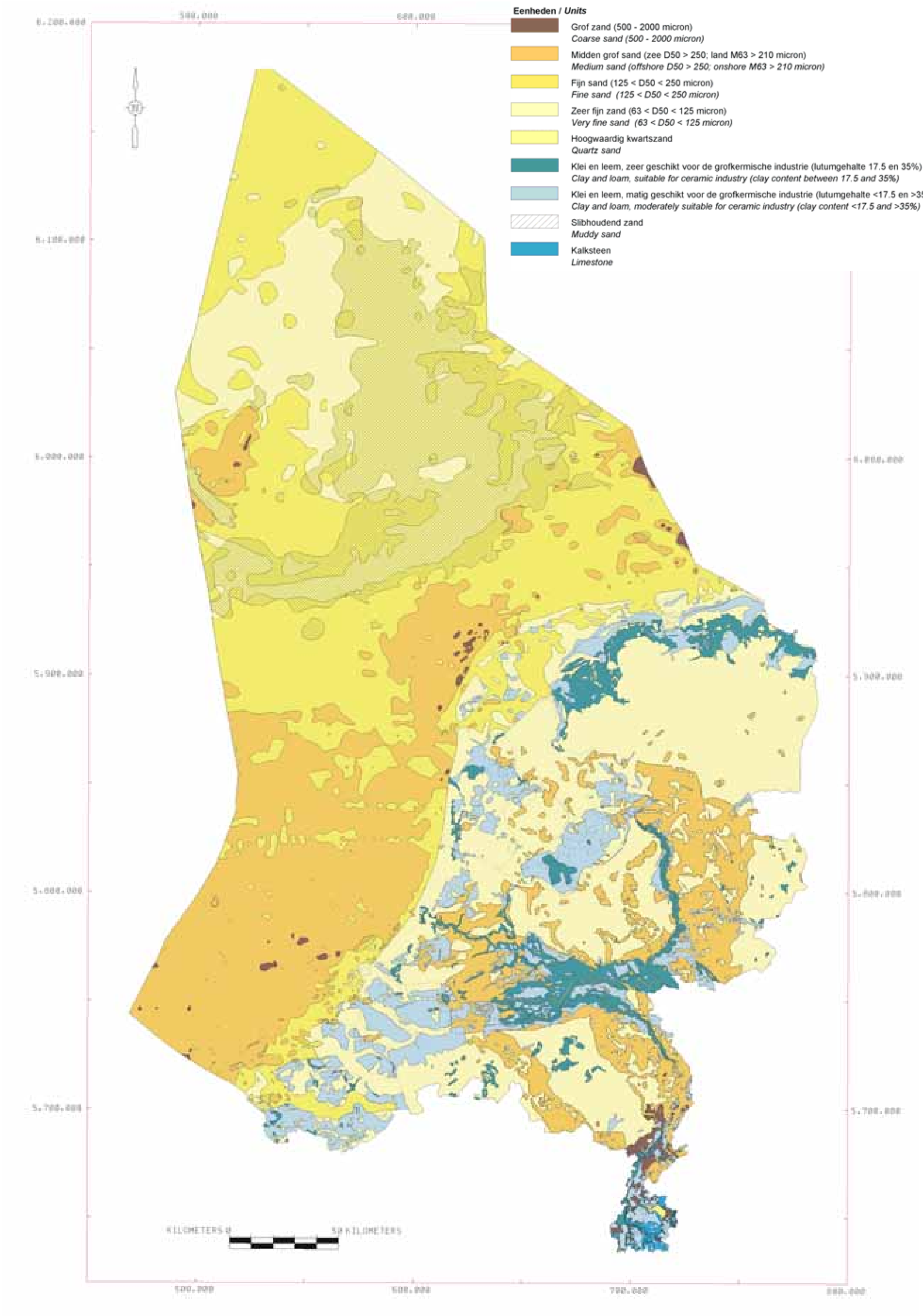


Fig. 3 Surficial sediments onshore and in the Dutch sector of the North Sea.

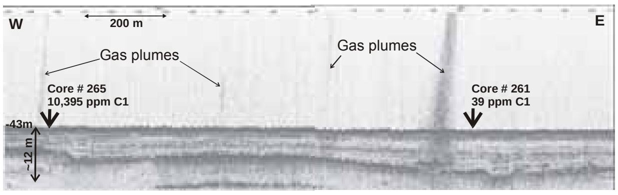


Fig. 4 Gas seeps in block B13 of the Dutch sector. Cores taken near the plumes revealed anomalies of 39 vppm CH_4 at a depth of 3.5 m below sea bed.

Some tens of miles east of the pockmark location, gas seeps have been detected with high resolution seismic records at a water depth of 43 m, and with plumes reaching as high as the sea surface (Figure 4).

Tidal channels

Below the sea floor off the central coast of The Netherlands, relicts of a former barrier island coastline are present. Tidal channels have been mapped, using seismic profiles (Figure 5). These channels are filled with fine sand with a high silt content. Along the Dutch coast several activities are foreseen for the near future, e.g. the construction of an airport island or the construction of offshore wind farms. For the extraction of large amounts of sand for an island, the location of these gullies is of importance. A too high silt content is not desirable from an ecological point of view. This gives rise to high turbidity during sand extraction. For the construction of wind farms the location of the gullies is important because of the stability of the foundation.

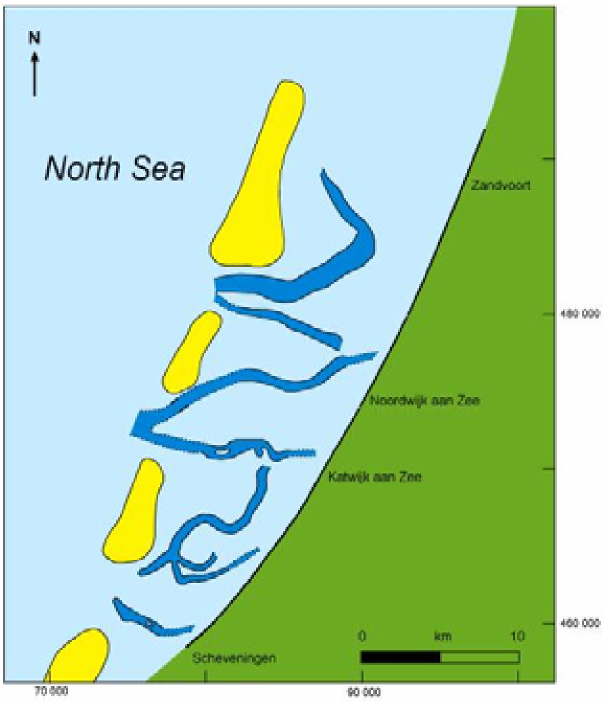


Fig. 5 The pattern of offshore Holocene tidal channels mapped with high resolution seismics west of the coast of South Holland.

Availability of data

Information about the data collected as digital maps, bathymetry, and core and borehole information is available at the websites www.tno.nl, www.eu-seased.net and www.noordzeeloket.nl.

EM-SLIMFLEX

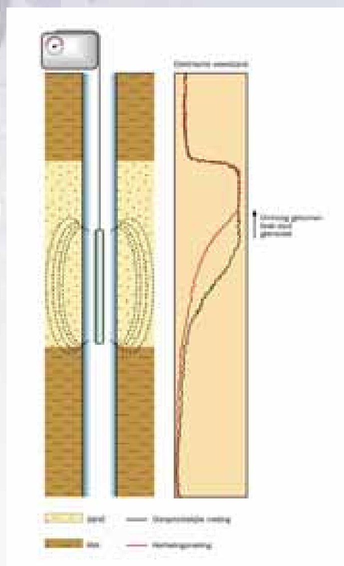
Een nieuwe toepassing voor opsporing van zoet, brak en zout grondwater

Kennisinstituut Deltares heeft plannen gemaakt voor het bouwen van een ultradunne flexibele boorgat tool welke zelfs in de dunste (éénduims) waterpeilbuizen past. Met een dergelijke boorgatmeting moet ook in deze peilbuizen continue informatie over grondwaterkwaliteit worden verkregen. Deltares is op zoek naar medefinanciers voor het bouwen, testen en valideren van deze nieuwe meetttool. Grondwaterontrekkende instanties krijgen hierdoor de mogelijkheid om voor een gereduceerd tarief meer continue temporele informatie over grondwaterkwaliteit te verkrijgen.

De Kaderrichtlijn Water schrijft voor dat veranderingen in stromingsrichting van grondwater veroorzaakt door menselijk ingrijpen, zoals grondwateronttrekkingen, niet mogen leiden tot zoutwaterintrusie. De kennisbehoefte aan de ligging van zoet-brak-zout water overgangen in het grondwater zal hierdoor de komende jaren meer aandacht vereisen. Dit houdt in dat de behoefte aan herhaalde metingen in grondwaterontrekkingsgebieden de komende jaren een belangrijk onderdeel zal moeten uitmaken van de meetstrategie van grondwaterontrekkers. Al tientallen jaren worden in Nederland diverse boorgatmetingen uitgevoerd om de overgangen tussen zoet en brak en zout en brak in het grondwater te bepalen. Naast bestaande boorgatmetingen, zoals geofysische metingen in en om gaten met grote diameter en chloride-analyses in dunnere peilbuizen, is meer continue informatie over grondwaterkwaliteit gewenst.

Reeds beproefde metingen – zoals de bekende 'zoutwachterkabel', die al bij plaatsing van de peilbuis moet zijn geïnstalleerd en op een beperkt aantal punten meet – zijn volgens Deltares voor verbetering vatbaar op vooral kostenefficiëntie en praktische toepassing. Hier ligt aan ten grondslag dat continue metingen in de diepte op zo veel mogelijk locaties op elk gewenst tijdstip moeten kunnen plaatsvinden. Het doel van het EM-SLIMFLEX project is om de mogelijkheid te creëren om ook continue informatie over zoet-brak-zoutovergangen te meten door het regelmatig uitvoeren van elektromagnetische boorgatmetingen in deze bestaande pvc peilbuizen. Dat is nu nog niet mogelijk, omdat de meeste peilbuizen te dun zijn voor alle bestaande meetapparatuur. In totaal zijn er in Nederland namelijk ongeveer 1350 potentiële meetpunten waarin ook continue informatie over de zoet-brak-zoutovergangen in het grondwater in kaart kunnen worden gebracht. Een kwart hiervan ligt in drinkwaterbeschermingsgebieden. Deze punten worden nu slechts bemeten door het oppompen van watermonsters uit beperkte dieptetrajecten en in zeer beperkte mate door het gebruik van permanente meetkabels.

Contact:
Rogier Westerhoff (rogier.westerhoff@deltares.nl, 030-2564862)
Rein van Schrojenstein-Lantman (rein.lantman@deltares.nl, 030-2564888)



Schematische weergave van een elektromagnetische boorgatmeting op herhaling in een peilbuis met pvc wand.

Solving geophysical problems

Guido Spanjaard *(Junior advisor Geophysics, Grontmij Geogroep, guido.spanjaard@grontmij.nl)*

Mara van Eck van der Sluijs *(Project leader Geophysics, Grontmij Geogroep)*

Abstract

Grontmij offers the expertise and techniques to solve virtually all geophysical problems. Geophysics minimises the risk of damage to subsurface objects and provides the input to anticipate on otherwise unforeseen subsurface problems. The used techniques are fast, efficient, cause minimal disturbance to daily routine and are non-destructive.

Introduction

Grontmij N.V., established in 1915, is one of the larger multidisciplinary consultancy and engineering firms in northwest Europe. More than 8,000 professionals in 140 offices are active in managing and solving socially relevant issues in a sustainable manner. Grontmij has a decentralised organization and an extensive network with offices in Belgium, Denmark, Germany, Hungary, Ireland, The Netherlands, Poland, Sweden and the United Kingdom. Grontmij also carries out work in Central and Eastern Europe, and on donor-financed projects all over the world. We distinguish ourselves through our regional approach. Each office provides the customer with a broad range of disciplines across the entire project chain.

Grontmij's department of geophysics consists of a dedicated team of professionals with in-house experience in geophysics, geodetics and GIS. We offer an integrated approach to our clients' problems. Our contribution ranges from advice in project planning to execution of the project and presentation of the results.

Since every engineering project is unique, all geophysical research is tailored to our clients' specific requests. Grontmij has the expertise to design and execute efficient geophysical research projects with excellent results. Our personnel, experienced in data collection and interpretation, delivers excellent results by using advanced equipment, thereby providing a clear insight in the invisible subsurface.

Techniques

Because the subsurface is the basis for nearly every engineering project, geophysics has a wide range of applications. Different techniques have been developed for different objectives. What these techniques have in common is that they provide information on subsurface structures and composition in a non-destructive way.

Grontmij offers expertise in a wide range of geophysical techniques, including:

- Ground penetrating radar
- Tracer
- Electromagnetic meter
- Radiodetection
- Resistivity measurements

These techniques are discussed below in more detail.

Ground Penetrating Radar (GPR)

GPR is a commonly used technique for shallow subsurface research. The equipment consists of one or more transmitters and receivers (antennas). The transmitter produces electromagnetic pulses. These pulses are propagated into the subsurface in a conical geometry. When the pulse reaches a boundary between two materials with different electromag-

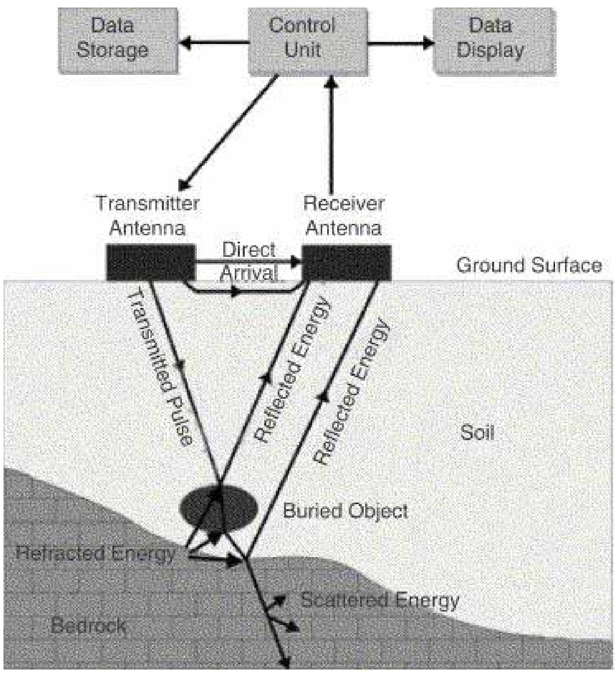


Fig.1 Schematic representation of GPR data-acquisition.

netic characteristics, part of the pulse's energy is reflected. This reflected energy is received by the GPR's receiver.

As the GPR is moved over the surface, pulses are transmitted at regular intervals (either time intervals or distance intervals). The received reflections are projected with travelled distance on the x-axis and depth (two-way travel time of the reflected energy in ms) on the y-axis. This creates a continuous image (radargram) of the subsurface.

Subsurface objects are presented as hyperbolas in the radargram. As the radar is moved towards a subsurface object, the distance between the GPR antenna and the object decreases to a minimum (depth of the object when the GPR antenna is directly above the object). When the radar has passed the object, this distance increases.

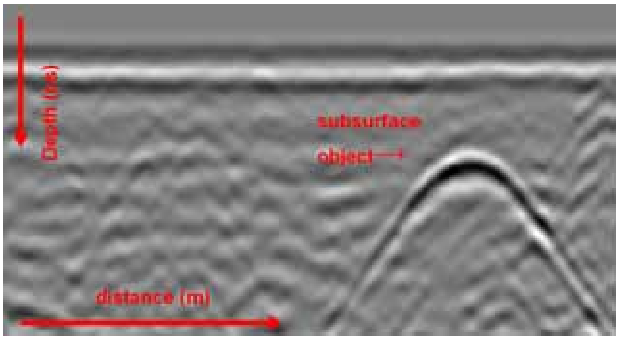


Fig. 2 Radargram showing the hyperbola-shaped reflection caused by a subsurface object.

The depth of the object equals half the two-way travel time (at the top of the hyperbola) multiplied by the propagation velocity of the subsurface medium. The width of the top of the hyperbola is an indication of the object's diameter.

When the radar is moved parallel to an elongated object, this object will be projected as a horizontal line in the data. This is also the case for large objects and geological layers/ groundwater. There are many applications for GPR. These range from the detection of cables and pipes, archaeological prospecting, subsurface pollution, concrete rebar detection, and asphalt quality and thickness research. Different antennas are available for these different applications. The main variable of these antennas is the frequency of the transmitted pulse. A higher frequency produces data with a higher resolution, but has a smaller depth penetration due to its lower energy. Low frequency antennas have a better depth penetration but a lower resolution. For every research project, the most suitable frequency is chosen based on research objective and subsurface specifics. Grontmij uses antennas with frequencies ranging between 100 MHz and 2.6 GHz.

The depth penetration of the radar signal is dependant on subsurface medium. For example, a 400 MHz antenna has a typical depth penetration of 2-3 m in sandy soils, but this decreases to 0.5-1 m for clay. This is mainly due to water content and the type of layering, which absorbs the transmitted energy.

Tracer

The tracer technique is based on the Earth's natural electromagnetic potential field. Subsurface objects cause local disturbances of this field, which are detected by the tracer's receiver (the tracer does not have a transmitter). The disturbances need to be filtered from the natural background values, which complicates data interpretation in the field. The tracer receiver is an antenna, comparable to a GPR receiver antenna, which is dragged or pushed over the surface. Usually, the tracer is used in combination with GPR. Tracer measurements are independent of subsurface medium. The data does not give an indication of depth or diameter of the subsurface objects.

Radiodetection

Radiodetection is a technique that detects electromagnetic fields around metal conductors (e.g. cables and pipes). These fields can be either natural (passive radiodetection) or induced by a transducer (active radiodetection). When active detection is used, individual objects can be identified. Passive detection only detects objects, identification is not possible. The use of radiodetection is limited to metal conductors. It is independent of subsurface medium. In Figure 3, an illustration of the principles of this technique is shown.

Electromagnetic meter (EM-meter)

The EM-meter uses 2 large coils to induce a magnetic field. This magnetic field generates an electrical field in the subsurface, which then generates a subsurface magnetic field. The secondary (subsurface) magnetic field, characterised by

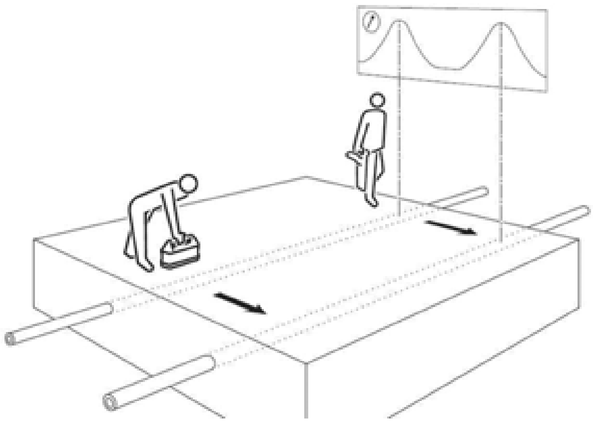


Fig. 3 Radiodetection measurements (source: www.radiodetection.com).

wavelength and frequency, is received by the antennas of the EM-meter. EM measurements are suitable for the detection of metal objects and large-scale subsurface structures (e.g. geology). The accuracy of this technique is lower than that of the techniques mentioned above.

Magnetometer/gradiometer

A magnetometer detects disturbances in the Earth's magnetic field, caused by magnetic objects. The magnetometer consists of two receivers at a constant distance. The magnetic disturbance caused by the object decreases quadratic with distance while the change in Earth's magnetic field is negligible. By using this method, the disturbance caused by the object is filtered out. Magnetometers are most commonly used to detect metal objects, e.g. tanks, pipelines, and archaeological remains. It can also be used to detect non-metal objects that cause local disturbances of the Earth's magnetic field, e.g. bricks. The magnetometer is also used underwater. It can be used to detect underwater pipelines, shipwrecks, anchors, etc. A gradiometer consists of several magnetometers. It measures the gradient of the changes in magnetic field. Gradiometers can give a good indication of size and depth of subsurface objects.

Resistivity

Resistivity measurements can be used to detect the presence of materials with different specific electrical resistivity. Every material has its own specific resistivity. The resistivity of wet sand for example, is lower than that of dry sand. This technique is used to detect differences in the composition of the subsurface, e.g. geological layering and groundwater table. For the measurements, electrodes are placed in the ground. The electrodes transmit and receive an electrical current whereby the resistivity is measured. The distance between the electrodes determines the depth of the measurements. Processing of the measured resistivity data results in a profile displaying specific resistivity versus depth. This technique is time-consuming and only suitable for the detection of objects that are quite large compared to the objects detected by e.g. GPR technique.

Fig. 4 EM-meter and GPS-receiver.

Applications

Grontmij is experienced in the use of all techniques mentioned above in a wide range of applications. These include:

- Detection of cables and pipes
- Detection of archaeological remains
- Detection of foundations
- Detection of rebar in concrete
- Detection of cracks and voids (in concrete, ceramics and in the ground)
- Asphalt thickness and quality measurements
- Detection of groundwater pollution
- Shallow geology
- Water bottom research

The GPR technique is used most commonly. This technique is widely applicable for the detection of all kinds of objects and structures. The GPR technique is user-friendly and efficient. Below, some of Grontmij's geophysical research projects are briefly discussed.

Grontmij geophysical projects

Industrial foundations Europoort

In Europoort, a chemical plant has been dismantled and the new owner of the terrain is interested in the remaining subsurface elements, mainly foundations. The area covers 15,000 m^2 and the terrain is rough and muddy. Grontmij has dragged a 200 MHz GPR antenna connected to a GPS receiver over this terrain (see Figure 5). The depth penetration of the 200 MHz antenna was approximately 4 m at this location. Measurements were made in perpendicular grid lines to detect objects oriented in all directions. The processed data showed foundation remains in several locations and a number of cables and pipes still present in the subsurface. This information is important input for planning of the development of this terrain.

EM research Hollandsche IJssel

The 'Hoogheemraadschap De Stichtse Rijnlanden', the organization responsible for the safety of the dikes along the Hollandsche IJssel, has asked Grontmij to identify geological structures below these dikes. The geological structures might have a negative influence on the stability of the dikes. In this project, the non-destructive nature of geophysical techniques is important, because any physical damage to the dikes will influence their strength. Grontmij used EM measurements to locate the geological structures. Due to a difference in electrical resistivity, geological structures like sand bodies could be identified. The EM results were used to minimise the number of required corings and other destructive techniques, required for further research into dike stability.

Mapping underground infrastructure using GPR

Grontmij has been requested to locate all cables and pipes at the terrain of a telematics service company in Rotterdam. Measurements were made in a perpendicular grid, to a depth of approximately 2 m below surface. For these measurements, a 400 MHz GPR antenna was used. All cables and pipes were detected and identified. Identification was based on surface elements of the cables and pipes (e.g. lampposts etc.), object diameter, depth, and radar signal. The result was a digital drawing indicating all cables and pipes within the local topography (see Figure 6).

Fig. 5 200 MHz GPR antenna (orange box), with GPS receiver mounted on top, measuring at the Europoort site.

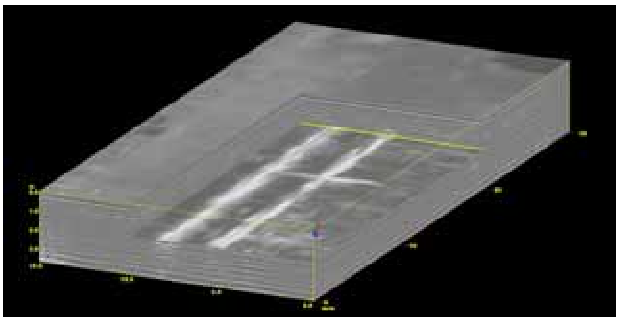


Fig. 6 3D image of the processed GPR data showing several pipes at a certain depth.

Integration of various geophysical and geotechnical techniques at the A2 tunnel project (Maastricht)

Bjorn Vink *(Consultant geohydrology/geotechnics, Grontmij Roermond)*

Introduction

This article provides an overview of the geological-, geotechnical-, and geophysical surveys that were performed in order to map limestone in the project area of the A2 highway near Maastricht. The A2 divides neighbourhoods in the eastern part of Maastricht. Local traffic is causing congestions on the highway and directly connected main roads in Maastricht. The area around the A2 will be reconstructed to re-establish the connection between the neighbourhoods.

At this stage, there are three different plans concerning the construction of a tunnel and reconstruction of the adjacent neighbourhoods. The competitor with the best overall plan within the financial restrictions will be selected to perform the make-over of this area. This choice will be made on July 1, 2009 by the responsible politician who represents the stakeholders. Selection of the contractor takes place with advice of the GAC, an independent commission of experts.

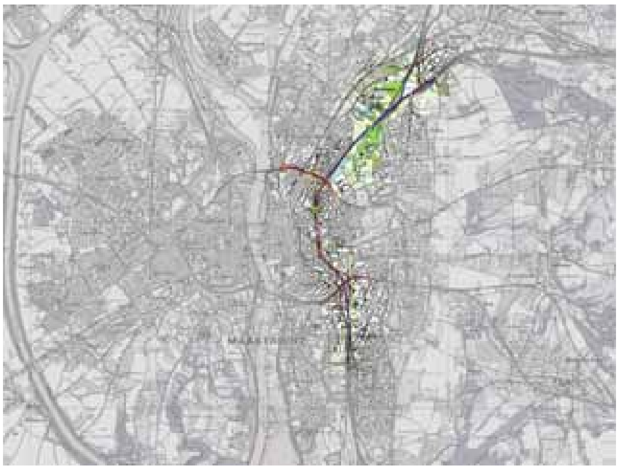


Fig. 1 Topographical map of Maastricht with A2 tunnel project area highlighted.

Geography and geology of Maastricht

The tunnel will be constructed in the eastern part of the city, approximately on the axis of the A2 highway (see Figure 1). Some decades ago this area was part of a spillway of the river Meuse and flooded during extreme water levels. The surplus of water surged through this former abandoned meander. The ponds just to the north of the Geusselt are relicts of this meander. The project area is situated in the lowest Meuse Terrace.

Maastricht forms part of the southern section of the Campina Basin and lies just east of the Brabant Massif and just north of the Viseanien High. Marine deposits from the youngest Cretaceous period (Maastrichtian) can be spotted in this area along the slopes of the Meuse valley. Below follows a general description of the geology in the project area:

- From surface level (+47.5 m NAP) to +44~41 m NAP: anthropogenic materials and building remnants overtopping a layer of river clay with gravel and sand
- From +44~41 m NAP to +37~35 m NAP: coarse gravel with cobbles and boulders, some of which have a diameter larger than 0.5 m at the base of these Pleistocene river deposits
- From +37~35 m NAP: limestone, upper part of marine deposits from the Maastrichtian. A residue of flint banks can lie just below the weathered top of the limestone
- From +37~35 m NAP to -40 m NAP: compressed layers of clayey and fine sandstone material
- From -40 m NAP to -65 m NAP: limestone with shales and probably layers of sandstone with dolines, upper part of Visean (Carboniferous)

Description of proposed construction methods

The proposal of the first consortium (BA2M) consists of a tunnel with two floors. The most challenging aspect of the construction of a tunnel is to conquer the complex geological situation. To prevent problems during the installation of sheet piles, BA2M will first remove gravel containing quartzite cobbles and boulders and underlying flint layers from the limestone by applying auger drillings. A mix of sand or very fine gravel will be used as a substitution for the removed material. Like the drilling method, the choice of the grain size distribution of this mix will be based on field tests.

Another consortium, Avenue 2, is also proposing a two floor construction with the same 2 x 2 x 2 traffic system. Avenue 2 applies a cement bentonite slot combined with sheet piles. To prevent the construction from floating, two ear-like construction elements will form part of the lower floor of the tunnel.

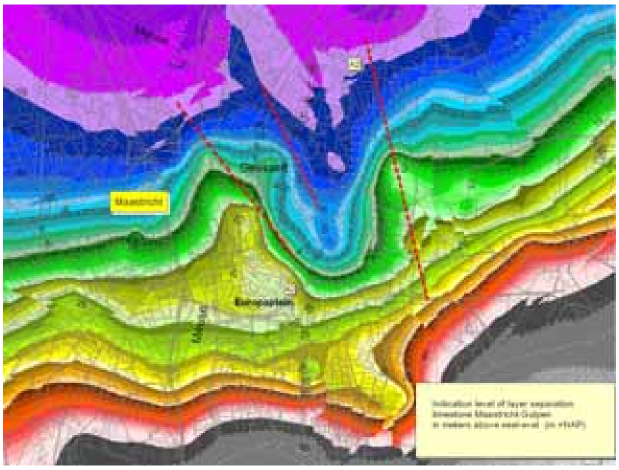


Fig. 2 Fault lines and top of Gulpen Formation, based on boreholes.

The third consortium, Unie van Maastricht, has proposed to construct a one floor tunnel with a 2 x 3 traffic system. Unie van Maastricht proposes to apply a bentonite slot with an armed under water concrete floor. Like BA2M this floor will be attached to piles that reach into the limestone, to prevent the tunnel from floating.

Site investigation program

Since 2005, Projectbureau A2 has conducted a few geological and geotechnical surveys. Starting point was the information gained from DINO together with some reports from studies performed in Maastricht. The first geological study along the A2 was conducted in 2005. Werner Felder made a geological stratification based on samples from 6 boreholes drilled by Heldens Horst using a sonic drilling technique to depths of 18 and 30 m. Piet van Rooyen combined these descriptions with the results from older boreholes into an initial geological profile. It became clear that at least one fault zone crossed the tunnel nearby the Voltastraat. A second fault zone crosses the A2 probably just north of the tunnel.

These initial findings were used to plan a more detailed geological and geotechnical study. The main objective was to provide the consortiums with enough information to base their business case and underlying construction methods on. The following site investigation program was carried out during 2007:

- 9 cored boreholes (ø100 mm) to approximately 30 m depth (Smet/Fugro)
- Lugeon tests (a lugeon test gives information about the primary horizontal conductivity in a 1 m section of limestone) at different levels in the limestone (Smet/Fugro)
- Visual logging of limestone (EGS)
- Description of limestone stratification (John Jagt/Paul Kisters)
- Various laboratory strength tests (TU Delft)
- 10 soundings in the limestone to the north of the Voltastraat (Lankelma)

Deltares was involved as overall advisor and quality controller in all these studies. In Figure 3, some combined results from the 2007 soil investigation program are shown.

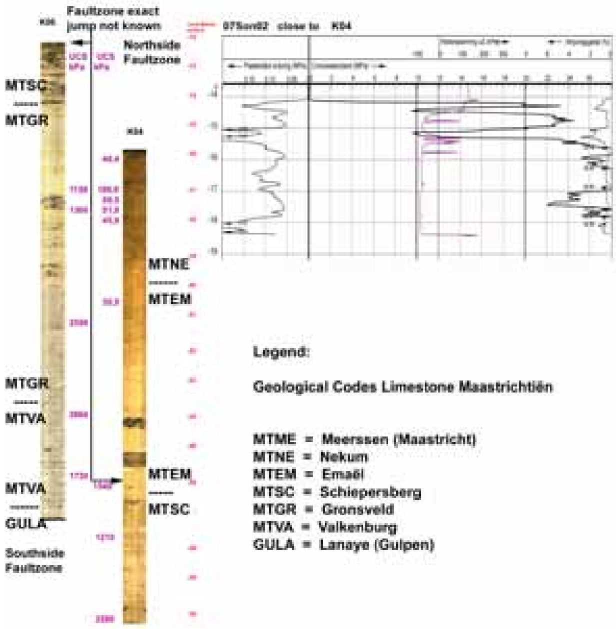


Fig. 3 Combined results of 2007 site investigation program.

Pilot study: geophysical survey methods

Objective

The objective of the pilot study was to find a suitable geophysical survey method or combination of methods in order to reduce the amount of unexpected geotechnical risks. A geotechnical risk could e.g. be whether the limestone is strong enough to act as a horizontal strut. It would be an outcome to be able to detect weaker parts of the limestone in these circumstances with a geophysical method. The expectation is that seismic velocity can give an indication of the location of weakened zones and indirectly point to more permeable zones in the limestone.

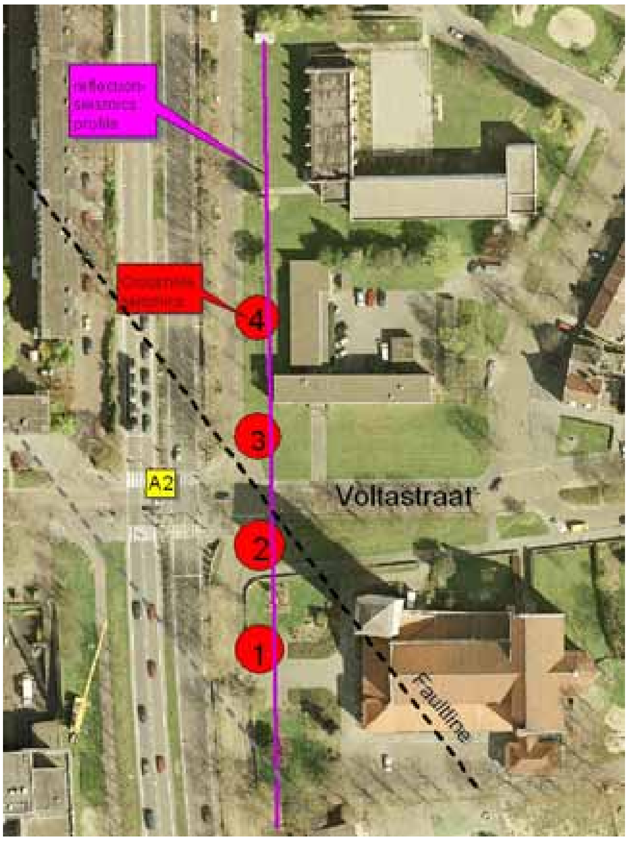


Fig. 4 Detailed site map.

A few questions that were asked in the search for an appropriate technique were:

- Which technique or combination is most suitable to detect the different separations between clay, gravel and limestone, as well as the major flint layers situated in the limestone?
- Can this technique supply a reliable and continuous image of relatively shallow layers?
- Can the P-wave velocity be correlated with results from pressiometer tests in these layers and with TU Delft laboratory results?
- Is it possible to detect thick silex layers with reflection seismics?

Another objective was that Projectbureau A2 also wanted to obtain a more detailed profile along the fault zone near the Voltastraat. The most suitable geophysical method could be applied by the selected consortium, whereby the method will partly depend on the chosen construction method and on the results of this pilot study.

Performed surveys

First, a combination of refraction and reflection seismics was performed along a 210 m profile, data acquisition was done by DMT. Different sources were tested: an accelerated drop weight, a hammer, and airwave pressure to obtain higher resolutions. The site was situated at only 20 m from the highway A2 with its high traffic intensity. To reduce background noise caused by traffic, measurements were carried out during weekend nights. A nearby traffic light on the highway was very helpful and gave a window of 30 seconds to carry out at least 4 shots which could be stacked to obtain a higher signal/noise ratio. Bad signals were rejected to minimise their influence on the results.

G-tec combined refraction seismics with the results of cross-hole seismics. For the reason mentioned above, this survey was also carried out during nighttimes and in the weekend. More or less the same measurements were taken to acquire a good signal/noise ratio. 4 boreholes were drilled (using sonic drilling) close to the Voltastraat on nearly the same profile as used for the reflection seismic survey. The boreholes were drilled to depths between 40 and 49 m and with a spacing of 30 m. The configuration of the 4 boreholes will give an optimal seismic profile of 2 x 15 m + 3 x 30 m = 120 m.

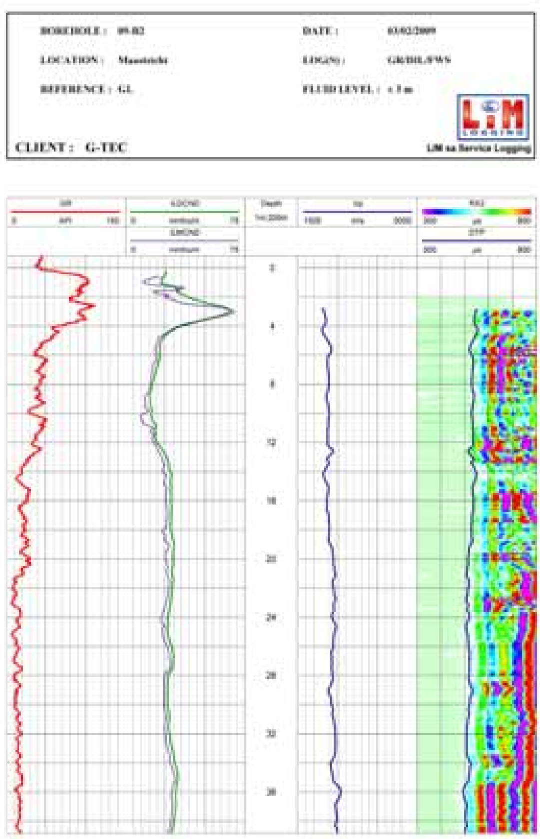


Fig. 5 Results from logging of borehole 2 (without geological interpretation).

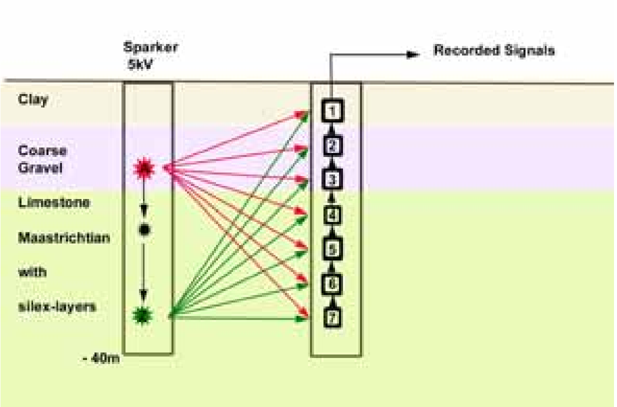


Fig. 6 Principle of crosshole seismics.

Crosshole seismics

The principle of crosshole seismics is illustrated in Figure 6. A 5 kV sparker induces a shock wave through the water column inside the borehole, whereby the source is lowered in the borehole to different levels. In two adjacent boreholes, a string of geophones at different depths will receive data. The image above shows some of the measured paths through the limestone.

In order to obtain accurate results from crosshole seismics, borehole deviation measurements were performed by EGS. Processed crosshole measurements need to be corrected in case boreholes are not perpendicular. EGS also performed gamma ray-, conductivity-, and seismic ray logging.

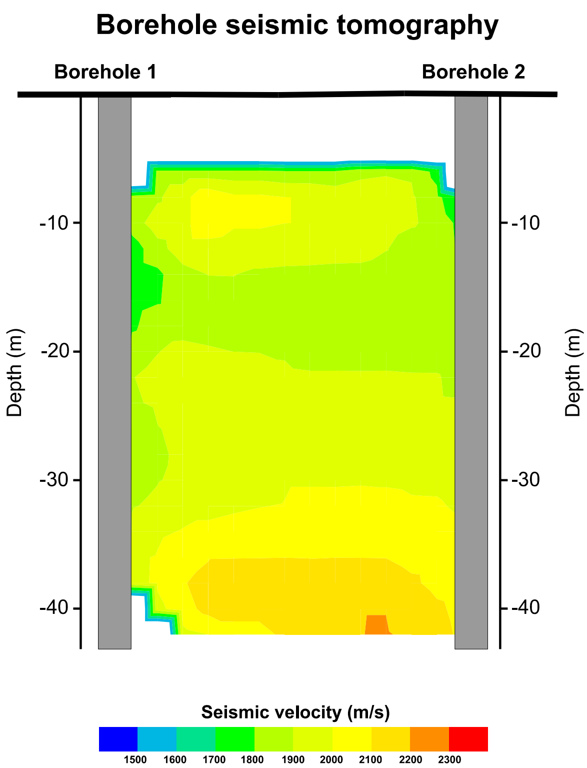


Fig. 7 Preliminary results from crosshole seismics between boreholes 1 and 2.

Results from the 4 used boreholes will be interpreted and combined with results from the seismic surveys. Processing and interpretation was still ongoing at the time of writing of this article and hence, the results will not be discussed here.

Further study

There are more questions related to probable causes of the lack of strength of the different limestone layers in some parts of the tunnel area. This forms part of further study in which all the available research from the past will be combined with the upcoming results from the geophysical pilot study. Conclusions about which geophysical techniques are most suitable can't be drawn at this moment. More detailed information about the A2 project can be found at www.a2maastricht.nl.

'Geophysiotechnics' in the harbour of Gothenburg: a most beautiful geophysical profile

P.M. Maurenbrecher, R. Stevens & B.T.A.J. Degen

March 4th, 1998: early spring in Gothenburg (Sweden) saw a number of researchers surveying part of the estuary of the river Göta (see Figure 1) on board of an ungainly service vessel of the harbour authorities. The vessel was a self propelled crane barge used to service marker buoys, that are used to guide ships from and into Gothenburg harbour along safe shipping channels. There was very little space on the bridge: normally used for navigating the crane ship, it now managed to squeeze in the geophysical equipment consisting of reflection seismics equipment (Chirp sub-bottom profiler), an echosounder and GPS. Sheltered spaces were few: the bridge, a container on the foredeck which scooped up the cold northern air, and a small ships lounge below decks. The survey was carried out as part of the European Commission financed research project H-SENSE (**H**arbours-**S**ilting and **En**vironmental **Se**dimentology), involving locally the University of Gothenburg, the harbour authority, and the Swedish Geotechnical Institute. Other participants involved were The University of Bergen, Technical High School Sondhal (both from Norway), the Latvia Geological Survey, and Imperial College (section Engineering Geology) (later substituted by Nottingham Trent University (section Engineering Geology) because Dr. Mike Rosenbaum took up a professorship at Nottingham Trent).

In 2 of the study areas in the harbours of Bergen and Gothenburg, geophysical profiling was carried out by TU Delft, using equipment from Ben Degen and with the assistance of Taco Wever. Taco was a final year Engineering Geology student from Delft and was seconded to Ben to help operating the equipment and with the processing afterwards in Delft and The Hague (see Wever, 1999). The principal objectives were to study the sedimentation morphology of contaminated sediments in harbour environments and to relate distribution patterns of the sediments with natural and man-induced processes such as sediment supply, currents, waves, storms, and vessel movements. The Chirp sub-bottom profiler that was used on the H-SENSE project consisted of a tow fish (4-24 kHz) made by EdgeTech, which was used in the range of 4 to 16 kHz to map the most recent, usually contaminated, top layer in the harbour and estuaries of Bergen and Gothenburg.

In February and March 1998, surveys were carried out which covered the harbour areas of Bergen and Gothenburg. Both surveys succeeded in not only mapping the top sediments but also in obtaining profiles at Bergen in water depths exceeding 300 m despite the signal return period exceeding the transmission periods. The survey of sediments in the Gothenburg harbour area did not show much variation as changes in profile came and went gradually. Once in the estuary of the Göta river amongst the granite islets consisting of hard glaciated bare rock, the soft sediment interface showed many rises and falls and a full profile up to 30 m below sea bed. Despite the high frequency range of the Chirp (4-16 kHz), the equipment achieved a relatively deep penetration. The profiles showed the need for the crane barge as a buoy servicing vessel, as shallow and hard granite sea mounts showing up beneath the water level could pose a serious hazard to a wayward ship led off-course by a malfunctioning or missing buoy.

I had just left the relatively warm lounge below decks and scaled 2 flights of stairs to look at the islets and at the same time at the screen of the Chirp equipment. This showed a geological profile of layered sediments, extending to 30 m depth, having incised valleys/channels which in turn were filled with layered sediments. Preserved in these sediments was an old slide at the top of one of the (infilled) channels.

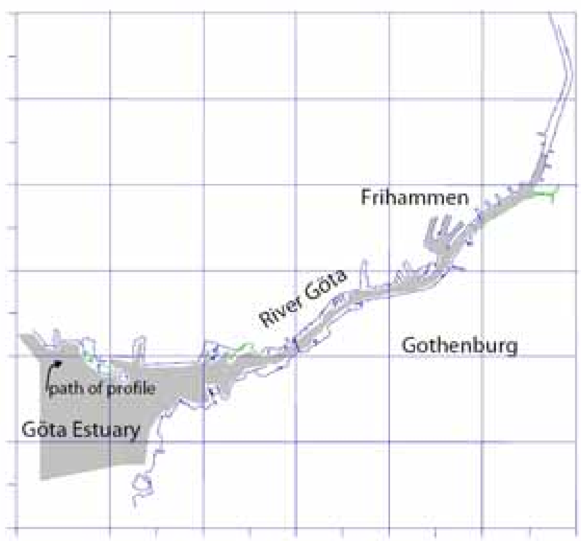


Fig. 1 Gothenburg Harbour and Göta Estuary, showing extent of survey (grey area).

My first reaction was not of elation but more of disbelief and I assumed Ben Degen (who had turned 50 that day) was having a bit of a party by showing a demo file from a built-in collection of profiles from the manufacturers to show off their equipment. "No", Ben grumbled, "this was the genuine image". The image in Figure 2 has since indeed become an image on the EdgeTech website (www.edgetech.com/subbottom.html) as an example what their small auv's can achieve!

Dr. Rodney Stevens from the geology department at the University of Gothenburg and head of the project carried out a dating analysis of the profile. I was curious to know if some significant event such as the Storegga slide off the coast of Norway (this slide had the size of The Netherlands, see Figure 3) may have triggered local sliding in the (at that time) tidal channels of the estuary. This slide is believed to have caused a significant tsunami about 8,000 years ago leaving in places raised beaches along the coasts of Norway and Scotland. The Storegga tsunami could have caused a rapid draw down condition (the same as occurred 2 years ago along the resorts in Thailand) in the tidal channels in the Göta estuary. There was even some discussion that shell debris layers found in a channel of the ancient river IJ during excavations for the Wijkertunnel beneath the North Sea Canal (the estuary of the IJ at about 8,000 years ago faced a northerly direction in-line of an oncoming tsunami from Storegga) were also derived from this event (Hartog, 1995). See Figure 3 for the location of the Storegga slide and other Norwegian submarine slides.

The Göta river slopes were susceptible to instability. A famous instance, almost 82 years previous to that day's survey (March 3rd, 1916), occurred in the harbour, thereby taking with it a complete quay wall. The slide was subject to underwater surveys to determine the extent of its reach into the river. Analysis of its stability has since become a classic in soil mechanics. Of course one became curious about the time the slip had occurred in the geophysical profile. There were plenty of layers of sediment one could count to determine its age. Rodney Steven examined the profile carefully and with his knowledge of local sedimentation, came up with the results shown in Figure 4 on the next page.

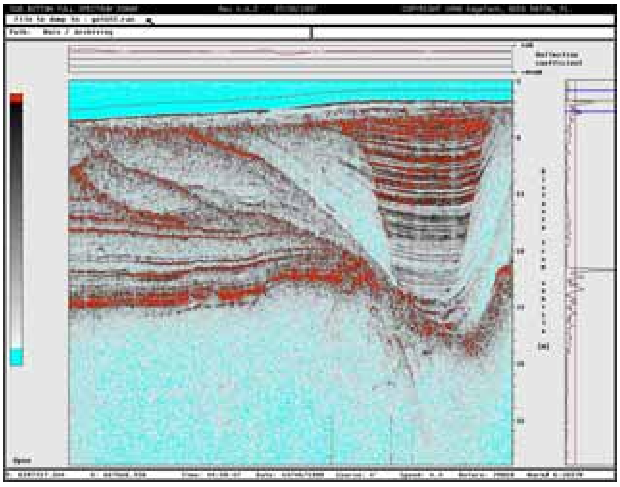


Fig. 2 Profile taken near the northern flank of the Göta Estuary (see Fig. 1).

Fig. 3 Sketch map showing slides offshore Norway.

References

Hartog, M.H. den (1995). The Wijkertunnel shell layer: evidence for a tsunami or a storm surge deposit? *Ingeokring Newsletter*, Spring Edition, 2-6.

Påsse, T. (1987). Shore displacement during the Late Weichselian and Holocene in the Sandsjöbacka area, SW Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, **109**(3), 197-210.

Wever, T.A. (1999). *Seismic interpretation of H-sense data and sub-bottom characterisation using chirp sonar technology*. M.Sc. Thesis, Centre for Engineering Geology in the Netherlands, CiTG, TU Delft, Memoir 177.

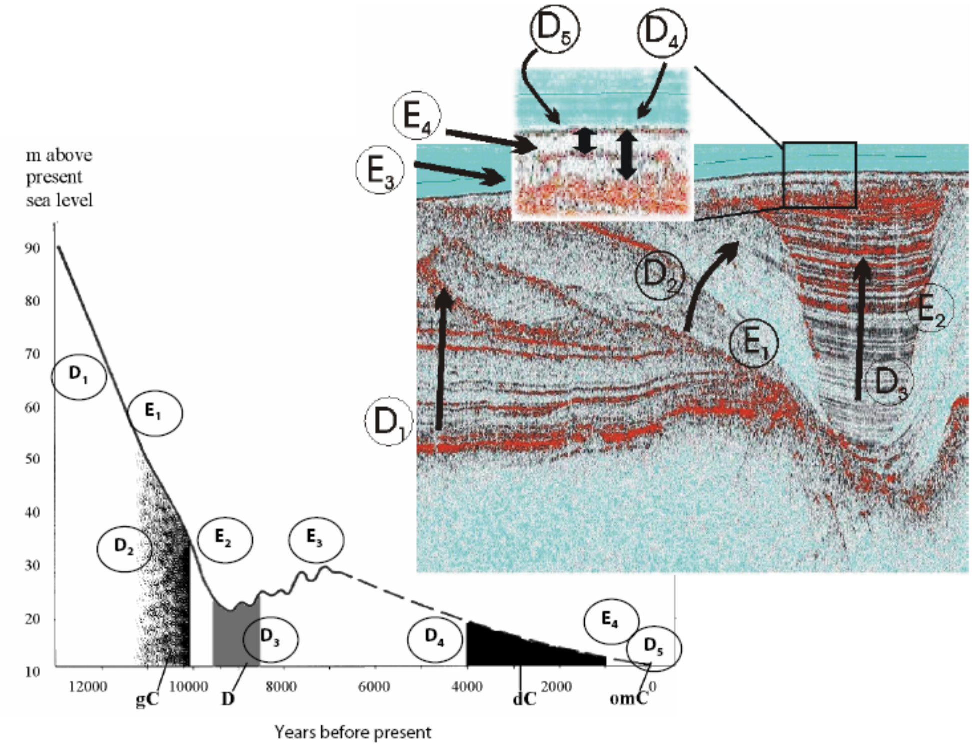


Fig. 4 Depositional and erosional phases of channels on the geophysical profile from the Göta Estuary, relative to the sea level curve from Påsse (1987).

Total engineering geological approach applied to motorway construction on soft soils

W.P. Munsterman, D.J.M. Ngan-Tillard *(Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Geo-engineering)*

A.A.M. Venmans *(Deltares/Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Geo-engineering)*

Abstract

Strong shallow ground heterogeneities in soft soils of the Western Netherlands have a large impact on construction and long-term evenness of motorways. In order to predict their frequency of occurrence, and reveal their size and location, the total engineering geological approach adapted to motorway widening is proposed as an alternative to the current practice in site investigation. In this alternative approach, first the local geology is depicted based on 1:50,000 geological-, soil- and geomorphological maps, archived geotechnical data and walk-over surveys in order to conceive a draft ground model. Second, laser surface altimetry data available for the whole of The Netherlands on a 5 x 5 m grid is exploited, on which buried man-made and natural heterogeneities in a horizontal plane are revealed. Third, the use of geo-electrical and multi-frequency electromagnetic techniques (GEM-2) is encouraged to characterise the geometry and position of the heterogeneities in a horizontal and vertical direction. Finally, all data available is integrated into an intermediate ground model which is used to optimise the spatial spreading of verticals of the next site investigation phase aiming to build the final ground model. In the pilot area, the altimetry data reveals the presence of many large silty sandy crevasse channels enclosed by deposits containing peat and clay. As a result of natural differential compaction, these crevasse channels are now 'highs' in the landscape. The surface altimetry data correlates well with GEM-2 data. In the topographically lower areas, both data sets are found to be complementary: the GEM-2 can differentiate between organic deposits and clay.

Introduction

As the deformation of a road pavement results from the deformation of the road structure itself and that of the soft ground it is built on, knowledge of the subsurface helps to respect strict design and performance specifications for motorway evenness in both the longitudinal and transverse directions. The total engineering geological approach advocated by Fookes and his co-workers (Baynes et al., 2005) has been adapted to motorway widening on the soft and heterogeneous soils of the Western Netherlands. The benefit of integrating, at an early stage, airborne laser altimetry data and multi-frequency electromagnetic data into ground modelling is highlighted. This new approach is proposed as an alternative to the current practice of site investigation, and it is applied to a pilot site, the widening of the A2 motorway linking Amsterdam and Utrecht.

Design and method

The current practice of site investigation for motorways can be summarised as an *engineering approach* rather than an *engineering geology approach*. It relies heavily on equally spaced cone penetration tests (CPT's) and boreholes. The main characteristics of the alternative approach are the application of geological models and expert geological knowledge, and validation of the models at site scale. Only after that, locations for CPT's and borings are selected for detailing the lithostratigraphy.

As a first step, the local geology is depicted based on 1:50,000 geological-, soil- and geomorphological maps and archived geotechnical data. A draft ground model is conceived, showing the expected architectural elements of the subsurface, with their frequency of occurrence and likely size inferred from the available geological interpretations. Architectural elements are easily derived from the new lithostratigraphical nomenclature for geological mapping of The Netherlands (Weerts et al., 2005). This nomenclature is based on macroscopically discernable lithological characteristics and the stratigraphical position of facies units. The draft ground model allows a first assessment of geohazards and the engineering consequences of motorway construction.

Second, the potential of the laser altimetry data available for the whole of The Netherlands is exploited to track buried man-made and natural heterogeneities. With a point density between 1 to 20 per 16 m^2, a point standard deviation and systematic error of 15 cm and 5 cm respectively and much better average performances, the laser altimetry data reveals, among others, the subtle results of differential compaction at the site scale. Many unexpected features become visible with a minimal effort. Contrary to the geomorphological and soil maps, the surface elevation maps show raw information without human interpretation. The novice eye can easily detect shallow and buried channels and their tributaries and select locations for additional site investigation. The expert eye can distinguish the architectural elements of a geological environment such as swales, scroll bars, residual channels and crevasse splays of a meander belt (Berendsen & Volleberg, 2007). It can also establish the relative chronology of events such as avulsions or bifurcations and filter out human interferences in the landscape. In some cases, inferred features can be recognised during a Google Earth flight and/or a walk-over survey.

Third, the use of geo-electrical and multi-frequency electromagnetic techniques is encouraged to characterise the geometry and position of the heterogeneities in the vertical direction.

Finally, all available data is integrated into an intermediate ground model used to optimise the spatial spreading of verticals of the next site investigation phase aiming to build the final ground model. The final model should reflect the 3D location of the facies units at the sites, the lithologies of the units and their engineering properties. Reference conditions may be defined: groups of geological materials with similar engineering behaviour. They are also used to communicate the geological conditions to engineers (Baynes et al., 2005).

The Dutch practice of construction of embankments on soft soil makes extensive use of the observational method. Data is collected and analysed to assess embankment stability during placement and to predict creep behaviour. Although the primary goal is to optimise construction, back analysis of this data allows validation of the engineering properties in the ground model.

Pilot site

The performance of the new approach to ground modelling is illustrated for a pilot case, the widening of a section of the A2 motorway linking Amsterdam to Utrecht in the vicinity of Abcoude (Figure 1).

Local geology

Depositional history

The geology of the study area is complex, as explained in Van der Meene et al. (1988) and Feiken (2005). The Holocene subsoil consists of layers of peat and organic clays deposited in a backswamp environment above blanket cover sands and periglacial deposits of Pleistocene age. In the Holocene, a large shallow fen lake existed in the flood-basin area of the river Angstel (Figure 2) that runs today through Abcoude. The fen lake with its high organic productivity, low rates of terrigenous sediment influx, and shallow water table made the backswamp environment ideal for deposition and preservation of plant debris. The lake became finally abandoned resulting in a large peat pillow, especially in the northern

Fig. 1 Situation of the pilot site (blue lined area) along the motorway A2 linking Amsterdam and Utrecht near Abcoude.

part of the study area. The river Angstel was a side branch of the meandering river Vecht, which was, on its turn, an important distributary of the river Rhine around 2,600 BP. During this period, the rivers Vecht and Angstel were more active and their sediment discharge was high. During several floods, the river water of the Angstel broke through its natural levees. Splays of large and small crevasse channels were formed, which transported sands and silts and eroded the existing soil. Subsequently, part of the lake became filled with sediments. The crevasse channels progressively lost their activity around 2,200 BP.

Conceptual geological model

Figure 3a schematically shows the terrain units of meandering lowland river deposits encountered at the pilot site. Figure 3b presents the geological formations and members typical for the subsurface of the pilot site and the spatial relation between their lithofacies. Its legend indicates the lithology of each lithofacies. Figure 3 implicitly shows the complexity of a crevasse splay. Crevasse flow rapidly dissipates into distributaries or sheetwash across the splay surface and sediment soon drops out. Small anastomosing distributaries, or braided channel systems, extend across the splay surface, and both channelised and unconfined flow occur during flood events. Grain size decreases systematically from the crevasse axis, but locally complex internal bedding results from the multiple scour-and-fill episodes that occur within the crevasse splay channels (Galloway & Hobday, 1996). The crevasse splay channels can develop to small-scale rivers, which create their own natural levees. These channels occasionally run into the flood-basin over a large distance (Berendsen, 2004). At the end of their active phase, they degenerate into residual channels that are slowly filled with clay.

On the 1:50,000 geomorphological-, geological- and soil maps (Maarleveld et al., 1975; Van den Berg et al., 1993; Van de Meene et al., 1988; Steur & Heijink, 1965; Steur & Vleeshouwer, 1970), only major crevasse channels are represented. Their levees are highlighted by hatched lines where they appear as obvious ridges in the landscape. Smaller crevasse channels and internal structures are not shown.

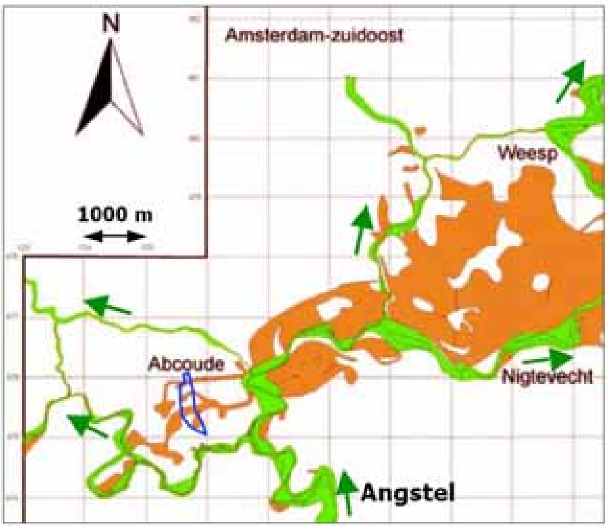
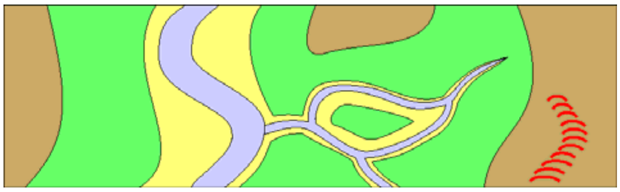


Fig. 2 Palaeogeographic map of the Angstel river area around 2,300 BP. Brown: active crevasse splay channels. Green: active meander belts. Green arrow: flow direction. Blue lined area: location pilot site (adapted from Feiken, 2005).

Airborne laser surface altimetry data

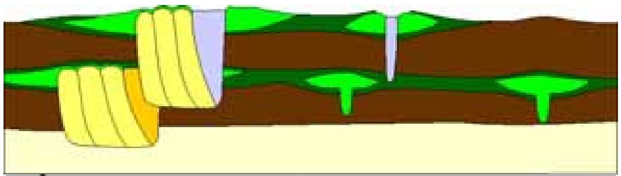
The airborne laser surface altimetry data (Figure 4) reveals the presence of large crevasse channels A and B (Figures 4 and 5) in the pilot area. In the past, crevasse channels were 'lows' fringed by clays and peats in the landscape. When they were active, sand and silt were deposited in their bed. When their activity declined, the channels were progressively filled in with clay. As a result of natural differential compaction accelerated by ground water table lowering, these crevasse channels are now 'highs' in the landscape with a narrow valley above the residual channel (label 1, Figures 4 and 5).

The surface elevation map indicates more precisely the geometry of the crevasse channels than the 1:50,000 geomorphological maps. The northern borders of the crevasse channel B (Figure 4) do not match with each other on the surface elevation and the geomorphological maps. The hatched lines symbolising its levees on the geomorphological map do not correspond to the highest ground surface elevations. Its southern border is prolonged on the laser altimetry map by a relatively high elevated ground level (at label 2, Figures 4 and 5), which is caused by crevasse splay sands chaotically deposited through the subsurface in lateral direction. These sands are not shown on the geomorphological maps.



Terrain units	
	Stream belt, natural levees
	Overbank deposits
	Flood plain
	Inversion ridge, buried channel

Fig. 3a Geomorphological map of low land meandering deposits.



Members		Types
Echteld Formation (Ec) – lithofacies units		
	Channel belt (FG/FZ)	Gravel, coarse sand, fining upward, cross stratification, lag deposit
	Natural levee, crevasse (FL)	Fine to medium sand, silty sand, sandy silt, laminated
	Flood plain clays (FKMA)	Clay, sandy clay, organic clay, massive
	Residual channel (FKLA)	Clay, sandy clay, organic clay, laminated, thin sand and peat layers
Nieuwkoop Formation (Ni) – lithofacies units		
	Peat (OVEU/OVME)	Peat, clayey peat, eutrophic to mesotrophic
Kreftenheye Formation (Kr) – lithofacies units		
	Fluvial sands	Medium to coarse sand, silty and sandy clay

Fig. 3b Corresponding cross section at lower boundary.

Fig. 3 Conceptual geological model of the pilot site. Letter codes refer to the lithostratigraphical nomenclature (Weerts et al., 2005).

Google Earth Flight

Several features revealed by airborne surface altimetry can also be recognised on Google Earth's aerial photographs from variations in size, shape, pattern, tone and texture (Figure 4).

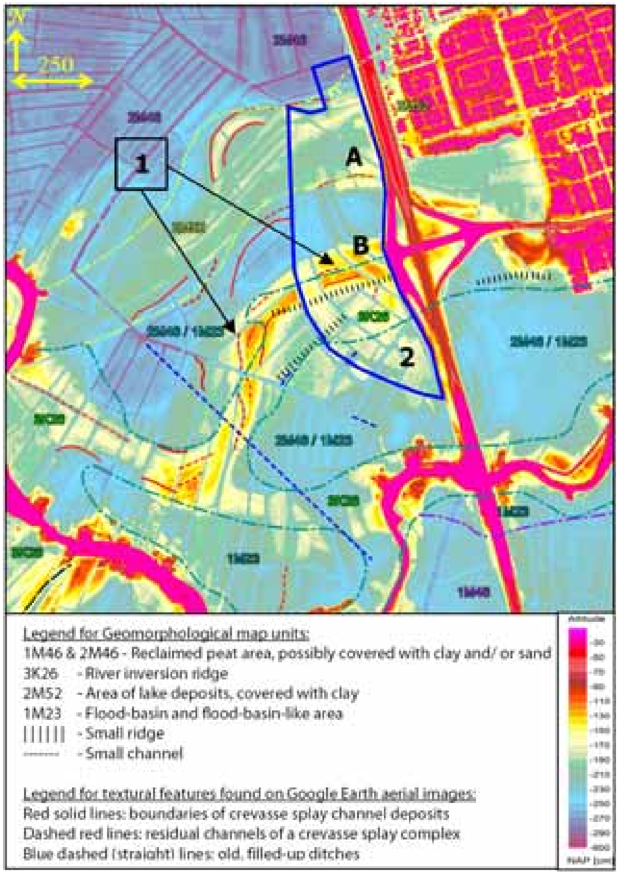


Fig. 4 Geomorphological unit boundaries (dash-dotted lines) superimposed on an airborne laser altimetry map, and combined with textural features found on Google Earth images. Unit codes and textural features are explained in the legend. Blue line: pilot site. A and B: main crevasse channels. The numbers are explained in the text. Note: elevation is in centimetres relative to NAP, and a larger scale is shown in Figure 5.

Walk-over survey

A Google Earth flight provides good insight into the site topography and its human utilization. However, it does not replace the walk-over survey. The walk-over survey is unusual in traditional site investigations in the Western Netherlands. Nevertheless, it is cost-effective as it provides valuable information on the site morphology, and does not require the expensive mobilization of rigs nor degrade farm land. Information on subtle surface elevation differences, vegetation, sponginess of the ground, geometry of ditches and nature of their banks is collected. All reflect the structure of the shallow subsurface. For example, a ditch water level which is low relatively to the top of the ditch banks indicates a high area in the landscape. This was observed for example at the northern boundary of the crevasse channel B (Figures 4 and 5).

Geotechnical data

Geological and geotechnical databanks maintained by the Dutch Geological Survey and Dutch engineering consultants were searched for verticals falling within or close to the pilot site. The locations of archived boreholes are shown in Figure 5 with blue dots. In addition, a series of 12 shallow gauge boreholes (red squares) has been drilled. Also for the Delft Cluster research programme entitled 'Permanently Smooth Roads', 19 CPT's have been performed along a line at a spacing of about 1.5 m (orange triangles). The line corresponds to a southern transition zone from main crevasse channel A (Figures 4, 5 and 6) to a peaty area. At this location, the motorway widening has been closely monitored. Results on interaction between subsurface heterogeneities and differential settlements are under study. In the next sections information revealed by the verticals is used to corroborate the surface altimetry and geophysical data (Figures 5 and 6).

Multi-frequency electromagnetic survey

One guesses that a buried sand body will be better captured by airborne laser altimetry if embedded at shallow depths in a thick layer of compressible peat than in a layer of silty clay. However, a quantitative insight into the relation between differential settlement and the characteristics of heterogeneities in terms of size, geometry, depth of burial and contrast with surroundings is lacking. Geophysics is thought to be a cost-effective alternative to a dense campaign of boreholes and CPT's to characterise the structures, which are responsible for differential settlement observed at the ground surface. Geo-electric and low- and high frequency electromagnetic techniques are preferred to on-land shallow seismic methods because of their user-friendliness.

GEM-2 survey parameters and theory

A GEM-2 survey was conducted at the pilot site. The GEM-2 is a hand-held ski-like device. It was connected to a Trimble AgGPS 114 receiver with a horizontal accuracy better than 1 m RMS. Measurements were taken along a dense grid of lines. An average of 3.5 measurements per m was recorded along lines which were spaced at 14 m on average.

The GEM-2 was operated in a frequency range of 2,725 to 45,025 Hz. The primary magnetic field of the GEM-2 induces a current in the soil. The properties of this current and the resulting secondary field that can be measured are dictated by both the soil magnetic susceptibility and electrical conductivity. The properties of this current are, amongst others, linked to the sensor properties through the induction number. The induction number is the ratio of the separation between the transmitter and receiver coils and the skin depth. The skin depth is the depth at which the amplitude of an alternating current falls to 1/e of its original value (McNeill, 1980). The theoretical skin depth of the GEM-2 survey based on the range of resistivities expected in the pilot site is estimated to vary from 43 m at 2,725 Hz to 11 m at 45,025 Hz.

The GEM-2 operates optimally in low- to mid-induction number range. The in-phase and out-of phase components of the secondary magnetic field measured are proportional to the frequency and the induction number respectively. Therefore, the low induction number assumption (induction number much less than 1 (McNeill, 1980) is valid to calculate the ground resistivity from the invert of the out-of-phase component. The total electrical conductivity is calculated by equal weighting of the individual frequencies in order to produce an average, frequency-independent electrical conductivity (Rucker & Sweeney, 2004). The depth of investigation is different from the skin depth. The former is affected by the properties of the target and host medium as well as by factors related to the investigation modality, such as sensor sensitivity, accuracy, frequency, coil configuration, ambient noise, and data processing and interpretation methods (Huang, 2005). For the A2 site, the depth of investigation is estimated to be between 7.3 m at 2,725 Hz to 3.5 m at 45,025 Hz.

GEM-2 results

As the frequency decreases, the depth of investigation increases, the low conductivity Pleistocene sands are reached and the apparent electric conductivity decreases. However, data sets gathered at different frequencies all follow the same patterns at this specific site. Hence, rendering imaging in the vertical direction impossible.

The total electrical conductivity map is shown in Figure 6. Features represented onto the 1:50,000 geomorphology map are superimposed onto the GEM-2 map. The east-west oriented low conductivity zones (purple to red) at label A and B correspond to the main sandy crevasse channel deposits. The high conductivity zones (yellowish green to blue) at label C are clayey flood-basin deposits. The medium conductivity zones (yellow to orange) at label D correspond to areas rich in organics. Note that the archived boreholes all confirm the interpretation of the subsurface. The lineaments of greenish blue patches (label E) are caused by buried cables, and a reinforced concrete path. Label F shows two anomalies of very high conductivities (light blue to blue) caused by interference with metal wired fences. No electrical anomalies are generated by cables lying in casings installed by horizontal directional drilling (label G).

Complementarities of GEM-2 and airborne surface altimetry data

The surface altimetry data correlates well with the GEM-2 data (Figures 5 and 6): sands saturated with fresh water have a lower electric conductivity (25 to 47 mS/m) than clays (55 to 85 mS/m) and are found below the topographic highs.

In the topographically lower areas, both data sets are found to be complementary: the GEM-2 can differentiate between organic deposits and clay, which is corroborated by boreholes. For example, at label D (Figure 6) in between the main crevasse channels A and B, elevations are medium to low indicating compressible soils. Where boreholes reveal the presence of soils that are more organic than clayey, electric conductivities are lower: 37 to 55 mS/m (label D, Figure 6) against 55 to 85 mS/m where clays were found (label C, Figure 6).

Where human activities have levelled off the ground surface, soil composition can still be derived from GEM-2 data.

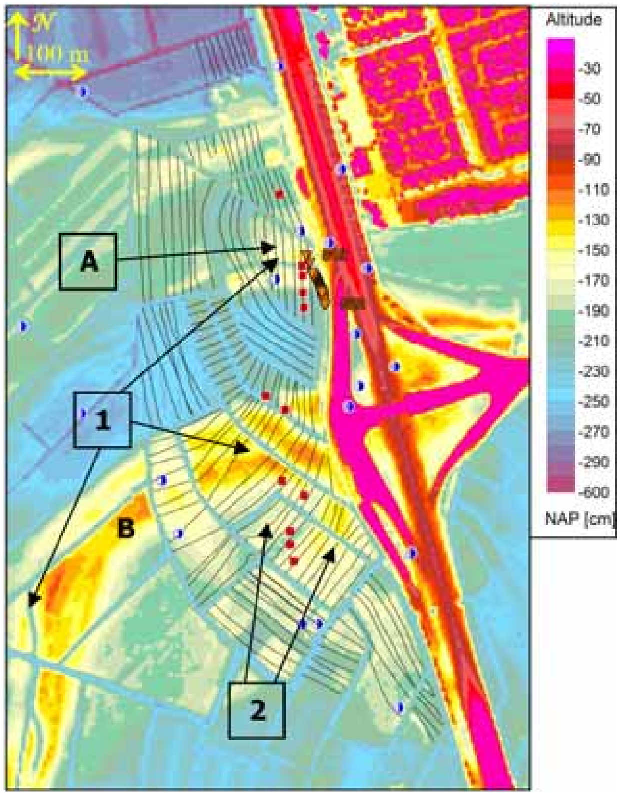


Fig. 5 Airborne surface elevation map with GEM-2 survey tracks in black. Orange triangles: Delft Cluster CPT's. Blue dots: archived boreholes. Red squares: hand-made gauge boreholes. The capital letters and numbers are explained in the text.

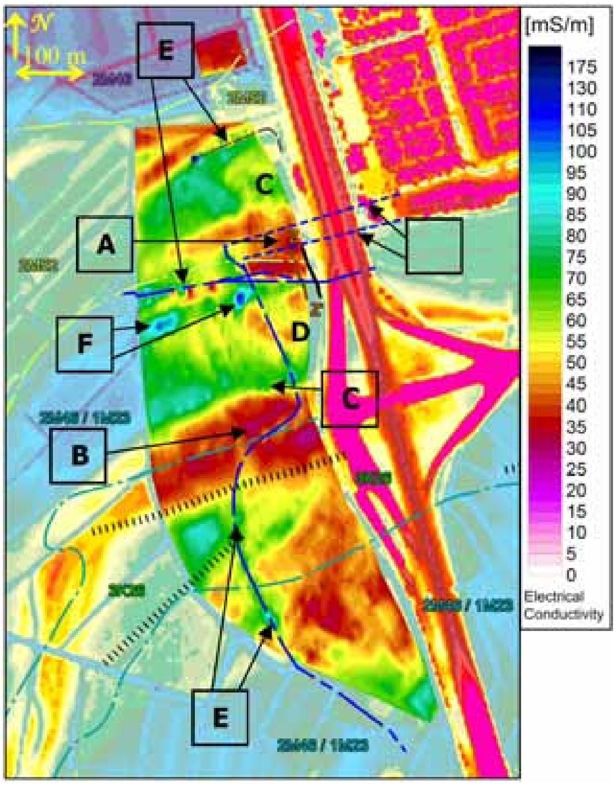


Fig. 6 GEM-2 total conductivity map superimposed onto the surface elevation map with geomorphological unit boundaries (long dash-dotted line). Blue long dash-short dashed line: telephone cables. Blue short dashed line: horizontally drilled cables under motorway. Grey dashed line: reinforced concrete path. Black solid line: geotechnical profile Z - Z'. Brown solid line: surface elevations and GEM-2 profiles for Figure 7. Capital letters are explained in the text.

Detailed validation of surface altimetry and GEM-2 data

The geotechnical profile along the line of closely spaced CPT's is compared to a GEM-2 total conductivity and a surface elevation profile drawn at about the same location in Figure 7. The location of these profiles is illustrated in Figure 6 by the Z-Z' lines. The upper boundary of the Pleistocene sand (Unit 1 in Figure 7) slightly fluctuates around -8 m NAP (Dutch mean sea level). It is sensed more strongly at lower frequencies. At the north (left) of the profile, a 2.5 m thick sand body (Unit 4) corresponding to a crevasse channel is present. It contains a small residual channel filled with a sequence of clay, sand and silts (Unit 5). Both features are visible on the surface elevation and GEM-2 profiles: the crevasse channel is associated with low conductivities and high elevations; the residual channel appears as a trough coupled to an increase in electrical conductivity. From the middle part of the profile to the south, natural levee/overbank deposits (Unit 3 in Figure 8) adjoin the crevasse channel. Their thickness decreases from 4 m to 1 m to the south. They are fining upwards and laterally away from the channel. The transition from the channel bed deposits to its overbank deposits coincides with a sharp increase in GEM-2 conductivity and a gradual decrease in altitude.

A peat layer (Unit 2 in Figure 7) underlies the channel. Its thickness increases from 1.5 m at the north of the profile to 4 m at the south. Where peat dominates, the electric conductivity is medium high and surface elevation is low. In brief, first, the surface elevation map is a precious help to identify the depositional environments of the geotechnical units revealed by the CPT's. Second, the airborne surface elevation profile is in general agreement with the geotechnical and GEM-2 profiles. Sands, clays and peats score high, medium and low on the altimetry data while they score low, high and medium on the GEM-2 conductivity data. Third, the altimetry profile has a lower horizontal resolution than the GEM-2 profile. Nevertheless, both profiles are found to be sensitive to transitions between the lithofacies units that form the local deposits. Transition from sand to clay is sharper on GEM-2 data than on the surface altimetry data since it involves the passage from low to high conductivity values rather than from low to medium values.

For the profile in Figure 7, the laser altimetry data and GEM-2 scan would suggest a preliminary site investigation with CPT's placed at the locations marked with a triangle in Figure 7. The difference in lithology and hence engineering properties may result in differential settlements of the road embankment built at the site. The residual channel might prove to be critical in this respect, because of the very short distance of 10 m over which the lithology changes.

In the suggested approach the CPT density is related to changes in lithology. These changes are concentrated around crevasse channels. In the flood basin deposits the average spacing will be greater, because of the relatively uniform lithology. The average CPT spacing along the line Z-Z' is 17 m, which is small compared to the traditional approach. However, it may not be necessary to investigate every crevasse channel in detail. A possible approach is to classify channels on basis of laser altimetry and GEM-2 signature, and investigate in detail only a limited set of channels representative of the different classes. Feasibility, accuracy and cost-effectiveness will need further research.

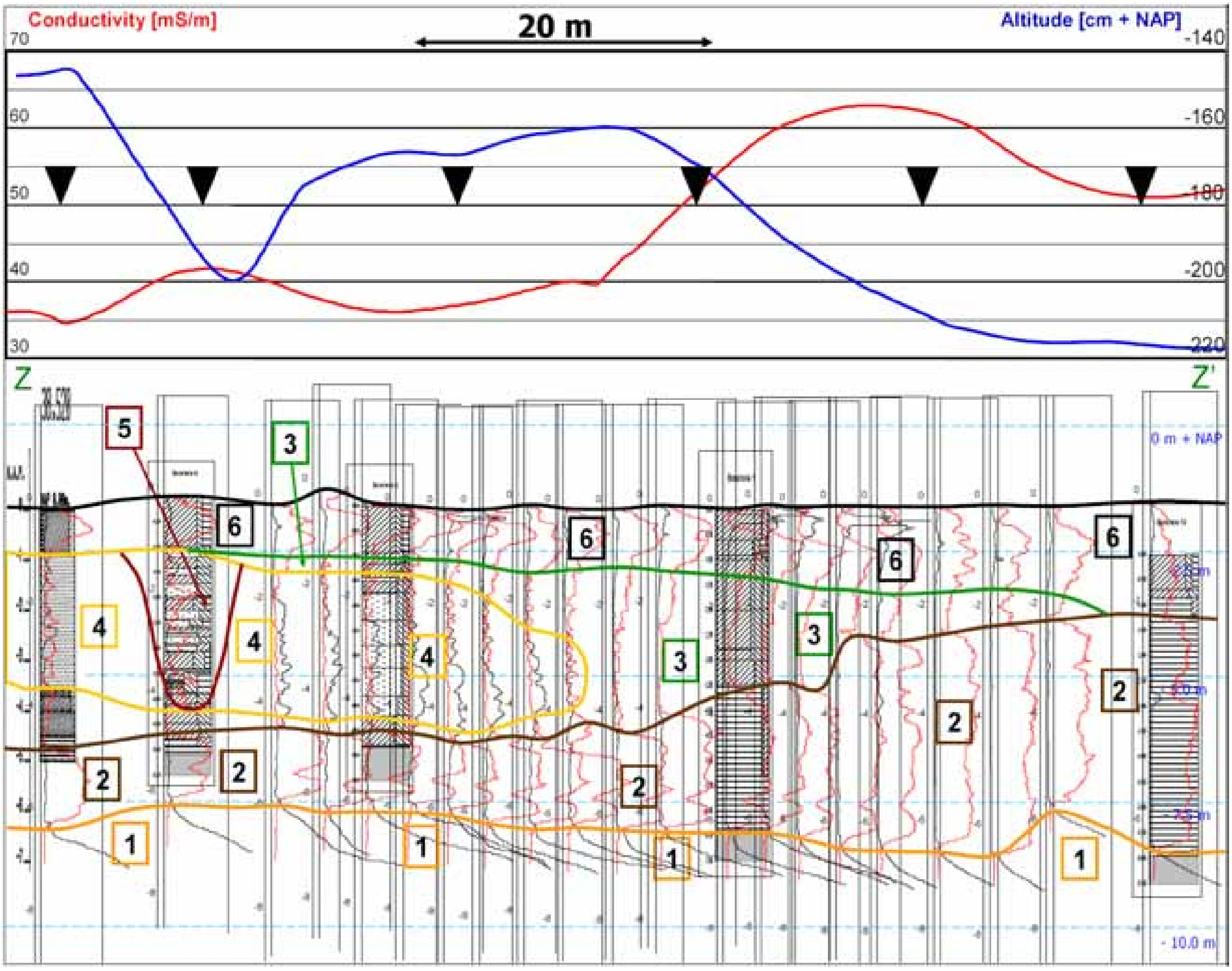


Fig. 7 Geotechnical profile Z-Z' compared to GEM-2 total conductivity profile (red line in mS/m) and a surface elevation profile (blue line in cm relative to NAP).

Conclusions and recommendations

Ground heterogeneities that are shallow and strong have a large impact on the construction and long-term performance of motorway evenness. Their frequency of occurrence can be predicted using geological expertise and 1:50,000 geological and geomorphological maps. Their position in the horizontal plane can be inferred from laser surface altimetry data readily available for the whole of The Netherlands and low cost electromagnetic surveys. Their geometry in the vertical direction can be estimated in theory from multi-frequency electromagnetic data. This was however not possible with the GEM-2 data recorded for the pilot site. Instead, a geo-electrical resistivity survey is recommended to delineate sand bodies at depth.

At the pilot site, GEM-2 and surface altimetry data were found to be complementary. Sands correspond to high elevations, low conductivities, clays to medium to low elevations and high conductivities and peat to low elevations and medium high conductivities. A transition from sand to clay is sharper on GEM-2 data as it is associated to the passage from low to high values rather than from high to medium low or low values. The relation between soil type, electrical conductivity and surface elevation is however site dependent as conductivity of peat and sands is very much related to the concentration of dissolved ions. More research is needed to link frequency dependent geophysical parameters such as electrical conductivity and chargeability to soil index properties.

Instead of ordering verticals at constant spacing for the preliminary site investigation, CPT's and boreholes should be placed between suspected boundaries between terrain units and lithofacies units.

Acknowledgement

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References

Baynes, F.J., Fookes, P.G., & Kennedy, J.F. (2005). The total engineering geology approach applied to railways in the Pilbara, Western Australia. *Bull. Eng. Geol. Environ.* **64**(1), 67–94.

Berendsen, H.J.A. (2004). *De vorming van het land - Inleiding in de geologie en de geomorfologie.* Van Gorcum, Assen, The Netherlands.

Berendsen, H.J.A., & Volleberg, K.P. (2007). New prospects in geomorphological and geological mapping of the Rhine-Meuse Delta - Application of detailed digital elevation maps based on laser altimetry. *Neth. J. Geosci./Geol. Mijnbouw*, **86** (1), 15-22.

Berg, M.W. van den, Pruissers, A.P., & Wildenborg, A.T. (1993). *Geomorfologische kaart van Nederland 1:50.000, Blad 25 Amsterdam.* Rijks Geologische Dienst, Haarlem, DLO-Staring Centrum, Wageningen.

Feiken, H. (2005). *De ontstaansgeschiedenis van het Vechtgebied met nadruk op het Vecht-Angstel systeem.* Verslag doctoraalveldwerk, Departement Fysische geografie, Universiteit Utrecht. Utrecht, The Netherlands.

Galloway, W.E., & Hobday, D.K. (1996). *Terrigenous Clastic Depositional Systems - Applications to Fossil Fuel and Groundwater Resources (2nd Edition).* Springer Verlag, New York.

Huang, H. (2005). Depth of investigation for small broadband electromagnetic sensors. *Geophysics*, **70**(6), G135-G142.

Maarleveld, G.C., Cate, J.A.M. ten, & Lange, G.W. de, (1975). *Geomorfologische kaart van Nederland 1:50.000, Blad 31 Utrecht.* Rijks Geologische Dienst, Haarlem. Stichting voor Bodemkaartering, Wageningen.

McNeill, J.D. (1980). *Electrical Conductivity of Soils and Rocks - Technical Note TN-5.* Geonics Ltd., Mississauga, Canada.

Meene, E.A. van de, & Staay, J. van de, (1988). *Geologische kaart van Nederland 1:50.000, Kaartblad Utrecht Oost (31O).* Rijks Geologische Dienst, Haarlem.

Rucker, D.F., & Sweeney, M.D. (2004). *Plume Delineation in the BC Cribs and Trenches Area.* PNNL-14948, Pacific Northwest National Laboratory.

Steur, G.G.L., & Heijink, W. (1965). *Bodemkaart van Nederland Schaal 1:50.000, Kaartblad 25 Oost Amsterdam.* Stichting voor Bodemkaartering, Wageningen.

Steur, G.G.L., & Vleeshouwer, J.J. (1970). *Bodemkaart van Nederland Schaal 1:50.000, Kaartblad 31 Oost Utrecht.* Stichting voor Bodemkaartering, Wageningen.

Weerts, H.J.T., et al. (2005). Quaternary geological mapping of the lowlands of The Netherlands, a 21st century perspective. Quaternary International, **133-134**, 159-178.

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Geophysical logging in the Rhenish lignite mining district

Robrecht Schmitz _(RWE-Power, Mines Engineering Centre, Germany, Robrecht.Schmitz@rwe.com)_

Ekin Erydin _(Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Geo-engineering)_

Jochen Linde _(RWE-Power, Geophysics Department, Germany, Jochen.Linde@rwe.com)_

Introduction

This edition of the Ingeokring Newsletter focuses on geophysical methods in geo-engineering. Therefore we decided to highlight the sophisticated geophysical logging used in the Rhenish lignite mining district. The tools we describe are known to the reader, most probably from petroleum engineering. What is less known is that the same tools are used on a day to day basis to optimise lignite mining in RWE-Power's mines. First an introduction is given to this mining district, followed by a short literature review of geophysics in (coal) mining. An explanation why geophysics is so important for lignite mining is given thereafter. Then the geophysical logging tools and the logging processes are highlighted.

The Rhenish lignite mining district

The three open-cast mines operated by RWE-Power in North Rhine-Westphalia follow a long tradition of lignite mining in this region. Lignite is used to produce more than 50% of the electric energy required by the industries and cities in North Rhine-Westphalia (18 million inhabitants, one of the 15 most important economic regions in the world). The mining district is located in between two 'branches' of the Rhenish Slate Mountains. During the Tertiary, the Rhenish Slate Mountains were weathered down. The sediments were transported and deposited by rivers traversing the plain area, which was subjected to tectonic subsidence, towards the North Sea. Lush vegetation developed on this plain and along the coastline. During trans- and regressions, which are processes promoting the development of marshes (Pohl, 1992), dying organic material turned into peat. Due to subsidence of the plain, 400 m thick peat layers accumulated (Walter, 1995). This peat was transformed into thick (maximum 100 m) lignite deposits. Sand, clay and gravel accumulated during the remainder of the Tertiary and the following Quaternary, resulting in a several hundred metres thick layer of overburden. Loess was deposited on top of these layers (ENB, 2005). In the thick clay layer above the coal seam, siderite concretions (clay ironstone) can be found (Schmitz, 2007).

In the 18th century, the lignite deposits close to the surface were mined by manual labour. At the beginning of the 20th century mechanisation started. The bucket wheel excavators (BWE), conveyor belts and spreaders, developed in close cooperation with the mining societies in the region, became more and more sophisticated during the 20th century. In the 1970's the largest BWE ever built (operating weight: 13,000 metric tons; production in sand: 240,000 m^3) was con-

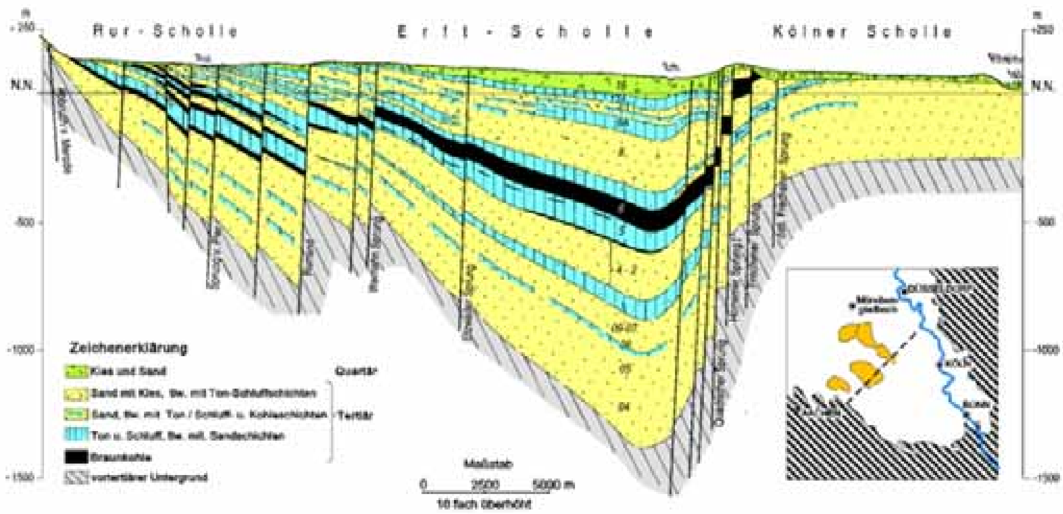


Fig. 1 Cross-section through the Rhenish lignite mining district.

structed on the site of the present Hambach surface mine (Figure 2). On average, approx. 100 million tons of coal are mined each year by these 3 mines. To reach down to this coal more than 500 million cubic metres of overburden are excavated, transported and stacked per annum.

Fig. 2. The standard bucket wheel excavator in Hambach surface mine. The encircled Land Rover serves as scale.

Why is geophysical logging performed in the Rhenish lignite mining district?

The geological information required for coal mining includes: the identification of coal, identification of depths to coal seam roof and floor, coal seam thickness, identifications of partings within the coal seam, and quality variations within the coal seam (Thomas, 2002). Exactly for these reasons geophysical logging is performed in the Rhenish lignite mining district. Only the coal quality is determined in RWE's laboratories by analysing the drill cores (coal layers are completely cored) and not on the basis of geophysical logging. The core is tested on its calorific value, water content and chemical composition. As the mine advances, hand samples are taken directly from the seam and analysed subsequently in the laboratory. On basis of this geophysical and laboratory data, providing information on geometry of the coal seam and its quality, a three dimensional geological model of the Rhenish lignite deposit is constructed. This geological model is used to determine the reserves and the quality of the coal deposit and provides the long-term planning, short-term planning, disposition and production with reliable data for mining and scheduling for power plant coal supply. On basis of the same geophysical logging, the thickness and position of the different overburden materials (gravel, clay, silt, sand and clay ironstone) is determined. This information is also part of the geological model and is used by departments like the dewatering department, the geotechnical department and the long-term planning department. The latter uses this information to prepare mine plans which make sure that the different materials being excavated in the future can be placed on the dump at a certain moment while guaranteeing its stability. The mine planning and production uses the same database to plan the short-term overburden disposition (Schmitz et al., 2008). Some stretches of the overburden are cored and analysed by the geotechnical department. This information is used as input parameter for slope stability analysis (and pyrite content for environmental reasons). Geophysical logging is thus performed to determine the depth of the different stratigraphic layers: from near surface to the footwall. Geophysical logging is not the only way to determine the geometrical build up of the stratigraphic column. Lithological information can also be obtained by analysing cuttings while drilling. When the airlift drilling method is used to drill large diameter water wells, cuttings are transported through the drill string upwards. These cuttings are analysed to determine the location of the different lithologies. However, when small diameter boreholes for observation wells are drilled, the cuttings are brought up through the annulus, the spacing between the drill string and the borehole. Since the overburden is not lithified, the shape of the borehole in the different soil layers is irregular (washouts). Therefore the retention time of the cuttings cannot be determined accurately and as a consequence an accurate *cuttings to depth analysis* cannot be made. The reason for applying geophysical logging lies in the determination of the exact location (the depth) of the different lithological layers and aquifers. Note that not all logging starts at the surface since some boreholes are drilled and logged from a bench in the mine (Figure 3). A summary of the drilling techniques used in the Rhenish lignite mining district has been described by Linde & Theißen (2008).

Geophysical logging in the Rhenish lignite mining district

The use of geophysics in the exploration for coal basins is now well established (Thomas, 2002). Large scale coal exploration studies make use of regional gravity-, deep seismic- and aeromagnetic surveys to determine the sedimentary and structural framework of the area under consideration. Smaller scale and more detailed examination of the coal deposit utilises shallow seismic, ground magnetic, electrical resistivity and microgravimetry coupled with the geophyisical logging of all boreholes, which in turn involves the use of density-, electrical-, electromagnetic-, and radiometric techniques. Coal has in general a lower density, a lower seismic velocity, a lower magnetic susceptibility, a higher electrical resistivity and low radioactivity compared with surrounding rocks in typical coal-bearing sequences (Thomas, 2002). Density of lignite is 1.1 ton/m^3, density of overburden is 1.8 - 2.0 ton/m^3 (except clay ironstone: 3.3 ton/m^3). The logs that are most useful and most used to identify coal and coal bearing sequences are therefore gamma-ray, density, neutron, caliper, sonic and resistivity (Thomas, 2002). Of these methods, gamma-ray spectra log, resistivity and density (not: neutron log) are used in the Rhenish lignite mining district. These are the same geophysical tools used in oil and gas exploration (the used calibration routines, however, are different). The geophysical tools can be used in the large diameter 1,500 mm airlift boreholes using a push tool (decentralisation springs), which presses the logging tool against the borehole wall.

The gamma-ray log measures the naturally occurring radiation in geological formations. Coals have a very low level of natural radiation. As the amount of included clay material, in the form of clay partings in the coal, increases, the natural radiation increases as well. These readings are used to discern between clays and non-clays. On basis of gamma-ray alone, the difference between a marine sand (marine sands are located in the footwall, fluvial sands in the hanging wall have a higher amount of clay and therefore higher gamma-ray emission) and coal (low in clays) cannot be determined. The location of the footwall cannot be determined with gamma-ray alone. Therefore, the tool is used in conjunction with the density tool: the density log is used as a principal means of identifying coal, mostly because coal has a uniquely low density compared to the rest of the coal bearing sequences. The density log is calibrated by measuring probe output in homogeneous blocks of material of known density (Thomas, 2002). The density tool is therefore used to

Fig. 3 Logging at a drill site in Hambach surface mine.

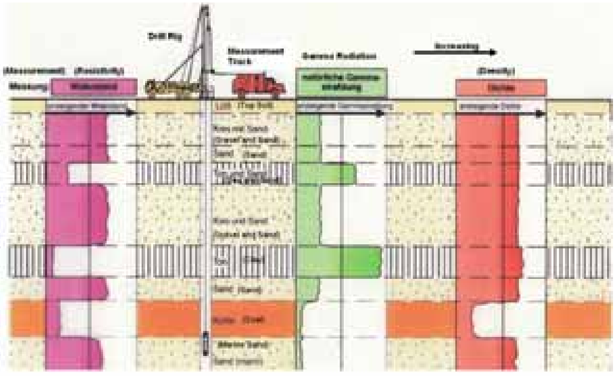


Fig. 4 Typical lithology encountered in the Rhenish lignite mining district and the readout on a schematic geophysical log.

distinguish between coal and non-coal layers. The resistivity tool readout is of course influenced by the salinity, but this is a fairly constant value for a particular ground water table at a particular mine site. The largest contrast is found between layers containing water (saline) and dry sands. The readout of these tools is used to determine the location of the different water tables. In a borehole made for later placement of piezometers, this measurement shows at which depth the filters and the plugs should be placed. Figure 4 gives an overview of a typical overburden column and the readouts of the different logging tools. A single borehole is generally logged more than once depending on the timing of casing placement and the timing of the employed cement stabilisation of the coal.

As explained above, the data from geophysical logging is the basis for the geological model and a means to improve it continuously. A recent example of the benefit of using geophysical logging arose when in 2005 clay ironstones appeared in great numbers in the clay formations above the coal seam in Hambach surface mine. These ironstones are very hard (unconfined compressive strength of 70 MPa and higher), too hard to be cut by the buckets of the bucket wheel excavator. For the production department it is important to know in advance where these nodules are concentrated. By re-analysing the geophysical logs, the density anomaly between clay ironstones (3.3 t/m^3) and the remainder of the overburden (at maximum 2 t/m^3) could be tracked in the logging records (Figure 5). Thereby, the geometrical distribution of the clay ironstones can be determined with a level of detail that is useful in mine planning. In the Rhenish lignite mining district in total 600 gamma-ray-, resistivity-, or density logs are performed per year resulting in 30 km of logging!

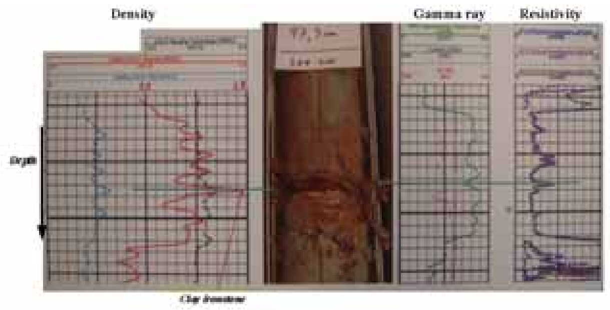


Fig. 5 The position of clay ironstones in the overburden is important for the long-term planning and production strategy. The clay ironstones can be found in geophysical logs because of their large density compared to the rest of the overburden (density log on the left).

Conclusion

Geophysical logging in the Rhenish lignite mining district is performed on a day to day basis to enhance the geological (hydrological) model providing information on coal quality, stratigraphy and hydrological data. Geophysics is not used as an exploration tool in the general sense, since the coal deposits within the concessions are proven. This geological model is used by the dewatering-, geotechnical-, and mine planning departments. To fulfil all requirements of this model, the position and thickness of the different lithological units (gravel above and below the water table, fluvial sands above and below the water table, clay above or below the water table, lignite, marine sands below the water table, clay below the water table) must be determined accurately. The coal properties are determined by coring and subsequent lab analysis. The boundaries between the different clay and sand layers are determined accurately by geophysical logging: gamma-ray logging, density logging, and resistivity logging. Because lignite has a relatively low density compared to the overburden, density logging is used to locate the lignite seam. With resistivity logging it is possible to distinguish clay layers (high water content) and dry sand layers and to locate the ground water level. Gamma spectra logging is used to locate clay layers which have a high content of potassium.

With these tools, mining can proceed continuously and efficiently as mine planners can look into the future, relying on a detailed geological model generated on the basis of geophysical logging.

Literature

ENB (2005). *Origin of the Lower Rhenish Lignite*. Brochure RWE-Power (in German).

Linde, J., & Theißen, L. (2008). The development of drilling technology in the Rhenish lignite mining area. *World of Mining*, 6, 346-360.

Pohl, W. (1992). *Lagerstättenlehre (4th edtion)*. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Schmitz, R.M., Kübeler, U., Elandaloussi, F., Lau, D., & Hempel, R-J. (2008). The introduction of IT into mass mining: the digital mine in Hambach surface mine. H. Schunnesson & E. Nordlund, E. (Eds.), *Proceedings of the 5th International Conference and Exhibition on Mass Mining*, June 9-11, Luleå (Sweden), 499-508.

Schmitz, R.M. (2007). Excavation of rock concretions in Hambach opencast mine: In situ tests. L. Ribeiro e Sousa, C. Olalla & N. Grossmann (Eds.), *Proceedings of the 11th Congress of the International Society for Rock Mechanics*, Taylor & Francis, Leiden, 593-596.

Thomas, L. (2002). *Coal Geology*. John Wiley & Sons.

Walter, R. (1995). *Geologie von Mitteleuropa*. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Static liquefaction analysis using simplified modified state parameter approach for dredged sludge depot Hollandsch Diep

R.R. de Jager, F.A.J.M. Mathijssen *(Royal Boskalis Westminster nv, Papendrecht/Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Geo-engineering)*

F. Molenkamp *(Delft University of Technology, Faculty CEG, Department of Geotechnology, section of Geo-engineering)*

A.H. Nooy van der Kolff *(Royal Boskalis Westminster nv, Papendrecht)*

Abstract

The historical background of liquefaction in the Netherlands and subsequent empirical guidelines are briefly discussed. The usefulness of this empirical knowledge for Geotechnical Category 3 (GC3) projects is limited, since quantification of risks and insight in the feasibility of projects are limited. During the tender stage and after award of contract of the Design, Construct and Maintenance project for the excavation of the dredged sludge depot in the river Hollandsch Diep in The Netherlands, an elaborate literature study was carried out, resulting in the formulation of a critical state framework. In this framework, stress points are analysed using the modified state parameter as representation for the state of the subsoil. The initiation of static liquefaction is analysed in an uncoupled analysis using the slope of the instability line as input for a commercial finite element code. Several planned and unplanned failures during the realisation of the dredging activities were successfully analysed using a simplified stochastic approach of the modified state parameter model. The article gives insight into the determination and application of the state parameter approach and discusses the practical and academic needs for further developments and research.

General

The phenomenon of liquefaction has a strong historical background in The Netherlands and even initiated the start of practical soil mechanics after causing the train disaster in Weesp in 1918. According to historical records dating back as far as the 17th century (Koppejan et al., 1948), erosion and sedimentation have caused hundreds of flow slides to occur in the dynamic delta environment of the province of Zeeland. The three conditions required for a flow slide, formulated by Koppejan et al. (1948), are still valid: (I) the soil must be susceptible to liquefaction; (II) the slope must be relatively steep and high; (III) there must be a triggering mechanism. As only *static* liquefaction is considered, it is assumed that there will always be a triggering mechanism during the lifetime of the slope. The required severity of the third condition is therefore not further discussed.

The results of an extensive analysis of the empirical Zeeland-data (Silvis & De Groot, 1995) can be summarised as follows: flow slides have mainly occurred in young Holocene marine deposits, generally loose to moderately packed sands with slopes steeper than 1(v):3(h) and slope heights of more than 5 metres. These findings comply with the first two conditions defined by Koppejan et al. (1948). Guidelines based on these results were already formulated at the end of the 1970's and applied during the construction of the Delta Works in the 1980's. Even though there have been some developments in the field of liquefaction related research in The Netherlands since that moment, e.g. Silvis & De Groot (1995), Stoutjesdijk et al. (1998) and De Groot (2004), the direct (practical) need for an improvement was lacking. However, during the tender stage of the Hollandsch Diep project in 2005, there was an urgent need for improvement as static liquefaction was considered to be one of the main risks during construction. Possibilities for implementing MONOT (Molenkamp, 1983 and Molenkamp et al., 1998) and a full stochastic analysis (Hicks, 2003 and Hicks et al., 2005) were investigated but rigorous simplifications were required to reduce the calculation time involved and to allow for project implementation and validation.

This article strives to address the topic of static liquefaction using a critical state approach with the state parameter as governing parameter. First, the simplified state parameter model is described and compared with Dutch experience. Subsequently, the applied numerical implementation using a commercial FEM code and possibilities for improvement are subject of discussion. This is followed by the actual project description including in-situ and laboratory data. The applicability of the model is discussed using experiences gained during the construction of the Hollandsch Diep project. The overall performance and possibilities for improvement and further research are discussed in the closing chapter.

Description of liquefaction behaviour

Description of soil behaviour is generally expressed in terms of relations between stresses and strains, i.e. constitutive relations. At the basis of these relations the concept of the existence of a Critical State has been widely accepted and a.o. applied in Critical State Soil Mechanics (CSSM). Liquefaction behaviour also comprises undrained instability (e.g. Molenkamp, 1989, 1991) in between the initial and final (critical) state. This is an essential element of the description of liquefaction. Both constitutive concepts, critical state and undrained instability, are used to explain the simplified modified state parameter approach (SMSP) in the current chapter.

Undrained formulation of liquefaction

The appearance of static liquefaction implies nothing more than imposing undrained conditions to the general, theoretical framework of soil behaviour. The most complete way to define this theoretical framework is by considering constitutive relations. The basic elements elasticity, yield locus (f), plastic potential (g) and hardening rule χ, depending on both plastic deviatoric and volumetric strains) determine the formulation of the stiffness matrix, which relates stresses to strains (see e.g. Muir Wood, 2004). After elaboration of the mutual relations, an apparently complicated stiffness matrix is found in the following formulation for triaxial effective stress states (De Jager, 2006):

$$\begin{bmatrix} \delta p' \\ \delta q \end{bmatrix} = \left[\begin{bmatrix} K & 0 \\ 0 & 3G \end{bmatrix} - \frac{\begin{bmatrix} K^2 \frac{\delta f}{\delta p'} \frac{\delta g}{\delta p'} & 3GK \frac{\delta f}{\delta q} \frac{\delta g}{\delta p'} \\ 3GK \frac{\delta f}{\delta p'} \frac{\delta g}{\delta q} & 9G^2 \frac{\delta f}{\delta q} \frac{\delta g}{\delta q} \end{bmatrix}}{K \frac{\delta f}{\delta p'} \frac{\delta g}{\delta p'} + 3G \frac{\delta f}{\delta q} \frac{\delta g}{\delta q} - \frac{\delta f}{\delta \chi} \frac{\delta \chi}{\delta \varepsilon_p^p} \frac{\delta g}{\delta p'} - \frac{\delta f}{\delta \chi} \frac{\delta \chi}{\delta \varepsilon_q^p} \frac{\delta g}{\delta q}} \right] \begin{bmatrix} \delta \varepsilon_p \\ \delta \varepsilon_q \end{bmatrix} \quad (1)$$

In which isotropic linear elasticity is combined with isotropic non-associative hardening-softening single-surface elasto-plasticity. The elaboration for undrained conditions however yields a much more simple formulation of the effective stress path:

$$\frac{\delta q}{\delta p'} = -\frac{\frac{\delta f}{\delta p'}}{\frac{\delta f}{\delta q}} + \frac{\frac{\delta f}{\delta \chi} \frac{\delta \chi}{\delta \varepsilon_p^p}}{K \frac{\delta f}{\delta q}} + \frac{\frac{\delta f}{\delta \chi} \frac{\delta \chi}{\delta \varepsilon_q^p}}{K \frac{\delta f}{\delta q}} \frac{\frac{\delta g}{\delta q}}{\frac{\delta g}{\delta p'}} \quad (2)$$

It is often assumed that for most situations hardening due to plastic compression is of minor importance for the behaviour of granular soils (e.g. Muir Wood, 2004), which means that the second term at the right hand side can be neglected. What is left is a basic term for the current yield locus

$$\left(\frac{\delta f}{\delta p'} \Big/ \frac{\delta f}{\delta q} \right)$$

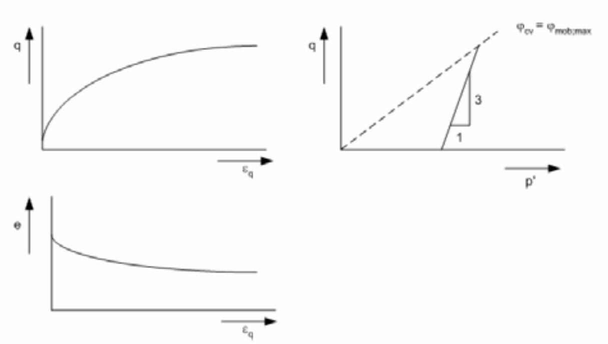
together with a term which describes the hardening of the soil due to deviatoric strains

$$\left(\frac{\delta f}{\delta \chi} \frac{\delta \chi}{\delta \varepsilon_q^p} \Big/ K \frac{\delta f}{\delta q} \right)$$

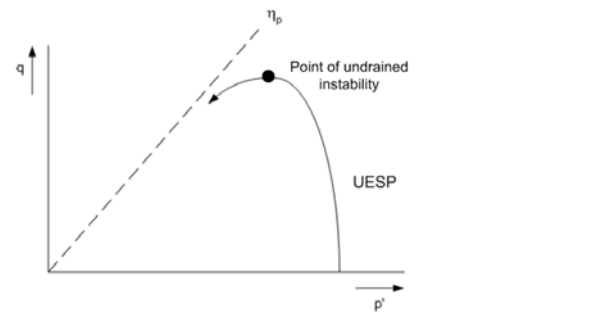
which is multiplied by a term which is literally a formulation of the stress-dilatancy relation

$$\frac{\delta g}{\delta q} \Big/ \frac{\delta g}{\delta p'}$$

The basic elements of constitutive modelling can thus easily be distinguished in the undrained stress path. In literature - at least literature which presumes Cam-Clay type of yield loci - the points of instability are often related to the formulation of the yield locus, which also contains a peak (Lade, 1992; Imam et al., 2005). This assumption can be explained by the formulation of the undrained stress path in equation (2) and the notion that the last term becomes very small for strongly contractive behaviour. A physical explanation for the peak in the yield locus is however lacking and a Mohr-Coulomb type of formulation would be more likely (De Jager, 2006). The peak in the undrained effective stress path should therefore primarily be attributed to the plastic potential (and stress-dilatancy relation), combined with diminishing hardening and a limit value of the yield locus.



(a)



(b)

Fig. 1 a) Drained behaviour of strongly contractive soils (triaxial loading); b) Undrained effective stress path (UESP) and resulting liquefaction.

The meaning of the preceding considerations can best be illustrated by an example. Figure 1a shows the drained deformation of strongly contractive sand with the mentioned characteristics. A simple way to describe the observed behaviour is by relating the mobilization of the current strength η_y (= q/p') below the critical state strength η_p to the (plastic) deviatoric strains ε_q (see Muir Wood, 2004).

If undrained conditions are imposed, the isotropic effective stress level p' has to decrease due to the tendency to contract. At the same time, the hardening is diminishing and the critical state strength should be approached asymptotically. This is only possible if a point of instability appears in the undrained effective stress path, as presented in Figure 1b.

Critical State

The concept of Critical State in terms of the void ratio and the isotropic stress at which the soil deforms at constant stress and constant void ratio, was first formally introduced by Roscoe et al. (1958) and is mostly attributed to Schofield & Wroth (1968), who applied this concept in their Critical State Soil Mechanics (CSSM) formulation. However, the relationship between the critical void ratio, initial void ratio and isotropic consolidation stress, as well as the laboratory determination of the so-called Casagrande critical void ratio (1936, 1938) was already clearly described by Taylor (1948). The main difference with the early researchers is that the isotropic stress p' is explicitly added to the critical state definition. For a more detailed elaboration the reader is referred to Schofield & Wroth (1968) and Muir Wood (1990).

The following drawbacks when using the CSSM-concept for the modelling of sand can however be identified:

- Dilative soils also tend to show a little contraction directly after application of a load, which may be sufficient for the initiation of liquefaction.
- Weakly contractive soils tend to show more contraction than needed to reach the Critical State Line (CSL).
- Describing the behaviour of structured sand is complicated.
- The concept verification at low stresses is difficult.

The first two drawbacks suggest respectively that stress paths are not always directed towards the CSL and that stress paths may intersect the CSL in particular situations. Both are essential for the description of liquefaction behaviour, as they suggest that (moderately) dilative soils are susceptible to liquefaction as well. The differences which were found for sandy and clayey soils were partly reason to define the steady state (Poulos, 1981). In this article the difference is ignored and the term critical state is used, following the findings of Been et al. (1991) that both states are identical for the sands tested. The two latter drawbacks are generally applicable. In spite of these restrictions, the critical state has shown to be useful for the formulation of a behaviour parameter.

State parameter/modified state parameter

The state parameter, defined by Been & Jefferies (1985), is a description of the physical condition of state in a parameter, which ideally combines the influence of void ratio, mean effective stress and a fabric parameter which characterises the arrangement of the sand grains. The state parameter (see eq. (3)) is defined as the difference in void ratio between the current and critical state:

$$\Psi = e - e_{cs} = e - \lambda \log p' \qquad (3)$$

Been & Jefferies (1985) postulate that sand has a unique structure at the critical state condition with a unique repeatable particle arrangement. A direct measurement of soil fabric in critical state conditions could confirm the correctness of this hypothesis. As clearly demonstrated by Been & Jefferies (1985) the state parameter describes the drained or undrained response of sand in triaxial testing better than the relative density.

A cautious application of the state parameter is advised since the sign of the state parameter can be misleading for the sand behaviour. Moderately dilative sand can result in liquefaction due to the small contraction before the dilative behaviour starts to dominate. A state parameter up to -0.10 can result in an undrained contractive response. The state parameter concept involves the isotropic effective stress but not the deviatoric stress nor the Lode angle (1925), which makes prediction of anisotropic soil response troublesome. A method to circumvent this problem is defining the state parameter at the maximum mobilised strength for undrained loading as a function of the applied Lode angle in accordance with the Mohr-Coulomb model. In this way the deviatoric stress is taken into account appropriately. The resulting modified state parameter Ψ_{mod} is defined as the difference in void ratio between the current state and the critical state at the mean effective stress corresponding to the maximum mobilised strength state (i.e. instability point, e_{cr}) for triaxial compression.

Instability line/-framework

The principle of the instability line was first introduced by Lade (1992, 1993), who clearly made a distinction between instability and failure for materials exhibiting non-associated flow behaviour. An instability line is the linear representation in the q-p' plane (see Figure 2a) of the top of the undrained effective stress paths. In natural conditions the soil can be at its instability point without resulting in instability. It should be noted that it is not possible to model liquefaction behaviour with an associated flow rule, as the point of instability coincides with the phase transformation point, thereby preventing the appearance of instability.

According to Lade (1992), a failure surface does not include all instability points, which generally fall well within the failure surface as obtained from drained tests (as clearly indicated in Figure 2a). More precisely, for triaxial compression the undrained instability points at the peak of the undrained effective stress paths occur even below the zero-dilatancy surface for drained behaviour (see figure 2b), at which the volumetric strain rate changes from contraction to dilation. Therefore, a failure condition expressed in terms of the maximum stress differences obtained from undrained tests initiated at the hydrostatic axis would clearly underestimate the true effective strength of the soil. Small disturbances such as load differences and even volumetric creep may

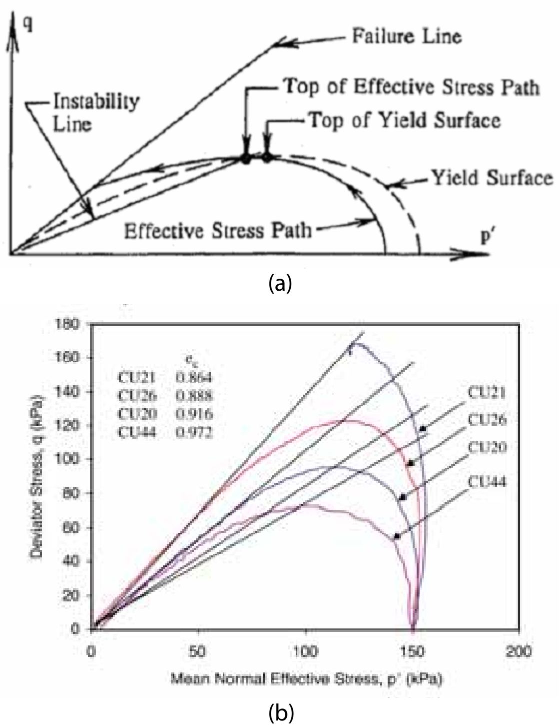


Fig. 2 a) Location of instability line for loose sand (Fig. 7 from Lade (1992)); b) Variation of instability line with varying void ratio after consolidation e_c (Fig. 3 from Chu et al. (2003)).

initiate undrained conditions in loose fine sands and silts resulting in the instability of the soil mass. Under drained conditions the soil will remain stable in the region of potential instability.

Chu et al. (2003) propose a new framework for the analysis of granular soil slopes using the previous described CSL and modified state parameter. The downside of their elegant framework, which is stated to enable the analysis of both loose and dense sand slopes, is that uncertainties regarding the liquefaction potential close to the CSL are not taken into account. Furthermore, taking into account consolidation of the soil would indicate whether or not instability also occurs during undrained loading of dilative soils, following the static and cyclic liquefaction definition of Castro (1969).

Simplified modified state parameter (SMSP) framework

The main purpose of the simplified modified state parameter framework is to predict the initiation of static liquefaction. The resulting model incorporates the modified state parameter, which is based on the critical state concept, and the undrained instability line concept and is notably extended with regard to the following aspects: a) after advanced site specific laboratory testing the contractant behaviour of moderately dilative material is taken into account by assuming a transition between drained and undrained behaviour at $\Psi_{mod} \sim -0.10$; b) a correction factor is taken into account for the undrained response for anisotropic soils; c) simplified stochastic analysis of soil and soil parameter variability, model uncertainty and geometrical uncertainty.

The following steps are taken into account using the SMSP framework:

- Determination of in-situ density/state parameter from interpretation of CPT(U) data for analysis of modified state parameter profile and comparing results with borehole data.
- Explicit rough correction for undrained response for anisotropic soil conditions. The slope of the instability line varies with the direction of loading (see e.g. Imam et al., 2005). It is thereby an appropriate measure for the susceptibility of liquefaction of stress points during anisotropic loading conditions as well. However, as anisotropic loading and instability are not coupled in conventional, commercial packages, iterative calculations are required to incorporate anisotropic loading.
- Implementation of instability line concept in discrete layers in Hardening Soil model in Plaxis (Vermeer, 1978).

- Stress generation using incremental weight generation (Brinkgreve et al., 2002).
- Staged construction/ excavation with updated mesh and staged adaptation of soil parameters.
- Failure analysis by both incremental strength reduction and weight increase.
- Approximate simulation of excess pore pressure generation in undrained shear by applying Skempton's ß-parameter. The simulation requires initial uncoupling of the hydrostatic water pressure from the soil input parameters, i.e. incorporation of submerged weights for soils below the freatic surface. Subsequently, the chosen value of Skempton's ß-parameter regulates the generation of excess pore pressures during an *undrained* safety analysis.
- Performing 2n+1 analyses for a number of independently assumed variables (Duncan, 2000).

Project description dredge sludge depot Hollandsch Diep

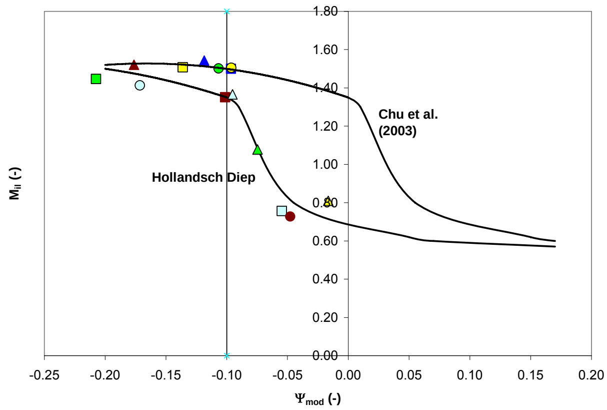
The dredged sludge depot Hollandsch Diep is a DC&M contract and involves the dredging of a disposal pit with a capacity of 10 million m^3 in the river Hollandsch Diep (see Figure 3a). The river Hollandsch Diep is typically 4-5 m deep and the depot after construction has an approximate depth, width and length of 38 m, 500 m and 1200 m respectively.

Soil investigation and resulting geometry

The subsoil conditions in the project area are very heterogeneous and typically consist of very fine Holocene silty sand layers from river bottom till ~ -18 m NAP. Under these Holocene layers a plastic Pleistocene clay layer (Formation of Kedichem) with varying thickness is overlying the deeper silty Pleistocene sand layers. The medium grainsize d_{50} of both types of sand layers varies between 70-120 μm with a uniformity coefficient d_{60}/d_{10} of 2-4.

Prior to award of contract, a total of 102 CPT's and 32 boreholes were lowered by the Client, while sieve analyses, minimum and maximum dry density testing and conventional triaxial testing were undertaken in the laboratory. After award of contract, advanced drained and undrained triaxial tests were carried out to determine the required soil parameters for the SMSP model. The resulting data points of the modified state parameter versus the slope of the instability line are presented in Figure 3b, together with the trendline according to Chu et al. (2003). However, it can be seen that the trendline has to be relocated in order to fit the

(a)



(b)

Fig. 3 a) Artist impression of dredge sludge depot Hollandsch Diep; b) Laboratory data of Modified State parameter versus slope of instability line M_{IL} (=q/p').

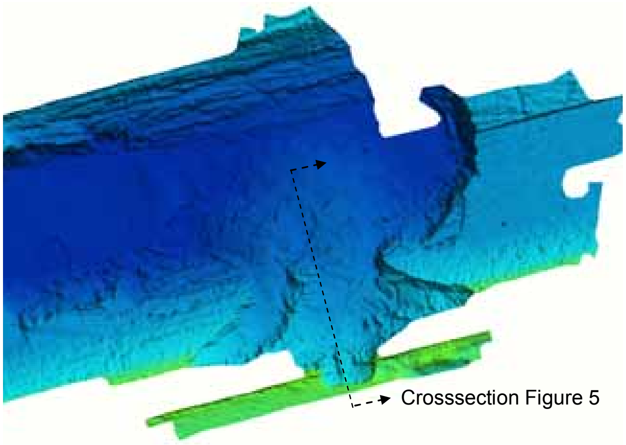
obtained data set. The transition between drained and undrained material behaviour lies around Ψmod = -0.10, which is in agreement with the findings of Castro (1969), Ishihara (1993), Jefferies & Been (2006) and others.

The CPT(U) data and some density cone data were converted into relative density and state parameter profiles by using correlations from Lunne et al. (1997) and Shuttle et al. (1998). The amount of uncertainty involved in the direct or indirect state parameter determination was significant (Ψ ± 0.05) where the indirect, relative density based method resulted in a lower boundary which was adopted for project application.

The original client's feasibility design assumed slopes of 1 (v):4(h) and awarded a bonus for making the slopes even steeper, increasing the volume of the depot. As a result of the analysis with the SMSP model, the design slopes of the consortium Sassenplaat typically had 1(v):4(h)-1(v):5(h) slopes in the Holocene layers and 1(v):5(h) in the Pleistocene sand layers. To allow for inaccuracies inherent in a dredging process with different types of equipment, the Pleistocene sand slopes are occasionally even excavated at 1(v):7(h).

Model verification and case histories

The predictions of the SMSP model were verified by various intentionally induced failures in the middle of the dredge depot. Steep front slopes were cut with a Cutter Suction Dredger (CSD) until failure occurred within several days after construction. Pre- and post surveys were compared and analysed with the model predictions. The results were used to determine the effect of several uncertainties on instability resulting in a quantification of the safety margin with implicit definition of equipment uncertainty for the following construction/excavation stages. During the excavation of the slopes of the dredge depot several small and larger failures occurred, involving volumes ranging from ~6000 to 350.000 m^3. On all accounts the heterogeneous, very loose, clayey, very silty sand layers above or below the Kedichem clay layer were involved in the instability. The most likely triggering events were generally construction related: temporary steeper slopes, the falling of anchors and spuds and on other occasions the building up of excess pore water pressures due to the construction activities in the slope.



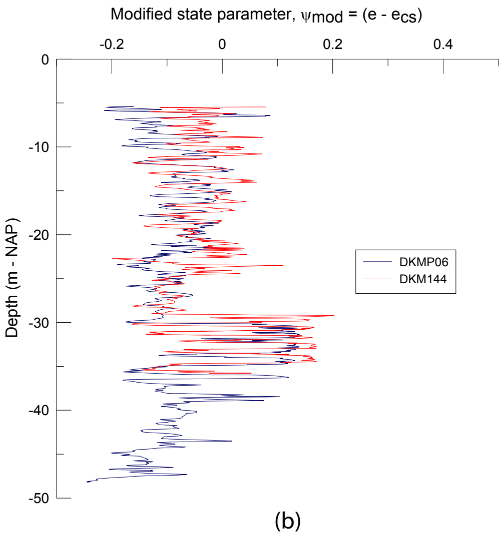


Fig. 4 a) Underwater survey of dike failure of August 26th, 2007 (~350.000 m^3) (source: Combination Sassenplaat); b) Modified state parameter profile at failure location.

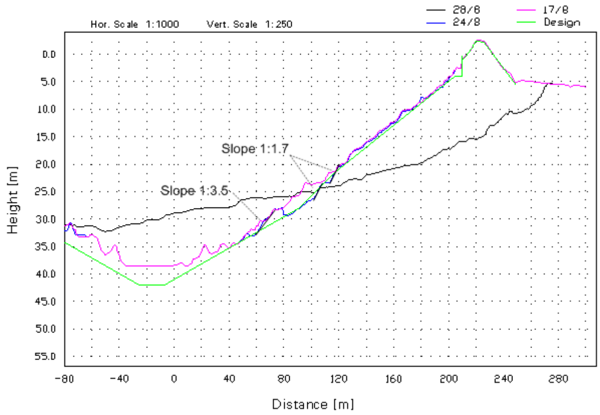


Fig. 5 Graphical representation of cross-section dike failure August 26th, 2007 and design slope, constructed slope and slope after instability (source: Combination Sassenplaat).

In Figures 4a and 4b, the bathymetric survey after the largest instability and the modified state parameter profile are presented respectively. One of the instabilities involved both the full slope and constructed dike section (see cross-section Figure 5). The extensiveness of the instability was most likely the consequence of an unfortunate combination of the following factors: the temporary existence of multiple, locally steep slopes as a result of the dredging operations, the use of water jets to increase the dredging production, non-occurrence of Kedichem clay layer, and the presence of a very loose clayey silty sand pocket/trough in the Pleistocene layer. Back calculation of the initiation of instability resulted in a safety factor ranging between 0.60 and 1.10 resulting in a high probability of failure. Unfortunately, it's not possible to predict the evolving processes after the initiation of static liquefaction with the SMSP model, as it is not possible to carry out coupled calculations.

Conclusions and recommendations

The presented simplified modified state parameter (SMSP) framework combines the concepts of Critical State (Schofield & Wroth, 1968) and stress-dilatancy (Rowe, 1962) with the modified state parameter (after Been et al., 1985, 1991 and Chu et al, 2003) as governing parameter for the resulting soil behaviour. Within reason, the resulting description for initiation of static liquefaction can be expressed as part of normal soil behaviour. However, at low deviatoric stress levels Rowe's stress-dilatancy relation does not describe the behaviour of soils very well, because the structure of the soil affects the deformation mechanism as well. Furthermore, Rowe's stress-dilatancy relation does not account for the grain crushing occurring at extremely high mean effective stresses (Yamamuro & Lade, 1997; Coop, 1990).

Structure (or soil fabric), anisotropy and localisation should be included in the description of strength and deformation as well as in the testing of the soil.

Despite the discussed limitations, the SMSP framework successfully captured the initiation of the planned and unplanned failures at the Hollandsch Diep project and allowed for project optimisation and risk reduction. The main achievements for Dutch engineering practice were that effects of both effective stress paths and -to a lesser extent- strength anisotropy in a layered subsoil can be analysed for the initiation of static liquefaction. In contradiction to Silvis & De Groot (1995) the Pleistocene layers were liquefiable as well and the slopes at depth needed to be more gentle.

From both academic and practical viewpoints, the following recommendations are believed to result in more insight into the material behaviour before, during and after liquefaction, to improve the site specific predictability and subsequently to result in more reliable predictions of initiations of liquefaction, enabling more reliable designs of potentially liquefiable sites:

- Scale testing in a fully monitored, tilting, hydraulic tank.
- Comparison of class 1-2 CPTU data with laboratory testing data of 'undisturbed' soil samples, obtained by applying a modern in-situ freezing and coring technique, to establish more reliable direct modified state parameter relationships.
- Fully coupling of stress–strain and groundwater flow/consolidation behaviour.
- Implementation of a dynamic large strain (ALE) formulation to capture the post-initiation behaviour.
- Incorporating full stochastic analysis according to Hicks et al. (2005).

Acknowledgements

The authors wish to thank both the contractors' combination Sassenplaat and the Public Works Department Zuid-Holland for the permission to use both the soil- and project data. Special thanks are due to Bart Hooiveld and Bart van Knapen for their participation in implementing the simplified modified state parameter model in the project 'Dredge Sludge Depot Hollandsch Diep'.

Editorial note: this article has been presented at the 12th International Conference of the International Association for Computer Methods and Advances in Geomechanics (IACMAG), October 1-6, 2008 (Goa, India). Richard de Jager has won the Ingeokring Student Award 2006-2007 for 'Best thesis in the field of Engineering Geology'.

References

Been, K. & Jefferies, M.G. (1985). A state parameter for sands. *Géotechnique*, **35**(2), 99-112.

Been, K., Jefferies, M.G. & Hachey, J. (1991). The critical state of sands. *Géotechnique,* **41**(3), 365-381.

Brinkgreve, R.B.J. et al. (eds) (2002). *Plaxis 2D–Version 8*. A.A. Balkema Publishers, Lisse.

Casagrande, A., (1936). *Characteristics of cohesionless soils affecting the stability of slopes and earth fills*. Presented at the meeting of the designers section of the Boston Society of Civil Engineers, Nov. 13, 13-32.

Casagrande, A., (1938). The shearing resistance of soils and its relation to the stability of earth dams. *Proc. Soils and Foundation Conference of U.S. Engineer Department*, June 17, A1-A20.

Castro, G. (1969). *Liquefaction of sands*. Ph.D. thesis, Harvard University, Cambridge, Massachusetts (USA).

Chu, J., Leroueil, S. & Leong, W.K. (2003). Unstable behaviour of sand and its implication for slope instability. *Can. Geotech. J.*, **40**(5), 873-885.

Coop, M. R. (1990). The mechanics of uncemented carbonate sands. *Géotechnique*, **40**(4), 607-626.

Duncan, J.M. (2000). Factors of safety and reliability in geotechnical engineering. *J. Geotech. and Geoenvir. Engrg.*, **126** (4), ASCE, 307-316.

Groot, M.B. de (2004). Liquefaction, flow and settlement of sand in dredging, hydraulic fill and flow slides. *Proc. International Conference on Civil and Environmental Engineering,* University of Hiroshima (Japan), 1-14.

Hicks, M.A. (2003). Experience in calibrating the double-hardening constitutive model Monot. *Int. J. Numer. Anal. Methods Geomech.*, **27**(13), 1123-1151.

Hicks, M.A. & Onisiphorou, C. (2005). Stochastic evaluation of static liquefaction in a predominant dilative sand fill. *Géotechnique*, **55**(2), 123-133.

Imam, S.M.R., Morgenstern, N.R., Robertson, P.K. & Chan, D.H. (2005). A critical-state constitutive model for liquefiable sand. *Can. Geotech. J.*, **42**(3), 830-855.

Jefferies, M.G. & Been, K. (2006). *Soil liquefaction. A critical state approach*. Taylor & Francis, Oxon (UK).

Koppejan, A.W., van Wamelen, B.M. & Weinberg, L.J. (1948). Coastal flow slides in the Dutch province of Zeeland. *Proc. 2nd ICSMFE*, **5**, Rotterdam (The Netherlands), 89-96.

Lade, P.V. (1992). Static instability and liquefaction of loose fine sandy slopes. *J. Geotech. Engineering*, **118**(1), 51-71.

Lade, P.V. (1993). Initiation of static instability in the submarine Nerlerk berm. *Can. Geotech. J.*, **30**(6), 895-904.

Lode, W., (1925). Versuche uber den Einfluss der mittleren Hauptspannung auf die Fliessgrenze, Z. Angew. Math. Mech., **5**, 142.

Lunne, T., Robertson, P.K. & Powell, J.J.M. (1997). *Cone Penetration Testing in Geotechnical Practice*. Blackie Academic and Professional.

De Jager, R.R. (2006). *The behaviour of soils during static liquefaction*. M.Sc. Thesis, Delft University of Technology, Fac. CiTG, section Geo-Engineering, Delft (The Netherlands).

Ishihara, K. (1993). Liquefaction and flow failure during earthquakes - 33rd Rankine Lecture. *Géotechnique*, **43**(3), 351-415.

Molenkamp, F. (1983). *Elasto plastic double hardening model Monot (3rd rev.)*. Rep. no. CO-218595, Delft Geotechnics, Delft (The Netherlands).

Molenkamp, F. (1989). *Liquefaction as an instability*. Report of ISSMFE Technical Committee on Mechanics of Granular Materials, to 12th ICSMFE, Rio de Janeiro, 157-163.

Molenkamp, F. (1991). Material instability for drained and undrained behaviour. Part 2: Combined uniform deformation and shear-band generation. *Int. J. Numer. Anal. Methods Geomech.*, **15**(4), 169-180.

Molenkamp, F., Choobbasti & Heshmati, A.A.R. (1998). Modelling of liquefaction and flow of water saturated flow. In: M.J. Adams, R.A. Mashelkar, J.R.A. Pearson & A.R. Rennie (Eds.), *Dynamics of complex fluids.* Imperial College Press/The Royal Society, 446-468.

Muir Wood, D. (1990). *Soil Behaviour and Critical State Soil Mechanics*. Cambridge University Press (UK).

Muir Wood, D. (2004). *Geotechnical modelling*. Spon Press (UK).

Roscoe, K.H., Schofield, A.N. & Wroth, P.W. (1958). On the yielding of soils. *Géotechnique*, **8**(1), 22-53.

Poulos, S.J. (1981). The steady state of deformation. *J. Geotech. Eng.*, **107**(5), 553-561.

Rowe, P.W. (1962). The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 269*, 500-527.

Schofield, A.N. & Wroth, C.P. (1968). *Critical State Soil Mechanics*. McGraw-Hill, London (UK).

Shuttle, D. & Jefferies, M. (1998). Dimensionless and unbiased CPT interpretation in sand. *Int. J. Numer. Anal. Meth. Geomech.*, **22**(5), 351-391.

Silvis, F. & De Groot, M.B. (1995). Flow slides in the Netherlands: experience and engineering practice. *Can. Geotech. J.*, **32**(6), 1086-1092.

Stoutjesdijk, T.P., Groot, M.B. de & Lindenberg, J. (1998). Flow slide prediction method: influence of slope geometry. *Can. Geotech. J.*, **35**(1), 43-54.

Taylor, D.W. (1948). *Fundamentals of soil mechanics*. John Wiley & Sons, London (UK).

Vermeer, P.A. (1978). A double hardening model for sand. *Géotechnique*, **28**(4), 413-433.

Yamamuro, J.A. & Lade, P.V. (1997). Static liquefaction of very loose sands. *Can. Geotech. J.*, **34**(6), 918-928.

Professor's Column: Measuring is Knowing...or is it?

Prof. dr. ir. Jacob Fokkema & Prof. dr. ir. Kees Wapenaar

It is a conventional wisdom that *Measuring is Knowing*. In fact, it is one of the oldest dicta of the engineer. In general it is not true. Of course it seems straightforward: when you measure an object with a flexible steel ruler, the number on the ruler is a quantitative indication of, for example, its length. Then one forgets that a person's mind is needed to interpret the reading as the length of the object. Hence the reading is always correct, the interpretation can be wrong. To state it in a formal way: you need a theory to convert your measurement into knowing. That is also the message of our most famous football player Johan Cruijff: you only see it when you understand it.

In seismic exploration for instance you need the wave theory of elastic waves and the knowledge of your sound source to convert the terabytes of recorded data into an image of the subsurface of the Earth. This is the active mode. You record the reflected sound waves after the shot was fired. Can we use the same technique when we listen to the ambient noise of the Earth? The surprising answer is that we indeed can. It has always been thought that noise doesn't carry any information. Think of the noise on your old gramophone records: it is a nuisance that masks the information (the music). You would rather be able to suppress it than having to listen to it. This has also always been the attitude in seismic exploration: first try to suppress the noise in the seismic data as much as possible and only then use your most advanced wave theory-based imaging methods to image the Earth's interior. However, since the turn of the century new theories have emerged that overhaul the traditional views on noise and diffuse wave fields. Contrary to their definition, diffuse wave fields appear not to be fully disorganised and without any information. It has been shown theoretically and experimentally that the geology of the Earth leaves an imprint on ambient seismic noise which is characteristic for the geology, just as a fingerprint identifies its owner. What was even more surprising was the fact that this imprint can be unravelled and turned into an image of the subsurface without knowing the ambient noise sources.

The last example illustrates how we can obtain an image of the subsurface from listening to the interior sounds of the Earth, albeit at the expense of a more complicated theory.

The Earth sends out more signals and we monitor them from all sides: on land, at sea, in the air and from space. They are important as the dashboard readings on how Mother Earth is doing. The last years we got alarming messages: global temperature rise, CO_2 level- and sea level rise, to name just a few. The numbers are differently interpreted depending on the case where they are used, in some cases even contradictorily. Although observations are interpreted in their own right, it doesn't mean that they can be understood together in an extended context. What we need is an encompassing theory that hosts the complementary input of the different observations as different aspects of the same 'reality'. This would be helpful in accessing the realistic state of our vulnerable Earth.

Do you get the picture?

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Onze medewerkers werken aan een scala van projecten. Het betreft veelal multidisciplinaire projecten, die uitdagend en grensverleggend zijn, zoals de Noord/Zuid-metrolijn in Amsterdam, de rioolwaterzuiveringsinstallatie Amsterdam West, Spoorzone Delft, Ruimte voor de rivier projecten, bodemsanering Volgermeerpolder en buitenlandse projecten als de eilanden in de Kaspische Zee, drinkwaterzuivering in Afrika en havens en kustbescherming in Indonesië.

Onze advieswerkzaamheden omvatten het hele traject van planstudie, ontwerp en engineering, besteksvoorbereiding tot en met de uitvoeringsbegeleiding en projectmanagement. Om de groei en ontwikkeling van Witteveen+Bos in Nederland en het buitenland verder vorm te geven, zijn wij over de volle breedte van het werkveld op zoek naar (aankomende) talentvolle ingenieurs in de civiele techniek, werktuigbouwkunde, elektrotechniek of andere passende studierichtingen.

Als ingenieur bent u continu op zoek naar nieuwe uitdagingen. U heeft de ambitie het beste uit uzelf en uit de organisatie te halen en elk project succesvol af te ronden. U maakt het verschil. Uw ontwikkeling wordt ondersteund door een uitgebreid intern opleidingsaanbod en door vaktechnische studies. Voor pasafgestudeerden hebben wij een specifiek starterstraject. U ontwikkelt zich verder in een vaktechnische, management- of commerciële richting en afhankelijk van uw capaciteiten en persoonlijke doelstellingen heeft u een interessante en uitdagende positie binnen de organisatie. In overleg wordt uw standplaats bepaald. Een tijdelijke plaatsing in het buitenland behoort tot de mogelijkheden.

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De Ondergrondse

Paulien Kouwenberg *(Education Commissioner De Ondergrondse board 2007-2008)*
Paul Spruit *(Chairman De Ondergrondse board 2008-2009)*

We don't have to convince most of you that Geo-engineering is a field of work full of excitement and interesting projects. Despite this fact there's a growing lack of qualified engineers. The projects become bigger, more expensive and more complicated in time, but the press only pays attention to a project when something goes wrong. This will probably never change, but at the end of the day nobody mourns and just uses the underground structures like they have been there forever. Let's return to the problem that the number of new qualified engineers is by far not enough to fill in the vacancies. The only solution to this problem is to educate new and more people. That's why De Ondergrondse adapts this opinion, and therefore its main goal is to attract new students for the Master study of Geo-engineering.

The 2007-2008 board was the second board of De Ondergrondse after the merge with DIG. It was time to start organizing activities to make more students enthusiastic about Geo-engineering. A new way to achieve this is the organisation of lunch lectures. These are lectures given by a sponsoring company with a topic related to Geo-engineering. Students can enjoy a lunch and are in contact with Geo-engineering while the companies get in contact with the students. Last year three lunch lectures were given: starting with Boskalis about working abroad as a Geo-engineer, the second was from Deltares about Geobrain and the last lecture, given by Fugro, about the San Francisco submerged tunnel retrofit.

Furthermore, several excursions where organised. Two excursions went to the north south line in Amsterdam. The first was at the central station where vertical micro tunnelling construction was visited and the other one went to the Ceintuurbaan where the deepest station of the north south line is under construction. Another excursion went to Rotterdam central station where the construction site of the metro was visited. The highlight of the year was the study trip to Istanbul. The choice for Istanbul was made on basis of the Bosporus tunnel and the Turkish culture. The Bosporus tunnel will connect Europe with Asia and is under construction in a tectonically active area. Johan Haan will tell you more details about earthquake activity in Istanbul in his article on page 71 of this Newsletter. The Ondergrondse Newsletter issue of December 2008 dealt with the study trip as well.

To keep in close contact with the Geo-engineering department, the annual Christmas dinner and a barbeque (together with an ALV) were organised. Many Geo-engineering students and staff attended and it was nice to mix both groups. One of the other tasks is to guarantee the quality of the education. After all, attracting new students only doesn't solve the problem. Therefore, courses are evaluated together with the department in order to keep them attractive and maintain the high level of education which TU Delft is well known for. Last year was a great year with a lot of nice activities and new experiences and fun. The old board consisting of Auke Lubach, Daan de Clippelaar, Johan Haan, Paul Gerrits and Paulien Kouwenberg was followed up by the new board on November 13th, 2008. The new board consists of (from left to right in the photo below): Etienne Alderlieste (Commissioner), Paul Spruit (Chairman), Stijn Biemans (Treasurer) and Werner van Hemert (Secretary). The latter is studying Engineering Geology and is also a member of the editorial team of the Ingeokring Newsletter. A contribution to this Newsletter which was written by Werner can be found on page 69 (Hambach excursion).

If you want to keep up to date you can visit our website at www.ondergrondse.nl. The latest news on Geo-engineering and reports of activities can be read in the newsletter of De Ondergrondse. If you wish to receive this newsletter, or if you want to contact us, please send an email to info@ondergrondse.nl.

Whishing you, on behalf of the board, a cordial *Glück Auf*!

Engineering geologist abroad

Sabine Stam-Backx *(geotechnical engineer, Rio Tinto, Australia)*

What a change…from working on the Dutch levee bank system to an underground coal mine in drought affected Australia. 3 years ago my partner (a mining engineer from Delft) got a job offer with Rio Tinto Coal Australia to work as a mining engineer at their only underground coal mine in this country. So I figured: "why not, it's a once in a lifetime opportunity." We moved to Emerald in Central Queensland, exactly on the tropic of Capricorn. Not realizing how desperate this country is for engineers I decided to enjoy a few weeks of doing nothing while my partner started working. That didn't last too long. Once the word was out that there was an engineer in town doing nothing, the job offers started to come in. I decided to go and work at the same mine, Kestrel Coal. The first few months weren't exactly easy. Let's face it, even though you studied *Mijnbouwkunde en Petroleumwinning* in Delft, my actual mining knowledge wasn't exactly developed. I knew the basic concept of a longwall mine and that was about it. So when someone stepped into my office on my very first day and said: "you must be the new geo, are we gonna change the spacing of the cogs in the tailgate?", I was slightly concerned. No idea what cogs or tailgates were….

So the rock mechanics books came out again and how again does a rock bolt work?

All this is second nature now. After a few months of learning from my senior (who arrived three months after me) it was time to go and work on shift in the crews. There is no better way to get to know a mine. So I've learned how to install bolts of a continuous miner, put up pipes, and hose down conveyor belts… Of course, on a Saturday nightshift when you're tired, wet and dusty and you are struggling to keep up, you do wonder how you ended up there. Didn't I want to be a ballerina when I grew up???

We are nearly three years down the track. Besides my degree in Delft, I have added a postgraduate diploma in coal mine strata control. Mining is such an enormous industry in this part of the world that you can actually get a degree that specialises in just underground coal mining. I am hoping to add a Masters in mining engineering geomechanics to the list in 2009.

The job is still great. I try to go underground 3 times a week to do audits, geological mapping, discuss issues with crews and react to strata conditions that are deteriorating. Back on the surface this results in support design, hazard plans, risk assessments and much more. I never realised how varied jobs on a mine site are. One day you are the *engineer* analyzing data, trying to predict conditions, the next day you're organizing concrete trucks to fill up exploration holes.

So what's different in Australia? Luckily, the work culture is largely similar to the Dutch one. Open doors, first names and a lot of fun. Biggest difference is probably that they are a bit more polite and therefore don't always make quick decisions. And the uniform. Orange with reflective strips doesn't look good on anyone, but not having to think about what to wear to the office in the morning is a nice change from an office job! And they wash them for you!

Living in Australia is extremely easy. At first we were slightly concerned about moving to a small town. But it has worked out really well. Most people are here for work in the mining industry and their families live somewhere else. And in Australia that is usually still thousands of kilometres away. So everybody is in the same boat. Social life is not an issue! Of course life in a remote area takes some adjusting. The town luckily has most facilities (hospital, restaurants, cinema's, sportclubs), but I wouldn't recommend a shopping spree in this region. The nearest decent size town is Rockhampton, a three hour drive. Brisbane is an 80 minute flight away. Life is very relaxed with no traffic jams (the mine is 50 km out of town and the trip takes 40 minutes, every day, no matter what time you leave), no parking issues, no traffic lights and the salesman in the bike shop is still wondering why I bought a lock. I know all my neighbours really well, have a dog and the sun shines 340 days a year.

Flooding after heavy rainfalls.

But no seasons. Never thought I would miss them, but when summer is hot (40 degrees) and winter is less hot (17 to 25) the scenery doesn't change. No falling leaves, snow or bloom. But you can't have everything. The drought is taking its toll on a lot of farmers. Probably not as much in this region since last year. The town flooded, big time. After intensive rain for a week our artificial dam filled up (from 30% to full in five days) and a large part of town flooded. Water came 4 m over the spillway. Considering the fact that there hadn't been any water over the spillway since the early 90's, this was a major event in itself! Over 2,000 people got evacuated and the water stopped about 20 metres from our front door. So here we were, filling sandbags in the middle of the night. A bit ironic I guess, coming from a 'Hoogheemraadschap' in The Netherlands. Must admit I have expressed my concerns about the quality of sandbag filling in this part of the world. But I guess they haven't had as much practice….

If anything, the only negative thing about Australia is that it is so extremely far away from the rest of the world where friends and family live (and probably that they serve chips with lasagna??). This immense country has nature from snowy mountains to desert, rainforest and the Great Barrier Reef. If you love nature and want to work in the mining industry, than this is definitely the place to be!

Excursion to the Hambach lignite mine

***Werner van Hemert** (Secretary De Ondergrondse board 2008-2009)*

For the AES1720 Rock Mechanics course we went to Germany on March 27th, for an excursion to the Hambach mine. We left Delft early in the morning and arrived at the mine at 9 AM, where Dr. Robrecht Schmitz was already waiting for us. We started with some well-needed coffee, a presentation about the activities of RWE and an introduction to the Hambach mine.

Fig. 1 The 90 m high bucket wheel excavator excavating grey, clayey soil (photo by Arjan Kochx).

The Hambach open cast mine is one of the largest surface mines in the world. The mine follows a long tradition of lignite (or commonly better known as *brown coal*) mining in the area to the west of Cologne. Lignite doesn't conserve as much kJ/kg as normal coal (10,000 kJ/kg compared to 30,000 kJ/kg), but the lignite seams are very thick (70 m) and thereby the mining operations are very efficient. The lignite is won with extremely large machines, well known from Discovery Channel (see Figure 1). After the lignite is excavated, it is transported with conveyor belts to a depot and from there it is transported to the RWE electricity plant. 90% of the lignite is processed in power plants of RWE Power producing herewith 50% of the energy needed by North Rhine Westphalia (NRW). 10% of the lignite is processed in RWE Power's factories. In the Hambach mine, approx. 40 million ton of lignite is mined each year. In total, 8 machines are excavating the coal as well as the 310 m thick overburden which consists of clay, sand and gravel layers. Correspondingly, the amount of material moved on a daily basis is enormous. At present, the Hambach mine tops this figure by excavating more than 1 million ton of coal and overburden a day. The overburden materials are used internally to fill the void where the coal is already excavated. To fill up the void with excavated soil, pockets of clay are made which are hold in place by sand dams. Because all overburden soils are excavated at the same time, all soil types can arrive at the deposit machines. The sand/clay structure should be made quite precise to keep it stable. Therefore, Robrecht Schmitz (together with a few TU Delft Engineering Geology students) is working on a laser based IT system for RWE.

After the brief introduction we went towards the mine in quite an impressive truck. First we drove through a 'forest' with many small trees. These trees are grown there as they help to reduce dust and visual pollution. The second item we encountered were water treatment sites where the rainwater which is pumped out of the mine, is collected for further treatment. The groundwater level is being lowered far away from the mine at great depths and is partly used for the power plants. To avoid a larger lowering of this groundwater level, water pumped from the different aquifers in the vicinity of the mine is re-injected close to the vulnerable surrounding wetlands. Next, we saw the surface mine, stretched out as far as the eye could see. Inside there were

Fig. 2 The IT-system inside the control room of the bucket wheel excavator (photo by Arjan Kochx).

kilometres of conveyor belt and some tiny looking excavators at the end of it. When we drove towards the first excavator (excavating the first 30-40 m below ground level), the different sand, silt and clay layers could easily be identified. Most of the slopes showed local slope instabilities, Robrecht explained us about the challenges they encounter with silty soil layers.

After this, we went to the second bench (excavating 70-75 m below ground level). Here we visited one of the excavators, and went into the control room where Robrecht showed us how his system works (Figure 2): the information obtained by site investigation (borehole drilling, coring and geophysical well logging) and exploration is used to generate a three dimensional subsurface model. This model is overlain by the up-to-date geometry of the surface mine. The actual mine geometry is subtracted from the subsurface model. In this way the actual 'outcrops' of the different lithologies in the surface mine can be displayed in three dimensions. In addition, the position of the bucket wheel excavators is given by continuous accurate GPS measurements. In this way the actual position of the excavators and the position of the bucket wheel can be displayed in the three dimensional subsurface model which is continuously updated depending on the excavation rate of the excavator (Schmitz, 2006).

After the visit to the excavator, we went to the lignite layer. The thickness of the layer was at least 60 m and a 10 m vertical displacement was visible. Unfortunately we did not have enough time to visit the clay layers which contain the bimrocks (block in matrix rock) that Robrecht had presented in one of his Rock Mechanics guest lectures. These bimrocks are quite large and strong, and therefore impossible for the bucket wheel excavator to excavate. Our last visit was to the Sophienhöhe, rising 200 m above the original surface. Here, Robrecht showed us the nature that had settled (after recultivation) after the mining activities. There was a forest and a large pond with some ducks, of which Robrecht ensured us that RWE hadn't put them there especially for this occasion. At the end, RWE offered us a lunch at the cafeteria, which was a perfect ending of a very nice excursion.

Editorial note: see also the article about the Hambach lignite mine on page 50 of this Newsletter.

Literature

Schmitz, R.M. (2006). *Provision of resources for the city by the Hambach opencast mine: engineering geological aspects.* Paper no. 791, IAEG Congress 2006.

Living under the threat of an earthquake

Johan Haan *(Member De Ondergrondse board 2007-2008)*

Introduction

During the Geo-engineering study trip of De Ondergrondse to Istanbul we had the opportunity to visit the Kandilli Observatory and Earthquake Research Institute (KOERI). After arrival at the institute, a presentation about the history of the company and earthquakes within Turkey was given by Prof.dr. Gülay Altay.

Kandilli Observatory and Earthquake Research Institute

KOERI was founded in 1868 as the Imperial Meteorological Observatory at Pera Hill by the Frenchman Aristidi Coumbary. Unfortunately the observatory was destroyed in 1908 during political riots. The centre was re-established at a new site by the scientist Fatin Gökmen in 1910. The astronomical and seismological observatories were developed between 1911 and 1933. The ministry of education annexed the research institute in 1925, and the centre was annexed by the Bogaziçi University in 1983.

The mission of KOERI beholds several aspects:

- Continuous monitoring on a real-time basis of seismic activity in Turkey and record earthquake parameters such as epicentre coordinates, magnitude and depth.
- Informing all concerned governmental agencies for the initiation of effective emergency response and search & rescue operations.
- Educating graduate students, providing seismic data for researchers.
- Carrying out R&D projects on the seismic risk reduction and risk mitigation issues.

Seismic activity in Turkey

The major part of Turkey is situated on the Anatolian plate (Figure 1), which is moving westward with a relative displacement speed (compared to the Eurasian plate which is moving in opposite direction) of 24 mm/yr along the North Anatolian Fault Zone and 30 mm/yr in a southwestern direction in the Aegean Sea. The Arabian plate is moving in a northern direction with 18 mm/yr and the African plate with 10 mm/yr in the vicinity of Egypt. The North Anatolian Fault Zone is one of the world's most important active strike-slip faults, not only because of its remarkable seismic activity between 1939 and 1967, but also because of its significance

Fig. 1 Active tectonics in the Eastern Mediterranean region (source: http://atlas.cc.itu.edu.tr/~okay/diagrams_%20maps/MapActiveTectonicsInEastMediterranean.jpg).

for the tectonic activity of the Eastern Mediterranean region. The fault zone is about 1,500 km long, extending from the Karhova triple junction in eastern Turkey to mainland Greece. Over the last century, 122 earthquakes with a magnitude between 6 and 7.9 have hit Turkey. In comparison, the strongest earthquake that hit The Netherlands took place in Roermond in April 1992 and had a magnitude of 5.8. The 122 earthquakes in Turkey took a toll of 82,112 casualties and 558,279 damaged buildings. In total 1.5% of GNP is spent for re-constructing permanent housing, repair and rehabilitation of damaged buildings in the aftermath of the earthquakes. The earthquake risk is large, with an expectancy of 2.5 years for a 6.0-6.9 earthquake and 7.4 years for a 7.0-7.9 earthquake.

Since 1939, a westward migration of earthquakes has developed with major earthquakes in 1939, 1942, 1943, 1944, 1957, 1967 and 2 in 1999. Logic shows that the next earthquake will happen in the Marmara Sea, the connection between the Mediterranean and the Black Sea. The available data shows that Istanbul lives under the threat of a major earthquake: a 65% chance within the next 30 years. When and how hard an earthquake will strike is hard to predict as the list of years previously mentioned is irregular, yet the longer it waits the more powerful it will become.

KOERI activities

The major activity of KOERI is the continuous monitoring of seismic activity. When a major earthquake strikes, a quick response is essential in order to provide aid and assistance effectively. A direct phone line towards the prime minister, and SMS- and e-mail-services to organizations and authorities will give the different parties the possibility to start up rescue and emergency operations immediately. KOERI developed and operates the Istanbul Earthquake Rapid Response and Early Warning System. Amongst others, KOERI has placed 42 seismic stations around the Marmara Sea and 10 (24 bit resolution) strong motion stations are sited at locations as close as possible to the Great Marmara Fault Zone (Prince's Islands and specific coastal areas around the Marmara Sea). The motion stations are in on-line data transmission mode to enable Earthquake Early Warning. Continuous telemetry of data between these stations and the main data centre is realised with a digital spread spectrum radio modem system involving repeater stations selected in the region.

Considering the complexity of fault rupture and the short fault distances involved, a simple and robust Early Warning algorithm, based on the exceedance of specified threshold time domain amplitude levels is implemented. The band-pass filtered accelerations and the cumulative absolute velocity are compared with specified threshold levels. When any acceleration in a given station exceeds specific selectable threshold values it is considered a vote. Whenever 2 or 3 (selectable) stations vote within a selectable time interval, after the first vote, the first alarm is declared. The early warning information (consisting of 3 alarm levels) will be communicated to the appropriate servo shut-down systems of the recipient facilities, which will automatically decide proper action based on the alarm level. Depending on the location of the earthquake (initiation of fault rupture) and the recipient facility, the alarm time can be as short as about 8 seconds. The early warning signals will be transmitted to the end users by employing several communication companies as service providers. The encrypted early warning signals (earthquake alarm) will be communicated to the respective end users by FM, UHF and satellite communication systems. Besides a quick reaction, it is also very important to know where most help is needed. KOERI created a grid-map estimating the locations and the number of collapsed buildings per cell for this purpose (a useful aspect of this grid is the application of help by an emergency response centre. During the studytrip we visited such a centre which holds a food factory capable of producing 100,000 meals per day. Three mobile bakeries can produce 500 breads per hour at any location).

The KOERI department itself houses one of the largest earthquake strong motion data acquisition facilities in the region. The inventory encompasses 90 digital 3-axial recorders with relevant peripheral equipment. Most of the strong motion recorders are placed as stand-alone dial-up units in Istanbul. Currently, 4 structures are instrumented to record their earthquake response: Hagia Sophia Museum, Sultan Ahmed Mosque, Is-Bank Tower and FSM Suspension Bridge). About 10 strong motion recorders are kept in the laboratory for post-earthquake investigations. A numerical model of the most important structures in Istanbul have been created to predict the response to a certain type of earthquake and to locate problematic areas which demand structural improvement.

References

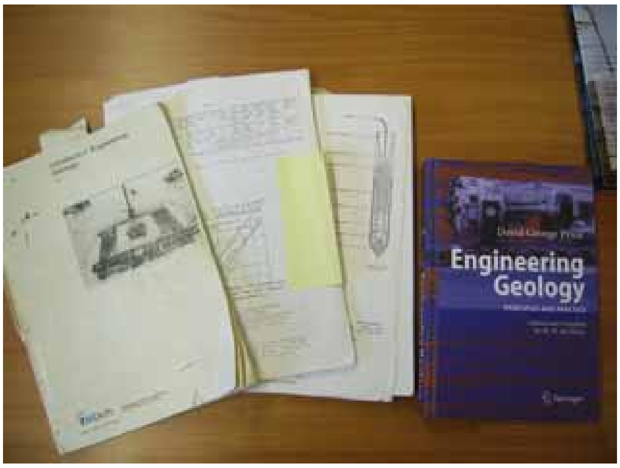
- Presentation by Prof.dr. Gülay Altay on April 7th, 2008
- www.koeri.boun.edu.tr/eng/topeng.htm
- www.koeri.boun.edu.tr/depremmuh/EWRR/EWEngWeb/TurAnaSayfa_eng1.htm
- nl.wikipedia.org/wiki/Aardbeving_bij_Roermond

Book review: 'Engineering Geology, Principles and Practice'

Peter Verhoef *(Royal Boskalis Westminster nv, Papendrecht)*

Engineering Geology, Principles and Practice by David George Price (2009). Springer Verlag, Heidelberg. ISBN: 978-3-540-29249-4, 450 pages, €85,55.

Engineering Geology, Principles and Practice is a comprehensive book, which gives what the title promises. After his retirement, David Price had one main project that he would like to finish: the production of this book on engineering geology. This would be the synthesis of his professional life's work. He wanted to present the essentials of his approach to site investigation for civil engineering works.



David was a gifted teacher and an excellent engineering geologist. He had a clear mind and a talent to grasp the essentials of the often complex issues that are at stake in large construction projects. The lecture notes that he produced in Delft, which form the basis of the book, are a reflection of this clarity and judgment. When I started to work within the Soil Department of Boskalis in 2002, I noticed there was always a worn copy of David's TU Delft lecture notes lying on a table in one of the rooms. The notes are the 1985 copy, belonging to Theo Berkhout, one of David's students from the early 1980's. The notes are regularly consulted by members of our team and are, since a few months, replaced by the book which arrived shortly after it was printed in October 2008.

Just recently I wanted to check something related to the Menard Pressiometer test and looked for David's book in the office. I couldn't find our library copy and it is still missing. So, the lecture notes were needed again! The picture shows the notes, next to my personal copy of David's book (which I took with me from home).

When, back in 1982, I started to work for David Price as his scientific assistant, I got a copy of an earlier version of the lecture notes, which already were based on the basic framework that he developed together with John Knill from Imperial College. These rules were:

- All engineering works are built in or on the ground.
- The ground will always, in some manner, react to the construction of the engineering work.
- The reaction of the ground (its *engineering behaviour*) to the particular engineering work must be accommodated by that work.

David gives the following commentary on the philosophy of engineering geology as he calls it:

"The first premise would seem to be fairly obvious but it would appear that, not uncommonly, the work of designing and executing a project is sub-divided between various types of engineers, architects and planners so that no single person may have a comprehensive overview of the complete project. Thus the vital concept that the structure is but an extension of the ground may be lost, or even never acquired, by a particular member of the team in the course of his contribution of the work."

This sets the scene which is familiar to us in our daily work. I also work in teams of varying composition. And although within a dredging company most of my colleagues are aware of the importance of the conditions of the ground within and surrounding the dredging project, for some people matters related to the ground remain a vague and elusive business. One of our tasks as engineering geologists is to communicate again and again the matters related to the ground, as clear and to the point as we can.

A great conceptual aid in outlining the ground conditions for civil engineering projects are the engineering geological equations, which are explained in the first chapter of the book:

Material properties + mass fabric = mass properties

Mass properties + environment = the engineering geological matrix (or more loosely s*ituation*)

The engineering geological matrix + changes produced by the engineering work = the engineering behaviour of the ground

The concept of these equations and the clear way in which the reaction of the ground on engineering works is discussed in the second half of the book makes this book a welcome addition to the available literature of our profession. Truly *Principles and Practice*.

David Price fell seriously ill and died in 1999 with the book nearly finished. Five of his friends and colleagues have taken up the task of the final writing and editing. These are Robert Hack (ITC Enschede), Ian Higginbottom (former colleague from Wimpey Laboratories), John Knill (Imperial College, now deceased), and Michiel Maurenbrecher (TU Delft). The editor was Dr. Michael de Freitas from Imperial College. The result of their effort is really admirable. I find that the book answers to the intention that David had, to present "what engineering geology is about and how it is done."

Many earth scientists find themselves in industry at some time in their career. Not all of those have background knowledge of engineering. I think that in the future the amount of people entering the geotechnical engineering environment without a dedicated training will increase. For those people the book of David Price is intended as well. David himself was a palaeontologist who started his career as a bauxite exploration geologist. When in 1958 he came to work for the large construction company George Wimpey, he and his colleagues at Wimpey's Central Laboratory at Hayes, more or less invented the profession. David worked in an environment which Michael de Freitas calls an *industrial university* in the preface of the book. "At that time formal education and training in engineering geology did not exist and as David recalled: …no one really knew what they were doing; we followed the principles of our subject, used common sense, learnt from what had happened on site and talked to those who seemed to know more than we on the subject in hand." Fifty years later we have now the fruit of this effort in our hands.

I asked my colleague Linda Wubben, trained as a surface water hydrologist and geomorphologist, who joined our group in October 2008, what she finds of David's book. This is what she replied: "working as a soil specialist at a dredging company, knowledge of engineering geology is a prerequisite. As an earth scientist with no specific knowledge of engineering geology I found Price's book very useful. This book clearly explains the different aspects of engineering geology divided in two main parts, investigating the ground and behaviour of the ground. The writer does not use extensive formulas, but explains engineering geology with clear words and when necessary with the use of illustrations, tables, figures and examples. As a reader I understand the book perfectly and will probably use it very often in the future as a book of reference."

Thesis abstracts

Earthquake-induced pore pressures in calcareous sands supporting revetments

Sanne Brinkman

Cyclic loading during an earthquake can cause liquefaction in saturated soils. This leads to a loss of strength and possibly failure of overlying structures, such as revetments or breakwaters. A vast amount of research has already been performed on the behaviour of siliceous soils during cyclic loading, but the knowledge on cyclic behaviour of calcareous sands is limited. The latter is particularly important with regards to the many man-made islands in the Middle East. Therefore, the main objective of this study is to investigate the influence of the revetment geometry on the susceptibility to liquefaction of the underlying carbonate sand layer.

The cyclic behaviour of sands is best explained using the critical state soil mechanics framework. However, in this research (and in engineering practice) the cyclic stress approach is followed to assess initiation of liquefaction. Hereby the earthquake-induced loading, expressed in terms of cyclic shear stresses, is compared to the liquefaction resistance of the soil, also expressed in cyclic shear stresses. At locations where the loading exceeds the resistance, liquefaction is expected to occur. Using this approach, the pore pressures that cause liquefaction are linked to cyclic shear stresses.

The liquefaction resistance of calcareous sands is assessed using triaxial tests and the results are compared to the available literature. Stiffness and damping reduction curves from the laboratory tests are similar to standard curves for siliceous sands and do not show the trends observed in literature about calcareous sands. Calcareous sands generally have a slightly higher liquefaction resistance under cyclic loading than siliceous sands of the same relative density. The fundamental behaviour that causes this difference is not understood and requires additional research.

The dynamic loading is calculated using the computer programs SHAKE2000 (operating in one dimension in the frequency domain) and PLAXIS (a finite element program, operating in two dimensions in the time domain). The design earthquake (representative for the United Arab Emirates) is introduced at bedrock level. The revetment geometry is divided into four zones that are approximated by 1D situations. The equivalent linear stiffness and damping that result from the 1D approximations of SHAKE are used as input in PLAXIS. In order to match the hysteretic damping ratio of SHAKE, the viscous Rayleigh damping parameters of PLAXIS are modified until the amplification functions resulting from both programs coincide. 1D- and 2D simulations are performed in PLAXIS and the influence of the revetment geometry on the dynamic behaviour of underlying sand is investigated by inspecting cyclic stress ratios (CSR). The CSR values are converted into cone tip resistances required to avoid liquefaction, including a correction for calcareous sands. Finally the influence of plasticity (by comparing the linear elastic and Mohr-Coulomb model) and the stability of the embankment are assessed.

Sand near the surface that is not overlain by revetment material is subject to liquefaction at the design earthquake loading. The presence of the revetment geometry reduces the CSR in the top few metres of sand. However, the CSR close to the toe on the sea side is higher due to the presence of the revetment geometry. The 1D approximation does not show this as a location that will be liquefied, as the 1D approximation largely underestimates CSR values on the sea side of the toe. The loss of strength in the liquefied area may in turn cause collapse of the revetment. This is avoided by making the berm sufficiently wide, so possible liquefaction below the toe and subsequent failure of the berm do not affect the revetment stability significantly.

The influence of static shear stress and rotation of principal stress directions on the cyclic strength are not taken into account. If further research shows that the influence is significant, it is recommended to use an advanced model that is able to predict pore pressure generation as a function of stress direction rotation and static shear stress.

The use of data integration techniques for a better prediction of heterogeneities in the subsurface applied during site investigation for highway construction projects on soft soils

William Munsterman

Objective: The deformation of a road pavement results from the deformation of the road structure itself, and that of the soft ground it is built on. Therefore, knowledge of the subsurface helps to meet the strict design and performance specifications for highway evenness in both longitudinal and transverse directions.

The total engineering geological approach advocated by Fookes c.s. is adapted to motorway widening above the soft and heterogeneous soils of the Western Netherlands. It is proposed as an alternative to the current practice in site investigation.

Design and method: The current practice relies heavily on equally spaced CPT's and boreholes: a CPT spacing of 100 m with one borehole every 4 CPT's. In the alternative approach, first, the local geology is depicted based on 1:50,000 geological-, soil- and geomorphological maps, archived geotechnical data and walk-over surveys. A draft ground model is conceived, showing the expected architectural elements of the subsurface, with their frequency of occurrence and likely size inferred from the expert geological knowledge available. Second, the potential of the laser altimetry data available for the whole of The Netherlands on a 5 x 5 m grid is exploited. Variations in surface relief are tracked to reveal buried man-made and natural heterogeneities. Third, geoelectrical and multi-frequency electromagnetic techniques are applied to characterise the geometry and position of the heterogeneities in the vertical direction. Last but not least, all available data is integrated into an intermediate ground model used to optimise the spatial spreading of CPT's and boreholes of the next site investigation phase aiming to build the final ground model.

Results: The performance of the new approach to ground modelling is illustrated for a pilot case, the widening of a section of the highway A2 linking Amsterdam to Utrecht. The subsoil in this area consists of layers of peat and organic clays deposited in a backswamp environment. Around 2,500 yr BP, due to the higher activity of the river Angstel its floodwaters poured through the natural levees creating splays of large and small crevasse channels, which eroded and intersected the existing peat.

The laser surface altimetry data reveals the presence of many large crevasse channels in the pilot area. In the past, crevasse channels were 'lows' fringed by clays and peats in the landscape. When they were active, sand and silts were deposited in their bed. When their activity declined, the channels were filled progressively with clay. As a result of natural differential compaction accelerated by ground water table lowering, these crevasse channels are now 'highs' in the landscape with a narrow valley (residual channel). The geomorphological data correlates well with low frequency electromagnetic data acquired with a GEM-2. Sands saturated with fresh water have a lower electrical conductivity than clay and peat. Where man levelled off the ground surface, the GEM-2 data proves to be useful. Results are validated with the help of hand boreholes and CPT's.

Conclusion: 'Strong', shallow ground heterogeneities have the largest impact on the construction and long-term performance of highway evenness. Their frequency of occurrence can be predicted from geological expertise associated to regional maps. Their position in the horizontal plane can be inferred from readily available laser surface altimetry data and low cost electromagnetic surveys. Their geometry in the vertical direction can be estimated in theory from multi-frequency electromagnetic or geoelectrical resistivity data. Further research is needed to derive soft ground index properties from the geophysical response, and to discriminate better between 'soft' heterogeneities.

See also the author's contribution to this Newsletter at page 41.

Conceptual model of groundwater and heat flow in ATES

Johan Haan

Aquifer Thermal Energy Storage (ATES) is being applied in The Netherlands more and more. A conceptual model is created for the groundwater and heat flow in ATES systems. Different underground thermal energy storage systems are studied and other activities in the underground are reviewed as well to show that ATES is not the exclusive user of the shallow subsurface.

The thermal radius of a system (how far heat reaches in the ground with injection) is an important design parameter, especially with regard to interference. Interference is the result of overlapping of the warm and cold *bulb*, or loss of benefit. Interference can be the result of multiple ATES systems or within a single system. Time is a factor that should be taken into account when analyzing the performance of ATES systems. The ground and its water are more likely to be out of equilibrium rather than in equilibrium. Heat island effects and altering groundwater heads are among the time dependent features. In modelling, these factors are neglected for simplicity. Legislation demands no remaining effects in the ground due to ATES, which should not be wrongly interpreted as leaving the ground in its initial conditions.

After an overview of the time dependent effects, the partial processes taking place, i.e. advection, external groundwater flow, conduction, density flow, dispersion and influences of temperature on the hydraulic head, are explained. These partial processes are estimated through back of envelope calculations. The processes reviewed are of pure water without any gasses and chemical processes due to mixing of groundwater are disregarded for the sake of simplicity. Advection is the process where thermal energy is distributed over grains and groundwater. When the injected water is retrieved, 1% of the stored energy will remain in the ground due to the spreading zone heat transfer from water to grains and vice versa.

More significant is the loss through external groundwater flow, which is in this context the groundwater flow not induced by ATES (e.g. natural groundwater flow, other groundwater extractions). The stored energy will be pushed away from the injection point and replaced by in situ groundwater, diminishing the efficiency greatly. Quantification of this partial process by a back of envelope calculation is omitted due to the great variety of possibilities for external groundwater flow (velocity, parallel flow/point source).

Conduction is a process of small amplitude in comparison to advection in an aquifer, in the confining layers it is the other way around. Energy is lost by conduction, efficiency decreased, but the loss stabilises after several cycles creating 'isolating' layers since conduction is a very slow process in the ground. The difference in groundwater density from 283 to 288 Kelvin is only 0.05%, yet this difference will cause a pressure difference and consequently, flow. The resulting difference in groundwater flow due to this density difference can be of the order of 1%. Differences in groundwater flow due to salinity changes can have a 2.5% influence on groundwater velocity in comparison to cylindrical development. Dispersion is the scattering or diffusion of values away from the average. In ATES several types of dispersion can be distinguished. Thermal dispersion is the combination of conduction and mechanical dispersion. Mechanical dispersion is the combination of macro dispersion (heterogeneity or anisotropy) and micro-dispersion. The latter is the result of water flowing around the grains, but this effect is smaller in ATES than in ground contamination as heat flow will counteract differences in temperature.

The temperature effect on the hydraulic head can be read as the influence on the density and viscosity. The ratio of density divided by viscosity decreases by 13% if the temperature is altered from 283 to 288K, resulting in a decline in groundwater head. Vertical anisotropy is a point of attention as it greatly influences the thermal radius of an ATES system. The concept behind vertical anisotropy is simple, but measurements of the permeability within an aquifer and the lateral continuation are complicated. The calculations presented can be applied to assess the order of magnitude of the processes taking place in ATES before numerical calculations are performed. It will give a quick estimate of the influence area and points of attention for site investigation to create choices for the numerical model, with which a more advanced model can be created.

Study of the repeatability of the lateral stress oedometer, and the possibility to define elastic parameters and (cross-)anisotropy in Pot Clay with the lateral stress oedometer

Niels van Leeuwen

Anisotropy can have a significant impact on engineering design. However, it is often neglected and seldomly quantified. The lateral stress oedometer is designed for standard testing as a simple, relatively cheap tool which can find anisotropy in the horizontal plane on one specimen. Previous research concluded that the lateral stress oedometer can measure anisotropy and that the principal stress axes in the horizontal plane can be found. Assuming a minimum principal stiffness axis in the horizontal plane, a horizontal test can be performed along the minimum principal stiffness axis found in the vertical test. From this horizontal test the maximum principal stiffness axis can be determined. Finally, an inclined test can be performed along the maximum principal stiffness axis in order to prove or disprove cross-anisotropy.

22 tests have been performed with the lateral stress oedometer to study its applicability in finding the principal stiffness axes in a natural (cross-)anisotropic soil and in determining the soil stiffness parameters. For the testing program, Pot Clay from the Peelo Formation at Marum has been used. From the first series of 8 vertical tests the repeatability of the experiments has been studied and it is concluded that the stiffness axes in the horizontal plane can be found within certain limits. This is consistent with the results from previous studies. It is recommended to perform testing in a climate room to neglect the influence from external fluctuations, especially temperature.

With the second series of 12 tests, from specimens cut vertically and horizontally, the principal stiffness axes of the Pot Clay could be determined assuming linear elastic cross-anisotropy. For a linear elastic cross-anisotropic soil, the stress strain relation can be described by 5 independent variables: Young's modulus and Poisson's ratio in the horizontal symmetry plane, Young's modulus and Poisson's ratio in the vertical direction and the shear modulus in vertical direction. These can be determined analytically and numerically depending on the assumptions made. Both methods (analytical and numerical) lead to almost the same results after removal of outliers. Some variation in the test results may be due to the possibly wrong assumption that Pot Clay is cross-anisotropic.

Two inclined tests have been performed along the maximum principal stiffness axis. Results did not indicate cross-anisotropy. This can be explained by the errors in both the horizontal and vertical tests and the inhomogeneity of the Pot Clay. Since the horizontal and vertical tests are used to determine the direction of the principal stiffness axes, errors result in not measuring exactly along the principal stiffness axis during the inclined test. For the eventual testing of the assumption of cross-anisotropy, a larger number of tests would have to be performed. By applying unloading-reloading cycles during 3 vertical and 3 horizontal tests some general observations were made. The elasticity modulus increases significantly during an unloading-reloading cycle, while the Poisson's ratio decreases. Again, more tests are necessary to remove outliers and better capture this trend.

Modelling peat dike stability - Back-analysis of Direct Simple Shear test results

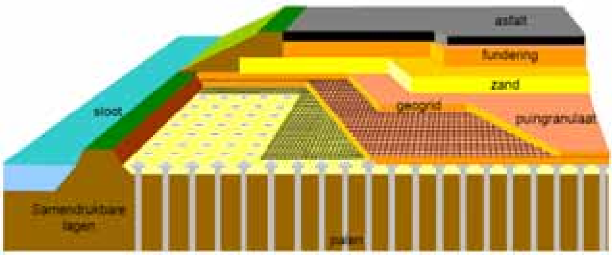
Koen de Jong

Flood defence systems in The Netherlands can be divided into primary and secondary defences. The secondary dikes in The Netherlands protect polders from flooding. Approximately 3,500 of the 14,000 km of secondary dikes are considered to be peat dikes. After the dike failure in Wilnis in 2003 it has become clear that the behaviour and safety of these dikes is still not well understood. Classical calculations of peat dikes return very low factors of safety, which are clearly below the realistic factor of safety of the peat dikes. Therefore this research focuses on possible improvements of these calculations. During the Holocene, large parts of The Netherlands were covered by peat layers. Especially in the western parts of the country, shallow peat layers have been removed on a large scale by human activities leaving large and shallow lakes. The need for extra space for agricultural use has led to the creation of polders from these lakes. The remaining peat ridges around these lakes are now often used as dikes to protect these polders. The properties of the peat layers in these dikes have been established on a data set that is used for a dike improvement project from the Hoogheemraadschap Delfland for which the design is made by Royal Haskoning. Most of the properties of peat can be related to the water content of the material, which is very variable. In the used dataset, water contents vary from 200% to 800%. In order to establish reliable design values for the strength parameters of peat, direct simple shear tests have been carried out at Trinity College in Dublin to supplement the existing cell-test collection of the Hoogheemraadschap Delfland. Since possible failures in peat dikes are expected at low effective stresses, a number of these tests are performed at the lowest possible effective stresses in order to study stress-strain behaviour in this stress region. The tests give reliable results which are expected to give safe values for peat behaviour since the fibre reinforcing effect of peat is not taken into account. The correlation with other peat properties shows that the friction angle and cohesion are related to the water content and to the in-situ vertical stress. The DSS tests are simulated using Plaxis, which shows that a constant volume direct simple shear test can be simulated, leading to a good fit with the experimental results. From this back-analysis it can be concluded that the extracted φ and c from a DSS test are an underestimation of the φ and c of peat. The resulting values from the back-analysis are then used to simulate an existing dike section which shows large stability problems using classical stability calculations. This simulated dike section remains stable under normal circumstances which is a realistic outcome considering the present situation of the dike and a large improvement compared to the classical methods. However, when a long rainy period is simulated using PlaxFlow, the dike fails which emphasises the importance of the water table in peat dike stability. The evaluation of the behaviour shows that the over consolidation ratio in the peat layers influences the stability significantly. Further research is needed to study the behaviour of peat at low stresses and the influence of the OCR on this behaviour. Moreover, the effect of desiccation has not been studied in this research, therefore additional research is needed to show the possibilities of simulating desiccation using Plaxis and PlaxFlow.

Gewapende matras op prefab palen

Marco Pettini

In het westelijke deel van Nederland worden wegconstructies aangelegd op zeer slappe, samendrukbare grondlagen, meestal klei of veen. Indien de wegconstructie direct op deze ondergrond wordt gefundeerd lijdt dit tot grote onacceptabele zettingen. Conventionele methoden zoals verticale drainage hebben als doel het versnellen van de zettingen tijdens de constructiefase zodat er geen tot nauwelijks meer zettingen optreden na de aanleg. Steeds minder voldoen de conventionele methoden aan de eisen. Dit heeft de volgende oorzaken: de zettingen zijn te groot na aanleg, de bouwtijd is te lang (waardoor uiteindelijke kosten hoger zijn) en de levensduur van de constructie is te kort. In deze gevallen is een paalmatras een goed alternatief. Paalmatrassen worden aangelegd op locaties waar een slappe ondergrond aanwezig is. De palen dragen het grootste deel van de belasting af naar de sterke zettingsvrije dieper gelegen zand lagen. Over de palen wordt een geotextiel wapening aangebracht. Deze zorgt ervoor dat de belasting die niet rechtstreeks naar de palen gaat alsnog aan de palen wordt afgedragen. Indien het geotextiel op de slappe ondergrond rust, wordt hier ook een deel van de belasting aan afgedragen.



Het doel van dit onderzoek bestaat uit:

- Het bestuderen van de verschillende methoden voor het ontwerpen van een paalmatras. In Nederland bestaat voor de aanleg van een paalmatras nog geen ontwerpnorm. Bij het ontwerp van dit soort constructies wordt voornamelijk gekeken naar Engelse en Duitse normen. Tevens bestaat er een aantal methoden die ook de belastingafdracht van de matras beschrijven: Terzaghi, Hewlett & Randolph en Bush-Jenner. Deze methoden zijn allen bestudeerd.
- Een vergelijk maken tussen de ontwerpmethoden en de gemeten data. Deze methoden zijn bekeken aan de hand van boogvorming (paaleffectiviteit) in de matras constructie, de reductiefactor voor de belasting op de ondergrond (spanningsreductiefacor) en het gedrag van de wapening. Het vergelijk van de data met deze methoden kan een beeld geven van de methode die het best de realiteit benaderd in de Nederlandse bodem. Dit kan helpen bij het opstellen van een Nederlandse norm.
- Uitvoeren van proeven op de aangelegde paalmatras ter plaatse van de N210 en het analyseren van de monitoringsresultaten. De provinciale weg N210 tussen Krimpen aan den IJssel en Bergambacht in de Krimpenerwaard, ook wel bekend als de C.G. Roosweg, wordt vernieuwd. Hier wordt een paalmatras op prefab palen aangelegd. Deze paalmatras is ontworpen volgens de Britse richtlijnen. In eerste instantie is er een startvak aangelegd van 50 m lengte. Hier zijn door Ingenieursbureau Fugro meetinstrumenten aangebracht om het gedrag van de constructie te analyseren. Het startvak bestaat uit twee meetvelden. Per meetveld is de matrasconstructie anders aangelegd waardoor er een ander gedrag van de belastingafdracht ontstaat. Bij meetveld 1 is de ondergrond tussen de palen afgegraven, waardoor er een gedeeltelijke spleet ontstaat tussen de slappe lagen en het geotextiel. Bij meetveld 2 is dit gedeeltelijk afgegraven en opgevuld met losgewoelde grond. De ondergrond draagt nu meer belasting. De volgende onderdelen worden gemeten:

  - Belastingafdracht naar de palen
  - Belastingafdracht naar de ondergrond
  - Optredende rekken in de verschillende geogrids/geotextielen
  - Optredende zettingen in de constructie (onderkant, midden en bovenkant matras)
  - Helling van de palen
  - Stijghoogte grondwater
  - Luchtdruk
  - Luchtvochtigheid
  - Temperatuur

Om het gedrag van de matras te analyseren zijn er verschillende proeven op de matrasconstructie uitgevoerd. Deze bestaan uit dynamische en statische belastingen. Ten eerste is de opbouw van de matras geanalyseerd. Hieruit kan de boogvorming ten opzichte van een bepaalde dikte van de matras worden geanalyseerd. Volgens de ontwerpmethoden bestaat er een bepaalde kritische hoogte voor het vormen van de boogwerking. Des te groter de boogwerking wordt des te minder belasting de ondergrond te dragen krijgt. Ten tweede is er een zogenaamde puntlast op verschillende locaties op de matrasconstructie aangebracht. Dit is nagebootst aan de hand van big bags die gevuld zijn met granulaat. Deze zijn per belastingstap verplaatst. De derde proef die is uitgevoerd betreft een terp van 2 m hoog granulaat aangebracht bovenop de matrasconstructie. Hierdoor ontstaat er een statische belasting over het hele meetveld (vlaklast). De vierde proef die is uitgevoerd is een dynamische belasting over het proefvak. Deze is uitgevoerd met behulp van een rijdende vrachtwagen over het meetveld. De belasting van de vrachtwagen simuleert het toekomstige verkeer dat over de constructie gaat rijden. Er zijn tijdens een periode van 3 weken 1500 vrachtwagen bewegingen over de matras uitgevoerd. Als vijfde proef is de vrachtwagen gedurende een aantal uur op 1 punt blijven stilstaan, bij deze proef wordt een aslast gesimuleerd.

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