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DEVELOPMENT OF SENSORS, PROBES AND IMAGING TECHNIQUES FOR POLLUTANT MONITORING IN GEO-ENVIRONMENTAL MODEL TESTS

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ABSTRACT

In order to be able to track the movement of pollutant plumes during geotechnical centrifuge and other geo-environmental experiments, a number of techniques have been investigated: fibre-optic photometric sensors, resistivity probes, resistivity tomography, and copper ion-selective electrodes. Methods of image analysis, signal processing techniques and multi-spectral image analysis were also explored and applied to images of moving plumes. In addition, an optical technique for detecting NAPL by cone probe was investigated. Their relative merits are discussed. This work was conducted as part of an EU-funded network programme: NECER (Network of European geotechnical Centrifuges for Environmental Research), and this paper summarises the conclusions of the sensors and imaging working group.

Key words: centrifuge, image processing, sand, clay, unsaturated and saturated soils, LNAPL, DNAPL, tracer, 1-g model

INTRODUCTION

To study environmental pollution using a geotechnical centrifuge is an attractive proposal for many reasons:

- rapid collection of data compared with 1 g methods;
- soil stress conditions can be maintained at the correct level;
- a number of relevant parameters can be scaled to predict full scale behaviour from the centrifuge model behaviour.
- 2 and 3-dimensional models with controlled boundary conditions can be tested.

But to make it possible, some means of measuring the pollutant is required. It was the objective of the sensors and imaging working group of NECER to investigate novel methods for monitoring pollutant movement, using either probes, sensors, or imaging techniques.

The following techniques were investigated:

Fibre-optic photometric probes; resistivity arrays (tomography); copper-selective electrode; NAFL cone probe using detection by refractive index; imaging of LNAPL movements through soils; multispectral imaging of LNAPLs in unsaturated sand; and imaging of DNAPLs in saturated sands.

SENSORS AND PROBES FOR MONITORING OF POLLUTANT CONCENTRATION

Fibre-optic photometric sensors (University of Cambridge: M.D. Bolton, R.J. Lynch, P. Sentenac, A.C.J. Treadaway, and LNEC Lisbon: H. Barker, N. Depountis, J.L.L. de Almeida Garrett, C. Santos, M.A.G. Silva)

The development of this sensor was a new approach in centrifuge probes. The aim was to be able to monitor continuously the concentration of a water-soluble dye tracer by measuring the photometric absorbance of a sample of pore fluid in a sensor buried in the soil. It is based on the well known use of photometry for measuring the concentration of dissolved chemicals in water, which is normally done in a laboratory spectrophotometer. For this project, the light source and detector were connected to a sensor cell in the soil by optical fibres, and electronics were developed which provided illumination and light detection.

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Four different designs of sensor cell were developed at Cambridge University. The final one gave excellent sensitivity, enabling a few parts per million of dye to be observed and the concentration of the plume as it passed through sensors was measured. It was tested both at 1 g and at 50 g in centrifuge tests. Baseline stability problems were overcome by using a more rigid design of sensor cell, by improving the electronics amplifiers, improving the light intensity of light emitting diodes and also the sensitivity of the photodiodes. Sensitivity to gravitational changes was also improved by using multi-fibre cables with less sensitivity to bending.

The sensors were tested at 50 g in sand and also in a sand / clay layer/ sand sample, which was a simulation of a landfill liner test. A similar soil model was also tested in a high pressure cell. The sensors have been used successfully under these conditions, however measures must be taken to keep the sensors free from air bubbles.

Figure 1(a) shows the early version of the photometric sensor (Mark 1), in which the pore water enters and leaves the cell through geotextile in upper and lower layers (Treadaway et al., 1997). The improved cell is shown in Fig. 1(b), which has axial symmetry, improving ease of placement, improved rigidity, and removable geotextile. An outline of the electronic system used to illuminate and detect light absorbance is shown in Fig. 2. The electronics were ruggedly mounted to withstand applied gravity forces.

A typical measurement of a plume of dye tracer moving through a sand column past two sensors at different depths, is shown in Fig. 3. Data was collected at 1 Hz. Mechanical dispersion of the plume is observed to increase with depth.

In early centrifuge experiments involving contaminant transport through sand, the sensors proved to be sensitive to gravitational changes. This 'g-effect' is clearly shown in Fig. 4 below, in which a pulse of dye contaminant was spilled (Treadaway et al., 1998).

The design was improved to eradicate the 'g-effect' and also reduce electronic drift. The improved system made use of more expensive fibre-optics, more secure couplings, higher quality and more suitable photodiodes, higher intensity light emitting diodes (LED's), and incompressible tubular sensor bodies, it was also made more robust in general (Fig. 1(a).).

The improved performance can be seen in Fig. 5; the 'g-effect' was eradicated and the electronic drift greatly reduced.

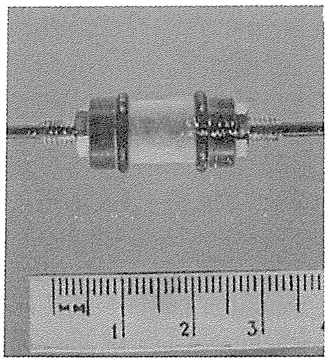


Fig. 1(a). Top view of the first type of the photometric sensor, showing porous geotextile filter and optical fibres (Mark 1)

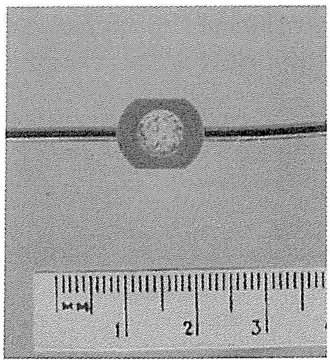


Fig 1(b): Photo of the improved sensor cell (Mark 4)

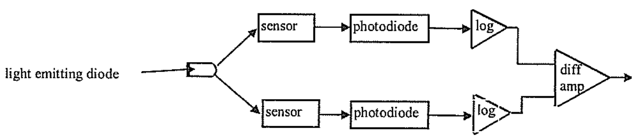


Fig. 2. Diagram of sensor electronic system

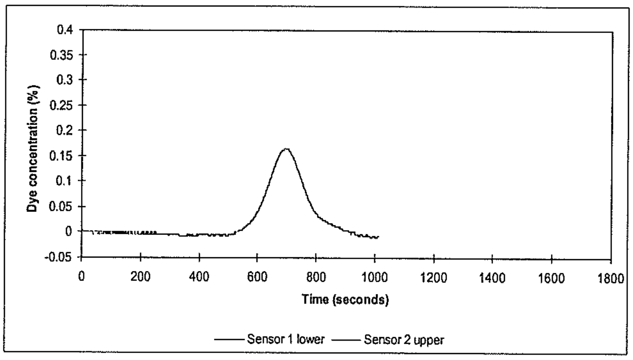


Fig. 3. Contaminant plume detected during a column experiment on sand, at 1g.

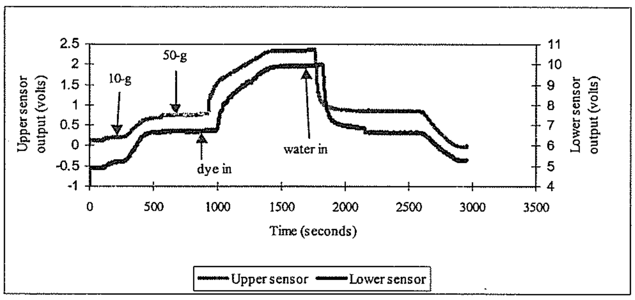


Fig. 4. Results from initial centrifuge experiment on sand

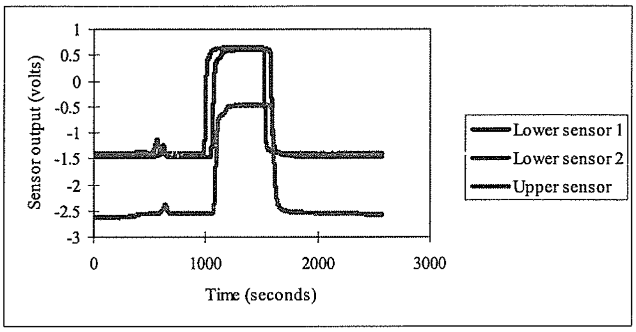


Fig. 5. Results from a centrifuge test on sand using the improved detection system

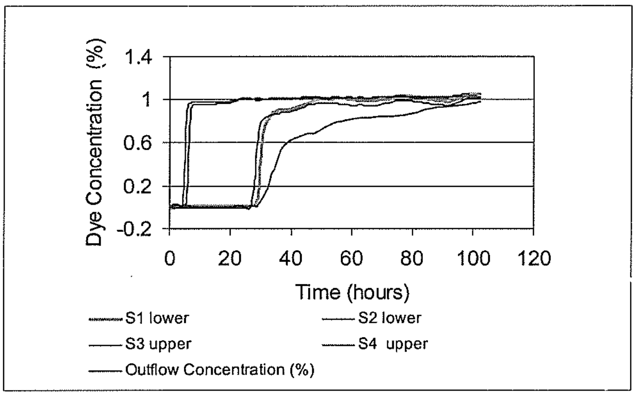


Fig. 6. Results from a clay layer experiment accelerated using high pressure (102 hour test)

Fig. 7. Fibre-optic reflective-type probes

Landfill liner simulation

The detection system was then used in contaminant transport experiments conducted on a model containing a layer of E-grade kaolin, accelerated using the beam centrifuge. The sensors buried in sand above the clay layer performed well but after several hours the sensors in the sand below the clay layer ceased to read accurately due to the presence of air bubbles in the sensors. Air is more soluble at higher pressures, and the pressure drop across the clay layer resulted in bubble formation under the clay layer. In later experiments, high pressure was used, instead of high gravity, to accelerate contaminant transport through a clay layer. A system was devised in which a hydraulic gradient identical to that used in the clay layer centrifuge test could be used to accelerate a test without air bubbles coming out of solution and causing sensor failure. Such measures were: 1. thorough de-airing of all sensors, fluids and soils used; 2. use of helium, which is less soluble than air, to exclude air and to apply pressure to accelerate flow; 3. use of a back pressure below the clay layer to keep dissolved gases in solution, and 4. use of a pneumatic piston to control the effective stresses in the soil.

The test results using these measures can be seen in Fig. 6. The output was satisfactory from all four photometric sensors and the results were consistent with the analysis of exit fluid samples.

Reflective sensors

The sensors described above are light transmission sensors, in which the light travels through the pore fluid and is collected by another fibre on the same axis as the emitting fibre. An alternative design using light reflection have been investigated Figs. 7(a, b). In these sensors, the light from a light-emitting diode is transmitted by a fibre to the soil sample. It passes through the voids, is reflected from the soil surfaces, and collected by another fibre. Optionally a layer of geotextile mesh can be used to increase the void space. This has the effect of increasing substantially the sensitivity but at the penalty of increasing the response time, since there will be a time associated with this mesh chamber filling and emptying of dye. In these experiments no mesh chamber was used. These small, un-intrusive sensors can be applied with minimal disturbance to the soil.

These sensor systems have been described previously (Lynch et al., 2000, Sentenac et al., 2001).

At LNEC, Lisbon, improvements were made to transmission sensor design by incorporation of graded refractive index lenses, to increase the optical transmission of the cell. Also pulsed light and phase-sensitive detection were used.

The main goal of those improvements was to increase the light power at the receiving sensor either by reducing transmission losses, either by increasing the source light power.

The reduction of the transmission losses at sensor level was achieved by collimating the light beam coming out the transmitter optical fibre and focusing the collimated beam into the receiver optical fibre. Graded refractive index (grin) lenses were used by their convenient cylindrical shape and small size (5 mm length, 2 mm diameter) as well as by its good light transmission efficiency (90%). On the other hand, grin lenses must be kept in a dry environment they react chemically with water and can be seriously damaged. So, a sapphire optical window, 2.5 mm diameter, 0.5 mm thick, 85% light transmission efficiency, was used to isolate the grin lenses from the measurement chamber. Figure 8 shows the main sensor components arrangement.

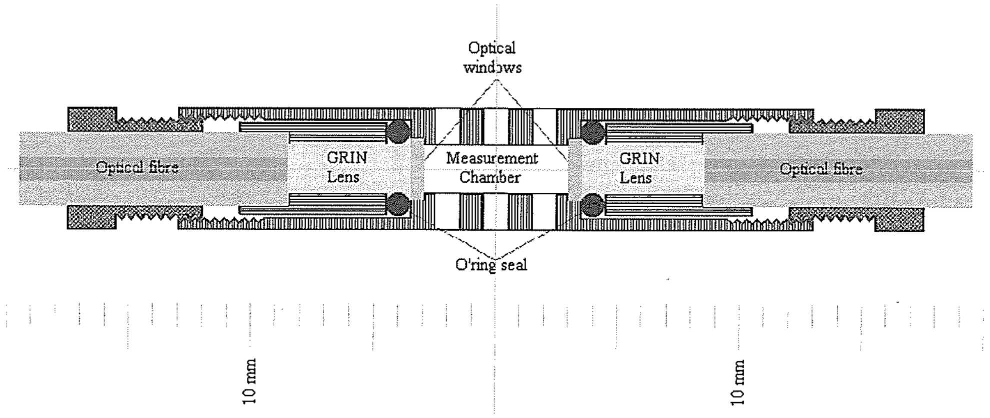


Fig. 8. Basic drawing of the photometric sensor

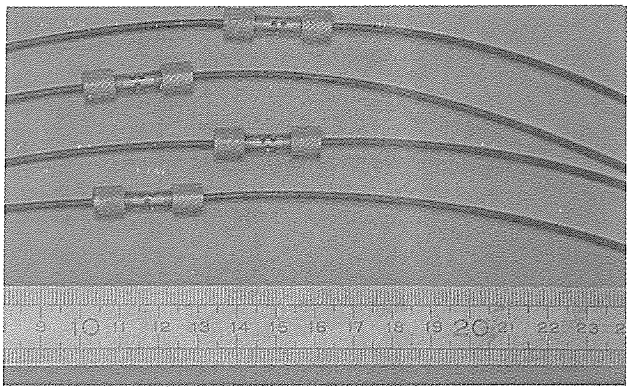


Fig. 9. Photometric sensors

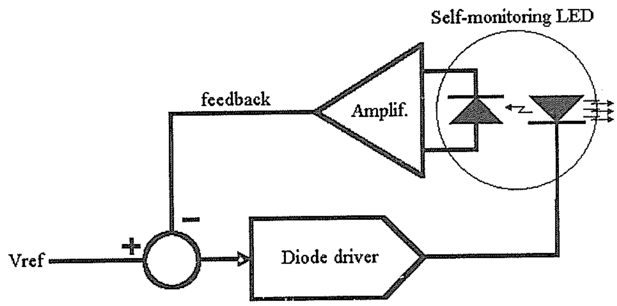


Fig. 10. Simplified diagram of the light power control system

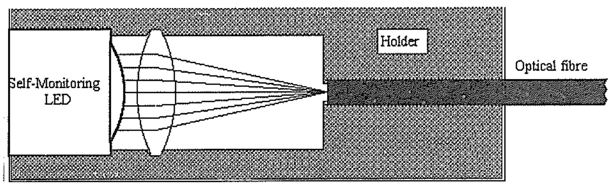


Fig. 11. Emitter arrangement

A photograph of this version of the sensors is shown in Fig. 9. With this sensor arrangement, and for a 5 mm measurement chamber length, a light transmission factor of 4 was reached in comparison with a no collimating sensor. However, the resulting sensor is too big to be considered un-intrusive and so this type of sensor was not used in centrifuge tests done up to now. Instead, "Mark 4" type sensor were used. Meanwhile, the sensor is being re-designed in order to reduce size.

A second improvement in light power was achieved by eliminating the need of the reference light path by controlling the light power at the light emitter. A self-monitoring LED, a device that includes a photo-sensor to measure the emitted light power, was integrated in a canonical feedback control system (Fig. 10) so that the output light power is proportional to the reference voltage applied at the input. The self-monitoring LED's are supplied with integral lenses mounted with the LED at focus. An additional 9 mm focal length lens feeds most of light power into the transmitter optical fibre (Fig. 11).

The increase of the source light power was achieved by using a pulsed Vref signal, which allows overdriving the LED without damage. Overdriving the LED means more light power is available. Figure 12 shows a functional diagram of the implemented electronic circuit. The output signal, which is proportional to the light power reaching the receiver photo-diode, is the difference of signal level when light is on and when it is off. This is attained sampling the received signal synchronously with the driver signal DV. Two sample & hold amplifiers controlled by signals SH and SL will sample the signal when DV is on and off, respectively.

With this technique, errors due to the photo-diode dark current and input offset voltage of the high gain current-to-voltage receiver amplifier are eliminated.

The relationship between the output signal V and the dye concentration C is given by the following equation

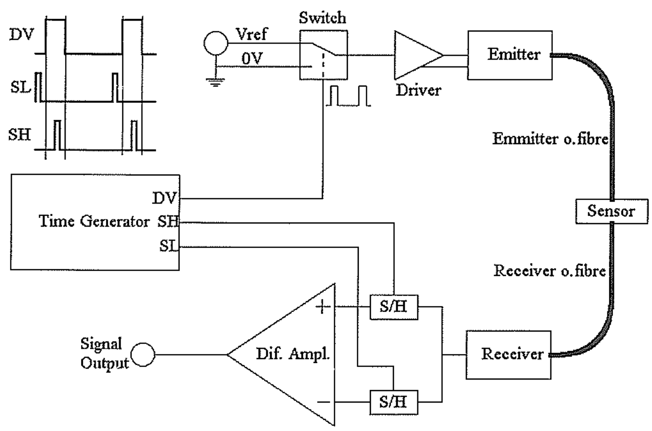


Fig. 12. Functional diagram of electronics

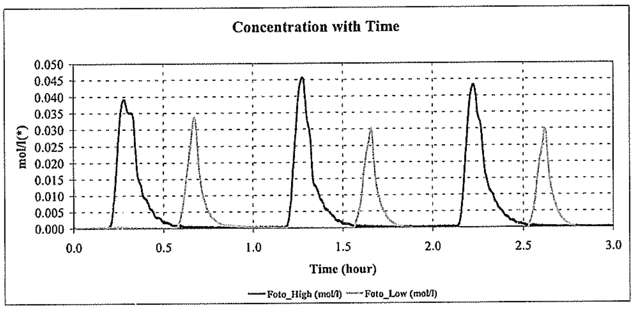


Fig. 13. Three plumes of copper sulphate in sand, detected optically by two sensors, at 20 g.

$$C = k \cdot \log \left[\frac{V_0}{V} \right]$$

where V_0 is the output voltage at 0% concentration and k is a coefficient that depends on the physical dimensions of the sensor, namely the light path length, on the dye and light wavelength used and on the optic and electronic conversions and amplifications. The coefficient k is obtained by calibration. V_0 is measured at the beginning of the test, prior to the introduction of dye. Note that this procedure is valid because the source light power is made constant.

Figure 13 shows a typical output from the system described above. Two sensors, Mark 4 type, were located at different depths in a sand column, one near the top, the second one on the bottom half of the column. Copper sulphate solution was added to the water flow three times during the test. The evolution of concentration can be observed on the graph.

In conclusion, the photometric detection system can be a useful tool for the continuous monitoring of contaminant transport in-situ. It has performed successfully in tests at 1 g, 20 g and 50 g. Care must be taken if this device is to be used in experiments involving large drops in pressure across a layer of low permeability soil. The sensors have been used successfully under these conditions, however measures must be taken to keep the sensors free from air bubbles.

Resistivity probes.

These miniature probes for measuring the movement of ionic model contaminants such as sodium chloride solution, were developed in the 1980's and early 90's at the universities of Cambridge and Western Australia. In the Cambridge type, 4 miniature electrodes, 3 mm long, with 1 mm spacing are used. Two electrodes apply pulses of current; the central two measure the potential drop across the soil. This is now established technology, and has been covered extensively in the environmental chapter by Culligan-Hensley and Savvidou in Taylor's book on centrifuge technology (1995). The same probes may be also used for water content measurement.

Resistivity tomography (Universities of Cardiff: C. Harris and Dundee: M.C.R. Davies, N. Depountis, and P. Sentenac.

A minaturised electrical imaging technique based on resistivity tomography was developed. It was based on field-scale resistivity equipment used for contaminant detection in the field. It consisted of two arrays of electrodes with a spacing of 30 mm, one on the soil surface and the other at the base of the soil sample, located in a centrifuge soil strongbox. The electrodes are successively connected to an earth resistance meter. A program incorporating inversion techniques is used to model two dimensional sub-surface resistivity. In an experiment to measure the movement of a pollutant through unsaturated soil a release of model pollutant sodium chloride solution was successfully seen moving down through the centre of the model recorded in a 10 g centrifuge experiment (see Fig. 14). The velocity of the plume migration was proportional to the gravitational field. Typical data collection time for a 2-D image is about 20 minutes. Further details are given in Harris et al. (2000).

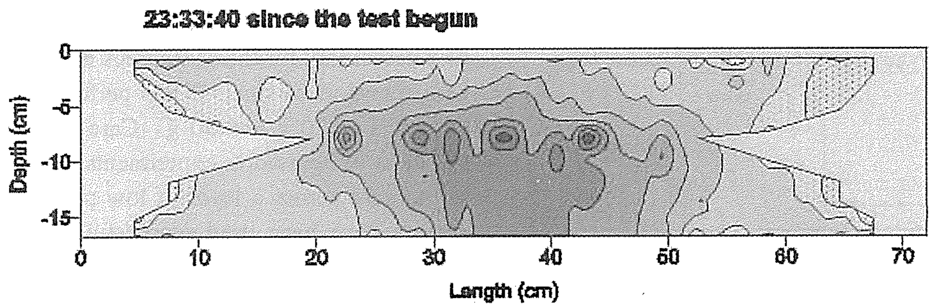


Fig. 14. Plume of sodium chloride tracer moving through sand at 10 g

Combined copper-selective electrode (F. Weststrate, A. Bezuijen and O. Oung, GeoDelft)

The basis of this sensor is a solid state electrode with a crystallised membrane and is called an ion-selective electrode, see Fig. 15. The membrane was chosen to potentially attract copper ions. In this work, the electrode was use to measure variation of concentration of copper ions with time. Attraction of copper ions at the membrane generates a stream of electrons which is directly related to the concentration of copper ions in the surrounding of the electrode. For use in a table centrifuge, it was required that the electrode has a size as small as possible and to be able to withstand the high g-field. The combination of the reference electrode (Calomel electrode) in one body with the working electrode has minimised room in the set-up. Moreover the optimised distance between the reference electrode and the working electrode enabled also a good sensitivity 0.008-84,000 ppm. The characteristics of the electrode used are summarised in the table below. The sensor has been used successfully to measure the breakthrough of copper solution passing through a layer of consolidated clay at 150 g, see Fig.16. The experiment was conducted in a table-top centrifuge; the A and B curves relate to an electrode in each balanced cup of the centrifuge. Copper ions were detected when adsorption on clay is mainly completed, indicating breakthrough (Oung, 2000).

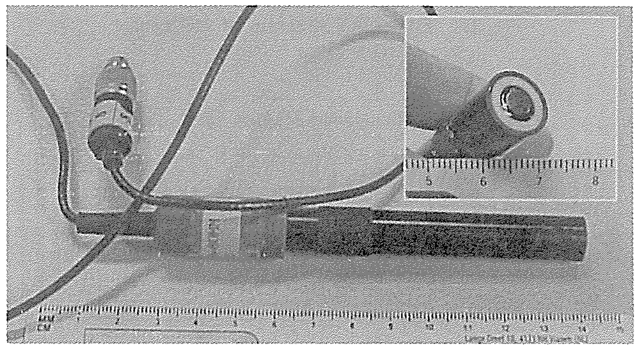


Fig. 15. Combined Cu-selective electrode

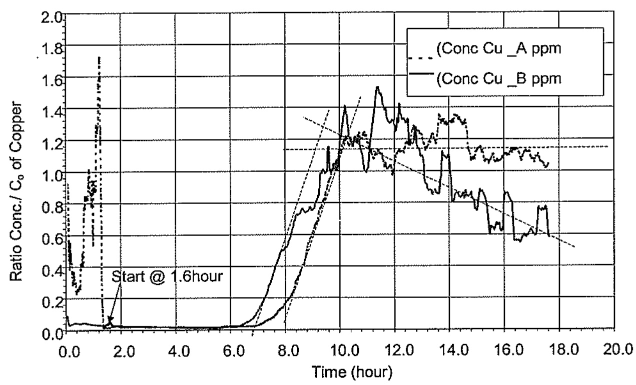


Fig. 16. Break-through curves resulting from the end of adsorption of copper in consolidated clay.

Characteristics of the Combined Cu selective electrode

Electrode	Conc. Range (M)	Limits (ppm)	Temp. Range (°C)	Main Interferences	pH Range
Cupric selective	1 - 1.E-7	0.008 - 84000	0 - 50	Hg^{2+}, Ag^{+}, S^{2-}, Cl^{-}, Br^{-}	2 - 7

Detection of NAPLs by refractive index changes (Cambridge University: M. Cartwright and R.J. Lynch)

The objective of this probe is to detect anomalies in the properties of groundwater indicating the presence of a pollutant, It measures changes in the refractive index, and hence is able to detect the presence of LNAPL's. The principle is shown in Fig. 17. An optical fibre is bent through a critical angle. When the polished surface is wetted with water, light is reflected from the surface and continues down the second fibre. However when a higher refractive index liquid, such as gasoline wets the surface, the refractive index of the plastic and the gasoline are similar, and light is not reflected. Less light enters the fibre. A photodiode attached to the end of the fibre gives a signal which is related to the light intensity received (Cartwright, 1997).

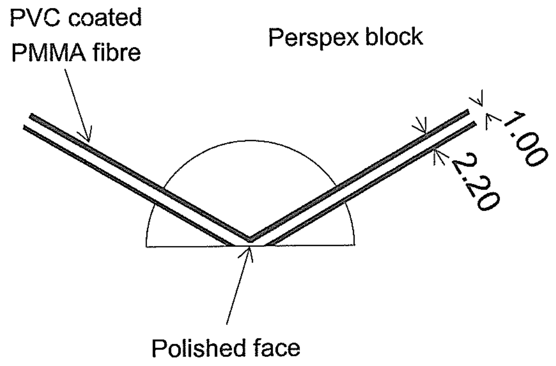


Fig. 17. Sensor construction

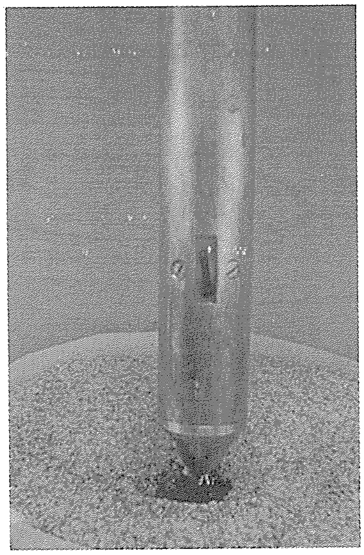


Fig. 18. Cone probe

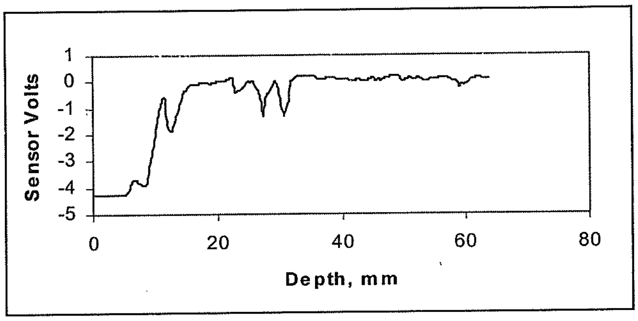


Fig. 19. Example of NAPL probe output during a push through oil-saturated sand.

The sensor voltage varies with angle and refractive index. Such a sensor was built into a conical probe see Fig. 18. Figure 19 shows the probe output as it was pushed slowly using a load frame through a sample of sand which had a layer of oil spilt on the surface. At the start, the probe was 5 mm above the surface. The probe voltage rises steeply as the sensor encounters oil. Some of the downward spikes are probably due to the presence of water in the soil pores. A limitation of this simple test was that the depth was limited to about 80 mm, and a film of oil remained, so entry into the water-saturated layer was not observed. This remains to be addressed in later work.

IMAGING PROCEDURES

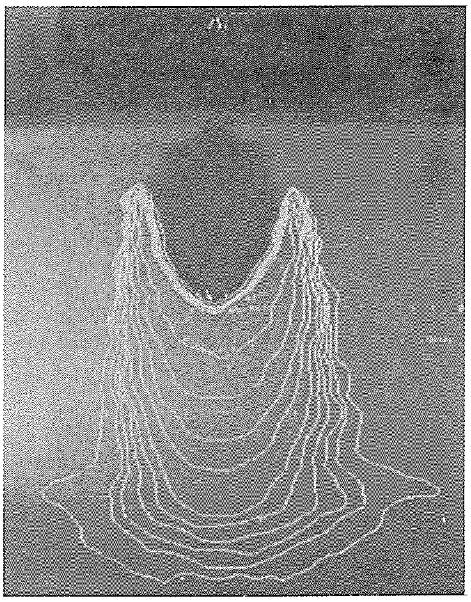
Optical analysis of pollution transport in geotechnical centrifuge tests. (Technical University of Delft: H. Allersma and G. Esposito).

The contribution of the University of Delft in the NECER project was to investigate the possibilities of an optical measuring method, based on digital image processing, to monitor the behaviour of pollution in model tests in a centrifuge.

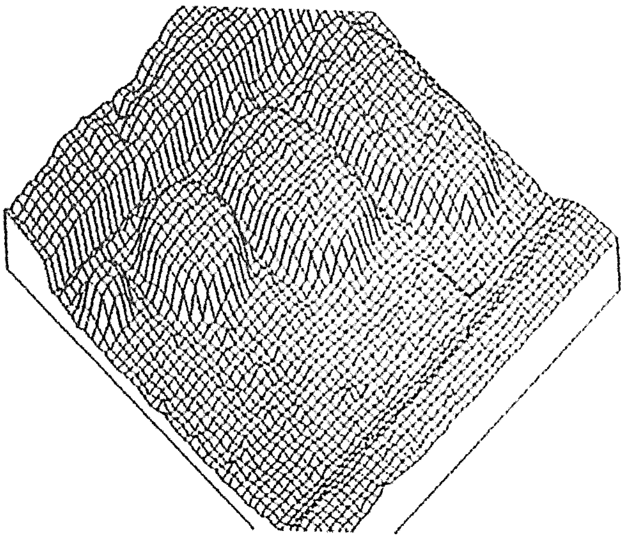
Imaging technologies can be considered as a universal tool for visualizing, digitizing and analyzing phenomena in experimental research. This observation technique was introduced in geotechnical centrifuge research (Allersma, 1990) in order to enable deformation measurements in model tests. In a small geotechnical centrifuge the space for mechanical sensors is so limited that it is not easily possible to monitor the progress of a test. By using digital image processing techniques, however, it became possible to extract significant data from the images captured by a video camera. An additional advantage of the method is that only a video camera is required as sensor and that, unlike mechanical sensors, light does not influence the behaviour of the soil.

Today, small cameras are available that can also be placed in a small centrifuge, so that the model can be viewed continuously via slip rings. A new development, however, is the use of a non-interlaced camera. This is a fixed camera which can make momentary exposures (e.g. 1/4000 sec). The camera is triggered by the centrifuge via the computer with frame grabber. The spinning model needs to be illuminated perfectly at the location where the exposure is made. The advantage is that a strong fixed light source can be used, which better guarantees a homogeneous illumination of the samples. This is particularly important if variations in grey values are used to estimate phenomena in tests, as is for example the case in pollution transport tests.

By performing two-dimensional tests the polluted area can be observed through transparent walls, which confines the soil sample. By means of image processing commands, which are supplied by a software toolkit, it was possible to measure automatically the displacement of the front and the concentration of the pollution in the contaminated area (Allersma and Esposito, 2000).



(a)



(b)

Fig. 20(a). Contour lines of different time steps during infiltration of a contaminant in partly saturated sand.
(b) 3-D plot to show the concentration of the contaminant over the surface of the plume in 4 time steps.

Imaging technology has proven to be a valuable technique for visualizing and digitizing phenomena in two-dimensional pollution transport tests. The system can be used to monitor the test in real time. As a result of this measuring technique, tests with a (small) geotechnical centrifuge have become more effective. Sensors can be replaced by a camera and image processing software. A camera requires less space and the light does not influence the test. The optical measuring technique is able to yield detailed information of a large area. The measurement of phenomena in a large area is very helpful in analyzing tests on pollution transport problems. Several variables can be measured by using digital image processing in tests simulating the infiltration of a contaminant in soil, such as; area of the plume; growth of area with time; width of the plume; height of the plume; velocity of the front in a horizontal and vertical direction; digitization of the contour of the plume; digitization of the oil concentration over the plume surface and oil supply in time.

The toolkit used contains commands which make it relatively simple to extract relevant information from tests. For that reason it is not necessary to develop elementary software of your own. There are several image processing toolkits available on the market.

The processing of the image can be performed automatically. However, in many cases it appeared to be helpful to use the image processing station in remote mode. In this mode the cursor behaves as an electronic ruler, local grey values can be visualized and the progress of a test can easily be visualized by subtracting images at different time intervals. For this reason an interactive on-line system is highly recommended.

The measuring method is applicable for two-dimensional problems, only. The tests have to be carried out carefully in order to assure an idealized two-dimensional test. In some cases the infiltration of the contaminant proceeds in plumes with a very complicated shape (e.g. fingering). As long as the test is two-dimensional the optical measuring technique is applicable. In the first instance the measurement is applied in the case that only one fluid is present. When the contaminant reaches the groundwater table it would be a good thing if both oil and water content could be measured. Future investigations will be performed to determine if this can be achieved, e.g. by using special tracers and/or light.

The measuring technique has been applied in several centrifuge model tests to examine the behaviour of a pollutant in sand (Esposito et al., 1999, 2000a, 2000b).

Multispectral imaging of LNAPLs (University of Cambridge: C. Kechavarzi and K. Soga)

The need for measuring dynamic fluid saturation distribution in multi-dimensional three-fluid phase flow experiments is hampered by lack of appropriate techniques to monitor full field transient flow phenomena. There is no conventional technique able to measure dynamic three-fluid phase saturation at several array points of the flow field at the same time. A multispectral image analysis technique was developed to determine dynamic NAPL, water and air saturation distribution in two-dimensional three-fluid phase laboratory experiments. Using a digital near-infra red camera, images of sand samples with various degrees of NAPL, water and air saturation were taken, under constant lighting conditions and within three narrow spectral bands of the visible and near-infrared spectrum. It was shown that the optical density defined for the reflected luminous intensity was a linear function of the NAPL and the water saturation for each spectral band and for any two and three-fluid phase systems. This allowed the definition of dimensionless lump reflection coefficients for the NAPL and the water phase within each spectral band. Consequently, at any given time, two images taken within two different spectral bands provided two linear equations which could be solved for the water and the NAPL saturation. The method was applied to 1 g two-dimensional three-phase flow experiments, which were conducted to investigate the migration and the distribution of LNAPL in the vadose zone. The method was used to obtain continuous, quantitative and dynamic full field mapping of the NAPL saturation as well as the variation of the water and the air saturation during NAPL flow. The method provides a non-destructive and non-intrusive tool for studying multiphase flow for which rapid changes in fluid saturation in the entire flow domain difficult to measure using conventional techniques (Kechavarzi et al., 2000).

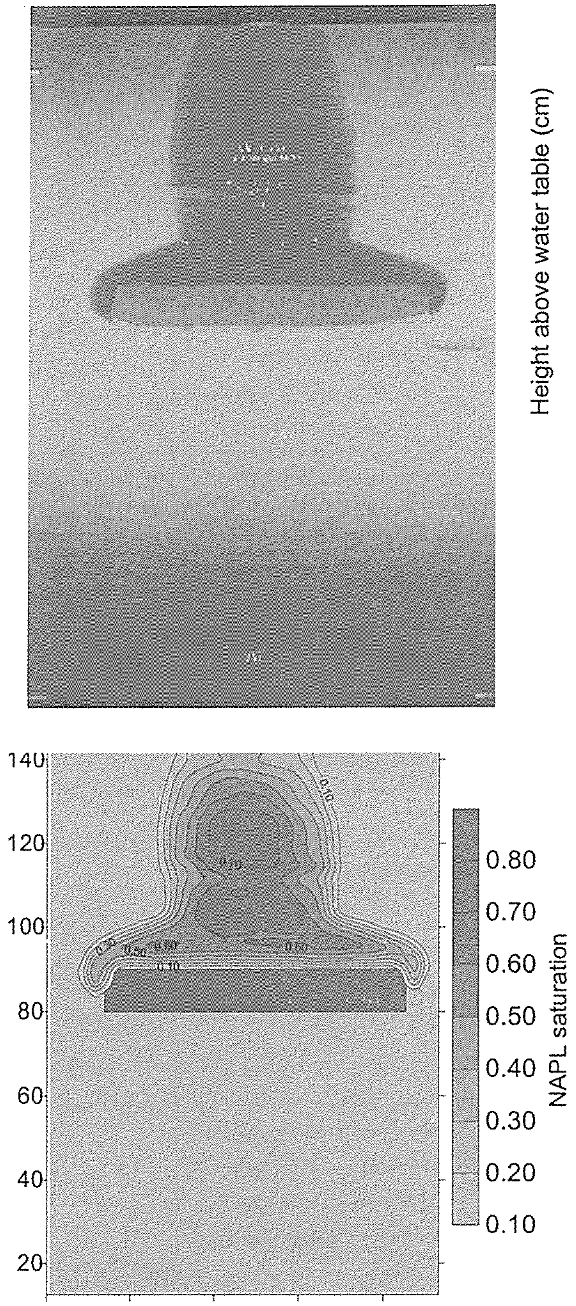


Fig. 21. NAPL spill in unsaturated coarse sand around a saturated silt lens, at 1 g.

Figure 21 shows an image of a NAPL plume at 500 nm moving down after redistribution has started (i.e. the injection is finished). It was taken 7h30 after injection had begun. The corresponding NAPL saturation contours are shown. The test consisted of an unsaturated coarse sand with a silt lens acting as a permeability barrier. The lens stays saturated with water and the NAPL does not overcome the entry pressure required to displace water in the silt, therefore it has to flow around it horizontally.

Imaging of DNAPLs in saturated sands (City University, London: S. Spiessl and R.N. Taylor).

The movement of a DNAPL (perchloroethylene) moving through saturated homogeneous sand and saturated glass beads of diameter 0.1-0.2 mm have been studied, using optical imaging. Plume fronts were obtained by image subtraction, plume areas, widths and lengths were obtained by a similar programme to Auto CAD. Boundary effects were minimised by sand-blasting the glass window of the strong box prior to the test. A number of runs at 5, 8 and 10 g were performed. Further details of the test are given in Spiessl and Taylor (2000). Direct visualisation of the advancing pollutant plume allowed detection of potential flows instabilities.

CONCLUSIONS

The main applications, advantages and disadvantages of all of the techniques investigated are summarised in the following table:

Overview of real time sensor and measurement technologies for pollutant measurement in geo-environmental modelling

Technique	Application	Advantage	Disadvantage	Future
1. Sensors and probes:				
Fibre-optics Photometric sensors	Dye tracer, copper; Pollutants with visible light absorbance	In-situ, real time	1. Only for coloured pollutants or tracers, 2. Bubbles (can be solved with helium)	UV light for organics
Resistivity tomography	Inorganic pollutants, and LNAPL in salt solution	Good resolution, good portability, reliable for field and experiments tests Depth adjustable with electrode spacing	Time for 1 scan = 20 min The fluid to be detected has to be conducting, i.e. ionic. Anomaly detection is an average not reproductive for the contaminant itself but for the soil + contaminant	Reduced scan time
Resistivity probes	Centrifuge tests with salt tracer. Ionic pollutants or tracers	Established technology	Must be calibrated in the soil. May not be a linear calibration	
Copper-sensitive electrode	Copper adsorption	Real-time	Drift can be a problem?	Very small ISFETs'
Resistivity / Conductivity	Ionic pollutants	Small probes	Exponential change of conductivity with concentration in certain ranges	
NAPL refractive index probe	Hydrocarbons, Chlorinated solvents	Only requires a film of liquid on the probe	Needs a separate phase (in principle, could measure dissolved concentration, if sufficiently high)	Improved probe designed
2. Image Processing:				
Delft University method: Non-interlaced camera, grey-scale processing	2-dimensional centrifuge test. Tested in LNAPL spill in unsaturated soil	Fixed camera + fixed light gives homogenous illumination in centrifuge. Concentration is estimated from grey scale. Some image processing can be automatic	Resolution probably limited by video image	
City University method: Centrifuge-mounted illumination. Plume areas and dimensions were determined by an Autocad-type program.	2-dimensional centrifuge test DNAPL spill in saturated soil	Boundary effects reduced by sand-blasting treatment of window	Flow observed against an interface : subsequent investigation revealed evidence of out-of-plan flow	
Cambridge University method : Multispectral imaging of LNAPL	2-dimensional 1 g tank test. LNAPL spill in unsaturated soil	Measures LNAPL and water concentrations	Absorbance spectra of pollutant and water must be quite different at some wavelengths	

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