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Soil Contamination

-a question of nature's bearing capacity

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Soil Contamination
-a question of nature's bearing capacity

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ABSTRACT

The soil beneath our feet has long been treated as an infinite waste bin. As a result of several serious contamination cases we have recognised that there are limitations to what the soil can bear. A nation-wide inventory in Norway revealed thousands of sites polluted by heavy metals, chlorinated and non-chlorinated hydrocarbons originating from waste disposal and industrial activities. Now we are facing a serious challenge in solving these problems.

Originally we relied on clean-up technology and engineering skills to solve pollution problems. Removal by excavation, containment techniques and in-situ treatment methods have been developed. However in recent years we have learned that the soil has a high potential for natural attenuation of contaminants. It is a major challenge to use this potential without exceeding nature's bearing capacity. This requires a multidisciplinary approach of chemists, biologists, geologists, geotechnical and environmental engineers.

INTRODUCTION

During Laurits Bjerrum's period as director of NGI (1952-1973) environmental issues were no major concern for the geotechnical community. However during this period the environmental movement was strongly established.

A major factor triggering this process was the publication of "Silent Spring" by Rachel Carson in 1962. In this book Carson, a biologist and nature author, exposed the hazards of indiscriminate use of pesticides like DDT. The most famous chapter " A Fable for Tomorrow" describes a town where all forms of life, from flowers, fish, birds and even children, have been silenced by the effects of DDT. Despite strong opposition from the chemical industry, her findings were confirmed by a Science Advisory Committee to President John F. Kennedy. The use of DDT was restricted and finally banned in 1972 in large parts of the western world. It is interesting to note that DDT has been used in Norway in spruce nurseries until 1989. Locally high DDT concentrations can still be found at waste dumps and growing fields at the nurseries (Sørlie et al., 1998).

POLLUTION HISTORY

Public awareness of environmental pollution was not born during the 1960's. Pollution problems have existed as long as people have been living in close communities of a certain size. Air and water pollution problems were already recognised during the Greek and Roman antiquity. In Europe the first regulations concerning air pollution date back to the 13th century when English towns were suffering from pollution due to coal burning. During the industrial revolution air pollution increased considerably and the British Parliament started looking into ways of pollution control. Proper legislation did not come into force before the beginning of the 20th century.

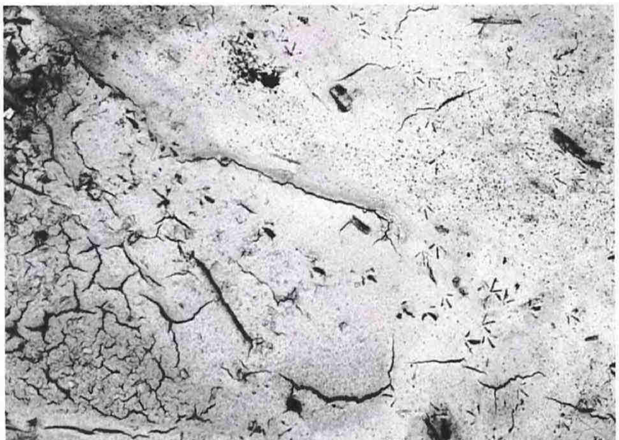

Fig. 1. Soil pollution from acid mine drainage.

Water management was already highly developed in the Roman culture. In ancient Rome waste water from it's 1 million inhabitants was handled by the Cloaca Maxima, whereas fresh water was transported from the mountains by aqueducts. This focus on clean water supply is surprising, since the possible existence of pathogens was not hypothesised before the 16th century. In Europe this level of water management was not achieved before the 19th century. In Dutch cities canals were simultaneously used as drinking water supply, sewage system and waste disposal, causing serious problems (Fig. 2).

Fig. 2. Water pollution in the canals of Leiden around 1950 (photo: Archief Natuur & Techniek, Maastricht).

However our use of the soil was not recognised as a reason for concern until the 1970's. Soil was really thought to be an infinite waste bin. As late as 1980 the Norwegian Pollution Control Authorities recommended to dig a hole to dispose of creosote sludge at a wood treatment plant. Soil contamination was first brought to wide international attention in 1978, when President Jimmy Carter declared a federal emergency at the Love Canal. This neighbourhood in the City of Niagara Falls, NY is named after William T. Love who tried at the end of the 19th century to establish a canal to provide a route to bypass the Niagara Falls. This project was never completed as a result of economic depression. In 1920 the land and open water area was sold and became a municipal and chemical waste disposal site. Nearly 21,000 tons of toxic chemicals were dumped at the site until site closure in 1953. After covering the landfill with soil the site was deeded to the Niagara Board of Education (Love Canal Collection, 1998). The site was developed into a residential area with numerous homes and an elementary school. Repeated complaints of odours and "substances" in yards and the school playgrounds were first reported in the 1960's and increased during the 1970's as the groundwater table in the area rose. Studies showed that toxic chemicals including chlorinated dioxins had migrated from the landfill to nearby creeks through the sewer system. Nine hundred and fifty families were evacuated from the site. The site was capped, a leachate collection system was installed and contaminated sediments were removed from sewers and surface water areas. At present the leachate collection system is in continued operation and groundwater monitoring is ongoing (USEPA, 2002).

The Love Canal case triggered a nation-wide survey of potentially similar cases and resulted in the establishment of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), better known as Superfund, in 1980.

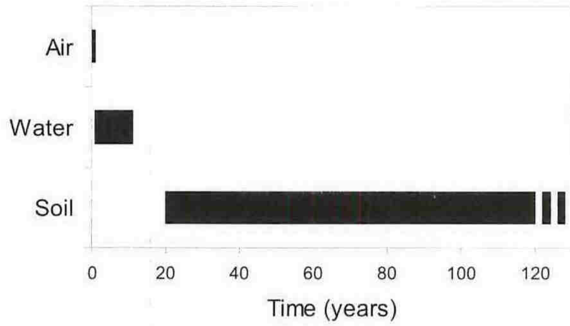

Fig. 3. Time span of response after pollution events in the 3 environmental compartments.

Why has soil contamination been neglected for such a long time? The major reason should be sought for in our inability to relate our actions to an environmental response. If we pollute air, we can often see and smell the result shortly after. If we pollute our rivers and lakes we find dead fish along the shores. However if we pollute the soil, the probability that we will be able to register the results of our actions is very small, as the system response will take several decades (Fig. 3.). Thereby we have created a problem for the next generation and a clear causal relation between pollution action and response is lost.

SOIL CONTAMINATION IN NORWAY

As a result of several cases of severe soil pollution uncovered in the USA and European countries like the Netherlands, Germany and Denmark, the Norwegian State Pollution Control Authorities initiated a nation wide inventory of potential polluted sites from 1989 to

1991 (SFT, 1991). A total of 3394 sites have been registered (Table 1). The sites with the highest priority (1) require remediation urgently. It is the intention that remedial action at these sites should be completed by 2005. Site assessment should be completed for priority 2 sites within the same timeframe. Priority 3 and 4 do not require further work as long as the present site use is unchanged.

Table 1. Inventory of contaminated sites in Norway and remedial action completed by 2000 (MD, 2002).

Priority	No. of sites	Completed
1. Remedial action	108	9
2. Investigation	621	120
3. Surveillance	1573	65
4. Registration only	1092	20

Soil contamination from industrial activities was under represented in this survey, as the main focus was on disposal sites for municipal and industrial waste. Recent experience from redevelopment of old industrial sites (brownfields) in Oslo, Trondheim and Bergen reveals that the real number of contaminated sites is much larger.

PRIORITY POLLUTANTS

Environmental pollutants are defined as compounds, which even in low concentrations can damage the environment. This can be a result of their toxicity, bio-accumulation properties, or low degradability (SFT, 1993). Based on their chemical origin, industrial use and environmental properties soil contaminants are divided in 3 main groups of priority pollutants which deserve close attention (Table 2).

Table 2. Priority pollutants in soil.

Contaminant class	examples
Heavy metals	Cd, Hg, Pb, Cu, Cr, Ni, Zn
Non-chlorinated hydrocarbons	Mineral oil, BTEX, PAH
Chlorinated hydrocarbons	TCE, PCE, PCB, pesticides, dioxins

Almost 50 of the common elements can be defined as heavy metals with a density of more than 5 ton/m^3. But from an environmental point of view the focus is on a small group of elements as a result of their widespread use and environmental effects. From a human point of view Cadmium (Cd), Mercury (Hg) and Lead (Pb) are of main concern, since they are none essential elements. This means that they have no beneficial effects for us and can only do harm. Exposure to these elements should be reduced as far as possible. Whereas heavy metals like Copper (Cu), Chromium (Cr), Nickel (Ni) and Sink (Zn) are essential elements which we need a minimum amount of for several enzymatic functions. Humans tolerate relative high concentrations of these elements without adversary effects. Soil living and aquatic organisms are much more sensitive for the elements and standards are often derived from ecotoxicological considerations.

Fig. 4. Car wrecks are a source of many priority pollutants (photo: Buro Kloeg, Bunnik).

Mineral oil products, like petrol, diesel and fuel oil are used in vast amounts in the western society, resulting in environmental spills during production, transport and distribution. Especially the content of aromatic hydrocarbons in oil products, like benzene, toluene, ethylbenzene and xylenes (BTEX), are of concern since they have toxic properties, are water soluble and can rapidly be transported by groundwater. Many polycyclic aromatic hydrocarbons (PAH) are known for their carcinogenic properties. They are found in large amounts in the environment. Important sources are incomplete combustion (cigarettes, cars), coal tar, creosote and mineral oil products.

Fig. 5. Uncontrolled storage and handling of pesticides has caused serious soil contamination (photo: F. van Veen).

Chlorinated hydrocarbons have in common that they are practically incombustible and have a very low acute toxicity. This resulted after World War II in wide spread use of tri- and tetrachloroethylene (TCE and PCE) as solvents in dry cleaning and the electronic industry. As a consequence chlorinated solvents are ubiquitous groundwater contaminants (Pankow and Cherry, 1995). Polychlorinated biphenyls (PCB) were used as cooling oils and isolators in large transformers and capacitors. Chlorinated pesticides like DDT were very effective. The low degradability of these compounds however resulted in increasing concentrations in all environmental compartments. Accumulation in the food chain resulted in high concentrations in top predators, like birds of prey, seals and polar bears and long-term toxic responses in their immune system. Although the use of these compounds is generally phased out, ecological effects are reaching far into the future.

In addition to the priority pollutants mentioned in table 2 there are many compounds used in industry of which only limited knowledge is available concerning their toxicological properties and potential harmful effect on the environment (Fig. 6).

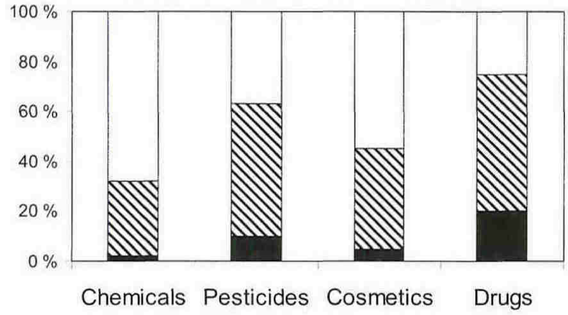

Fig. 6. Health hazard assessment of groups of compounds; ■ complete assessment, ▧ partial assessment, □ no toxicity data (NRC, 1984).

Of 50.000 chemicals commonly used in industry we completely lack toxicological data for 70% of the compounds. Even for drugs, the best studied group of chemicals in our society, it is obvious that a lot of essential information is missing for the 1800 substances evaluated. These compounds might be the priority pollutants of the future.

SOIL REMEDIATION

Once soil contamination was recognised as an environmental problem at the beginning of the 1980's discussion started on how these problems could be remediated. What should be the objective for remediation? In the Netherlands soil functions were the main focus (Table 3). After remediation the soil should be able to support all soil functions. This so-called "multifunctionality" principle required in many cases remediation down to background levels to protect children, crop production and soil living organisms.

Table 3. Soil functions.

Physical support for human activity
Plant production
Groundwater filter
Resource for gravel sand and clay
Residence for soil living organisms
Element cycling

The large number of sites, which required remediation, made it economically not feasible to realise multifunctionality. Treatment was made dependent on the actual or planned site use. During the last 20 years different methods to remediate contaminated sites have been developed. In general 3 categories of methods can be distinguished:

- Removal by excavation and subsequent containment or treatment
- Isolation/capping and monitoring to prevent exposure.
- In-situ treatment to remove or stabilise contaminants without removal.

In the following, examples of each of the 3 methods will be presented based on case studies.

<u>Offices at brownfield site</u>

The Norwegian Red Cross was allowed to build its new headquarters at the former municipal gas plant (MGP) site in the centre of Oslo (Fig. 7). Several large tar pits had been covered with soil and were first discovered during construction works. The site was heavily contaminated with PAH from the coal tar. This soil and waste material had to be removed for the foundations of the new building (Jonassen and Hauge, 1997).

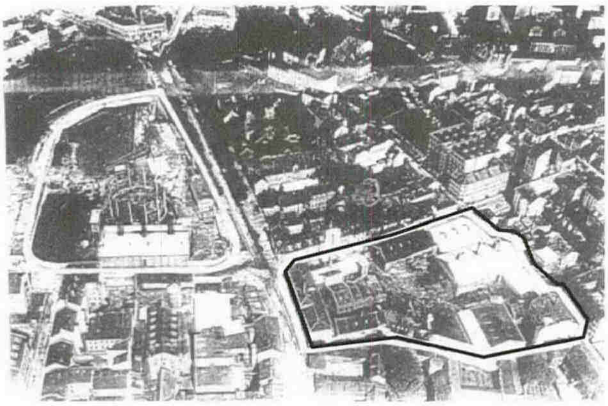

Fig. 7. Location of the former Oslo municipal gas plant site.

Heavily tar contaminated materials were removed and sent to the Netherlands for thermal destruction, since no treatment options were available in Norway at that time. Soils and ashes with lower levels of PAH were sent to a controlled landfill. Some remaining contamination in the original clay soil was isolated from the new building and a leachate collection system was installed (Fig. 8). In the old MGP buildings which were renovated it was not possible to remove all contaminants as a result of the foundation design. A vapour phase extraction system was installed below the new bottom liner and floor to prevent fumes from entering the building.

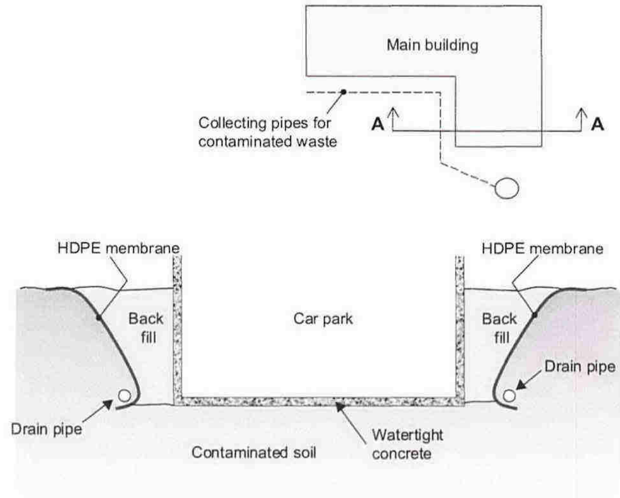

Fig. 8. Isolation of foundation of new offices with leachate collection system.

Containment of old landfill

An industrial waste disposal site in the community of Notodden was situated along the shore of a small river. Waste had been dumped from the river terrace over a length of approximately 200 m (Fig. 9). During spring floods the river eroded the bottom of the dump and exposed industrial waste containing PAH and heavy metals from metal plating activities (Otter et al., 1991).

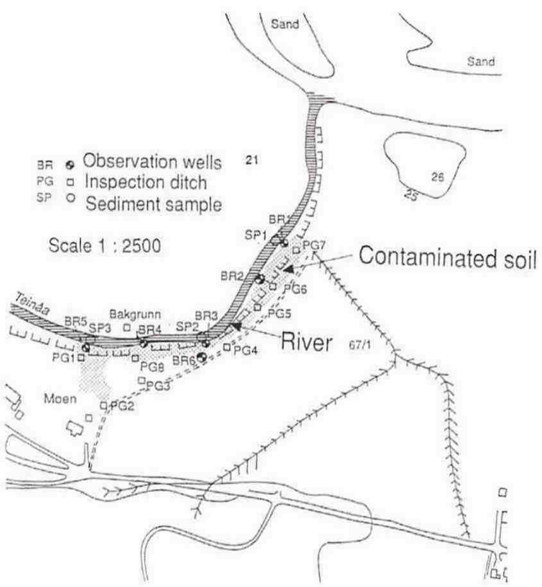

Fig. 9. Industrial waste dump along the river Teinåa.

The site was contained by isolation from rainwater, groundwater and surface water infiltration. This solution would eliminate physical exposure of the contaminants (Sparrevik et al., 1995). In addition the course of the river was changed and bank reinforcement was used to prevent erosion (Fig. 10).

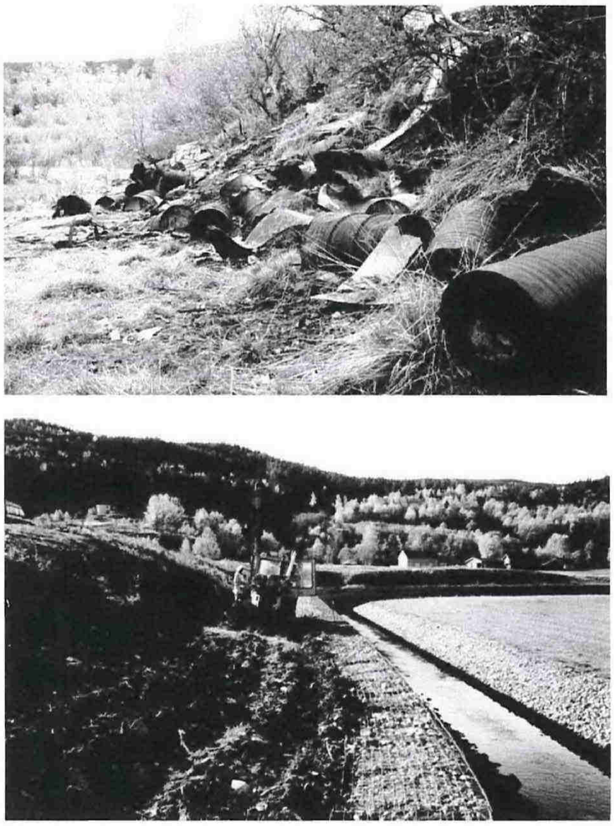

Fig. 10. Landfill site before (a) and after (b) remedial measures were completed (photo: P. Kolstad).

Fuel spill from underground storage tank

On October 12th, 1990 twenty thousand litres of fuel oil leaked from an underground storage tank at Trandum Army Base. The contaminants spread down to 24 m below surface level in the unsaturated zone and threatened the groundwater resources of the Gardermoen aquifer (Fig. 11). Removal of the approximately 1000 m^3 of contaminated sand and gravel by open excavation would have required handling 300.000 m^3 of clean sands and the demolition of several utility buildings. Therefore in-situ bio-remediation using active aeration by soil gas extraction (bio-venting) was chosen as the remedial measure (Breedveld et al., 1992). Three wells at different levels down to 28 meters were used to supply air oxygen and stimulate microbial degradation. In this way the water-soluble compounds in the oil were removed, which could cause groundwater pollution (Fig. 12).

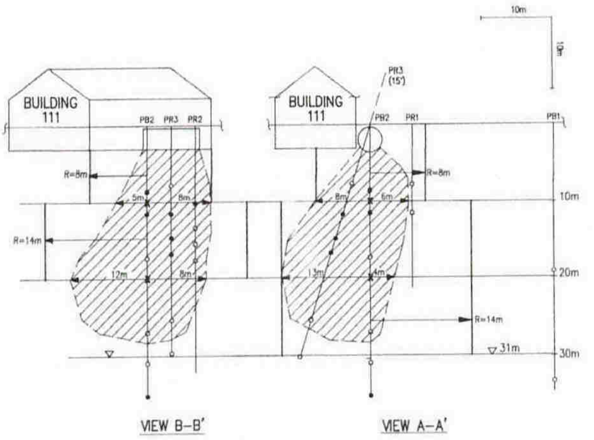

Fig. 11. Areal extend of the contaminant plume at Trandum.

After 4 years of operation the water soluble BTEX fraction was completely removed and a 30 to 70% removal of total mineral oil could be observed (Breedveld et al., 1995). Although the contaminants were not completely removed, the environmental risk associated with the pollution was largely eliminated.

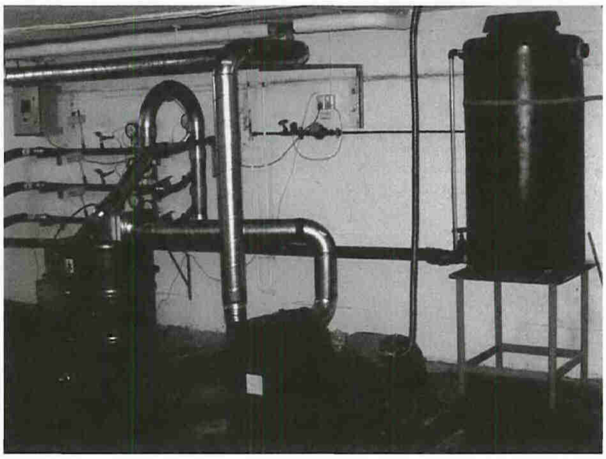

Fig. 12. Overview of the in-situ bio-venting design at Trandum.

The three case studies presented show that we have been able to find solutions for many pollution problems relying on our engineering skills. However the number of cases and extent of pollution is so enormous that it is not economically feasible to actively remediate all sites. This recognition rekindled interest in the natural processes interacting with contaminants.

NATURE'S BEARING CAPACITY

A waste disposal site will exert a load on the surrounding environment. This load can be divided into a physical component and a chemical component (Fig. 13). In geotechnical engineering the physical load the underlying soil can "tolerate" is defined as the bearing capacity. If the shear stress exerted on the soil surpasses the shear strength (the internal forces in the soil counteracting the shear stress), soil failure will occur (Fig. 13a). This will in many cases be immediately visible by soil deformation and slides (Lamb and Whitman, 1979).

The soil's response on a chemical load can be defined in a similar way (Fig. 13b).

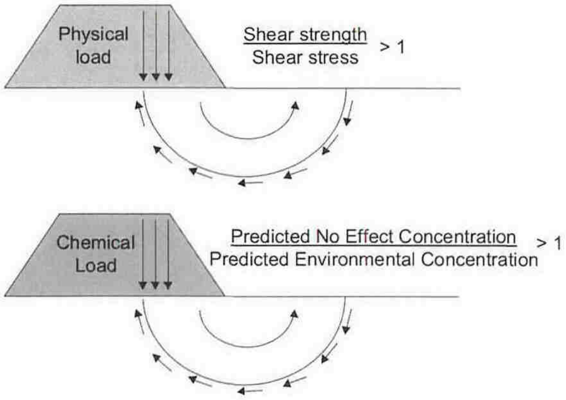

Fig. 13. Schematic representation of physical (a) and chemical (b) bearing capacity for a waste disposal site.

The "strength" or bearing capacity of a soil towards a chemical load is based on the soil processes interacting with the contaminants:

- Sorption to the soil matrix, immobilising the contaminants.
- Degradation, removal by microbial or chemical decomposition of the contaminants.
- Dispersion and diffusion, dilution of contaminant concentrations.

These processes will reduce the environmental load of the contaminants. If the resulting environmental concentration exceeds the predicted no effect concentration (PNEC) for the contaminants, environmental "soil failure" occurs (Vik and Breedveld, 1999). This will result in for instance, a toxic response in soil living organisms (reduced population densities), exposure of aquatic organisms by leaching of contaminants to rivers and lakes or contaminants in food crops. In general these effects of "soil failure" will be invisible on the short term. Only through advanced analytical methods and long-term monitoring it is possible to determine environmental "soil failure". This means that there is a long time lag between actual loading of the soil and the stress response.

Soil's bearing capacity for chemical loads is dependent on the intrinsic properties of the contaminant. Degradability and mobility in the soil environment in combination with the contaminant's toxicity are the main parameters determining the soil's bearing capacity.

Combination of the three parameters will result in a 3 dimensional plane, where areas of high, medium and low bearing capacity can be identified (Fig. 14).

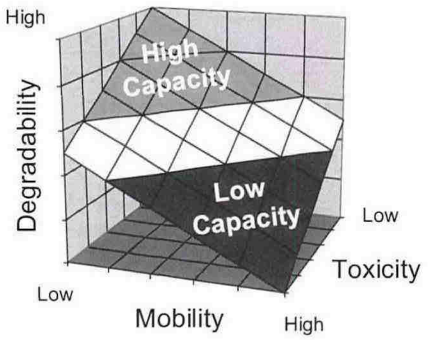

Fig. 14. Areas of high, medium and low bearing capacity based on contaminant properties.

Enormous progress has been made the last 10 years in our understanding of microbial degradation processes in the soil and groundwater environment. Until the 1970's it was generally believed that microbial processes were operating in the upper 1 meter of the soil. During the late 1980's and 1990's it became clear that microbial processes are active in deep sedimentary deposits and aquifer systems (Chapelle, 2000). These findings have a direct implication on the bearing capacity of the soil system.

The presence of oxygen has often been thought to be a prerequisite for degradation of organic contaminants. However studies of old contaminant plumes have revealed that many contaminants are removed under anoxic conditions. Other compounds in soil and groundwater take over the role of oxygen (terminal electron acceptor). Dependent on availability in the soil and groundwater system; nitrate, manganese and iron minerals, sulphate and carbon dioxide will consecutively take over oxygen's role as oxidant (Fig. 15).

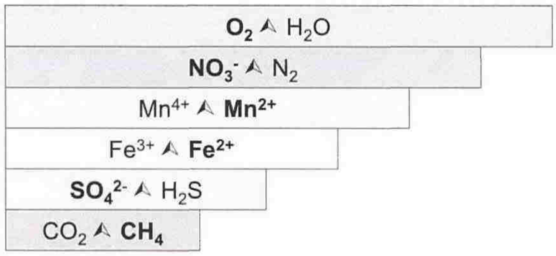

Fig. 15. Soil and groundwater compounds which can take over oxygen's role in degradation of organic contaminants under anoxic conditions.

These processes will reduce contaminant transport considerably. This is clearly observed at the fire fighting training field at Oslo's airport Gardermoen, which has been polluted by jet fuel (Fig. 16).

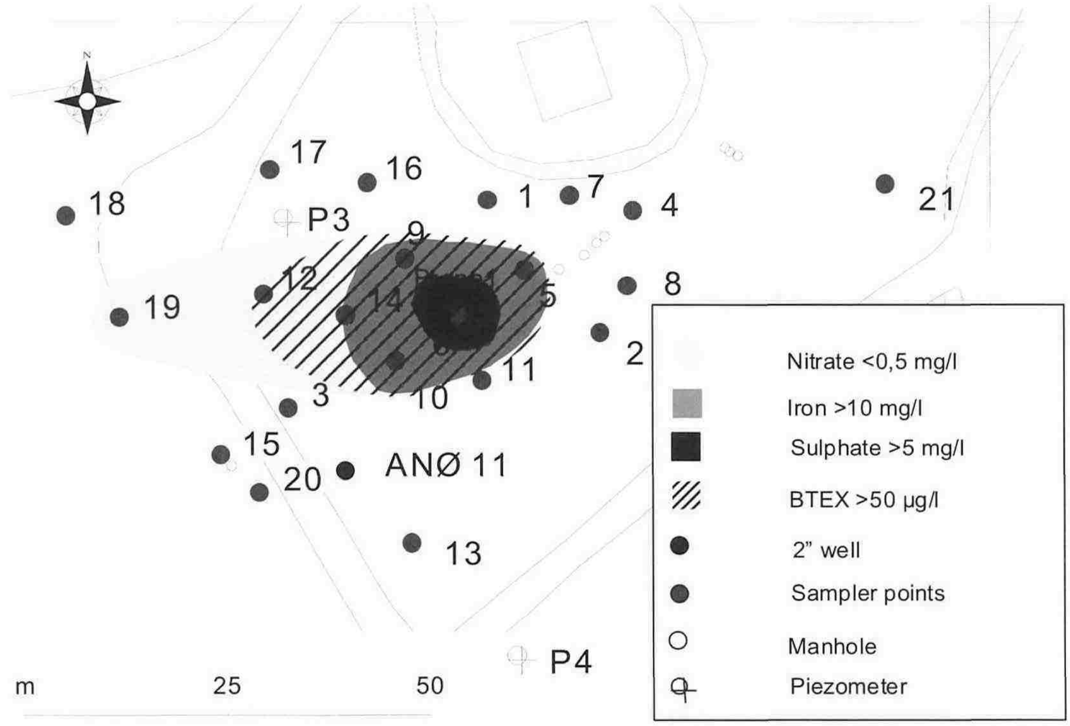

Fig. 16. Changes in groundwater chemistry at the fire fighting training field at OSL Gardermoen.

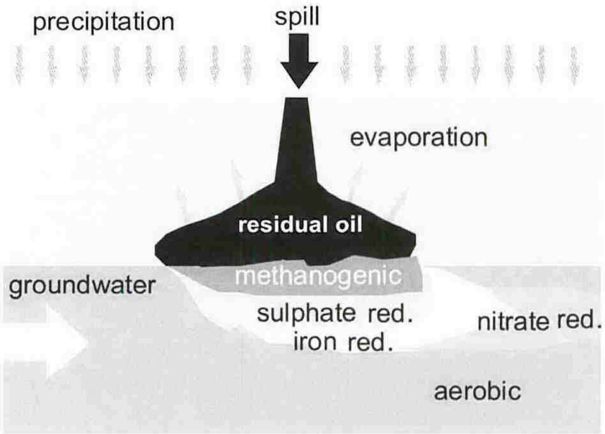

Fig. 17. Conceptual model of contaminant transport at a jet-fuel contaminated site and the resulting redox zonation.

As a consequence of the successive use of the different compounds a zonation in groundwater chemistry is observed (Breedveld et al., 2002). Oxic conditions prevail farthest away from the contaminant source while the most reduced conditions (methanogenesis) prevail in the source zone (Fig. 17).

The use of natural attenuation as a remedial measure is by the general public easily considered as doing nothing. However thorough documentation of the degradation processes is required as well as continuous monitoring of the stability of the contaminant plume (NRC, 2000). To assist in evaluation of the feasibility of natural attenuation at a site, models can be used to integrate the available site data. An example of a simple box model is given in figure 18. Instead of an advanced geohydrological model, the total contaminant load and available sources of oxidants are assessed on an annual basis. This allows a conclusion concerning the stability of the contaminant plume. Especially in the case of seasonal changes in contaminant load and degradation potential, this approach is successful. This is observed in the case of the use of de-icing chemicals at airports during wintertime (Breedveld et al., 2001).

With every new scientific development there is a large danger that its benefits will be overrated. Natural attenuation is typically a solution for specific contamination problems and cannot be applied indiscriminately, despite the large economic benefits compared to engineering solutions. A general classification of the various remedial options is presented in figure 19. If the degradation potential is larger than the contaminant's mobility, natural attenuation might be the preferred solution. If the mobility is much larger than the degradability, engineering solutions are needed. In the intermediate zone, in-situ treatment might be a good alternative.

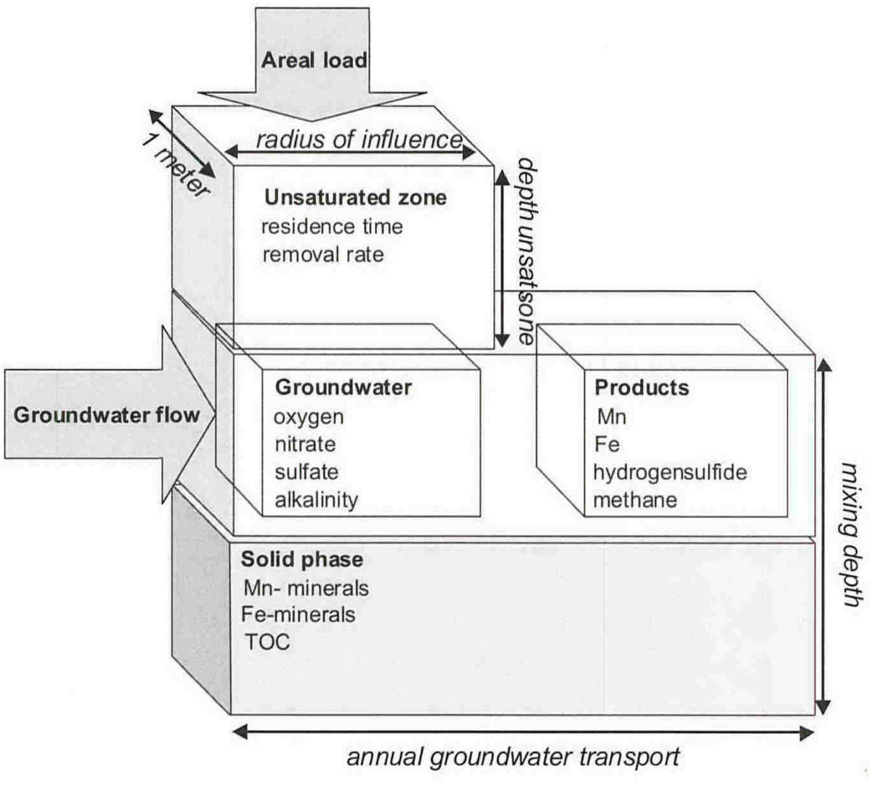

Fig. 18. Simple box model to assess annual contaminant removal potential in soil and groundwater.

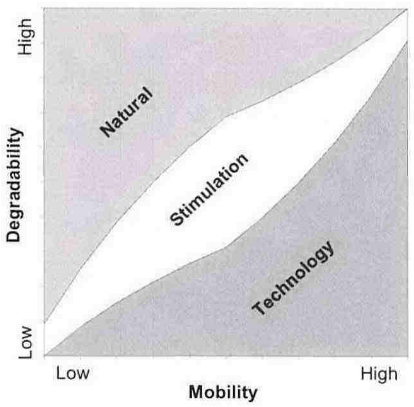

Fig. 19. Preferred remedial options as a function of contaminant properties and site conditions.

SUMMARY AND CONCLUSIONS

A historic review of the development of our appreciation of soil functioning and soil contamination reveals that an original "blind" trust in the infinite waste bin has been replaced by a human engineering approach at the beginning of the 1980's. Excavate and treat or containment of the contaminants was considered the best solution. In-situ methods building on engineering natural processes evolved at the end of the 1980's. During the 1990's a new belief in nature's own bearing capacity in the form of natural attenuation has emerged (Fig. 20). Where will this lead us for the future? New engineering challenges, like gene modification of the organisms responsible for natural attenuation, have been suggested. Hopefully we can direct our effort instead on a better understanding of nature's way of handling contaminants and prevention of new types of potential pollutants entering our environment.

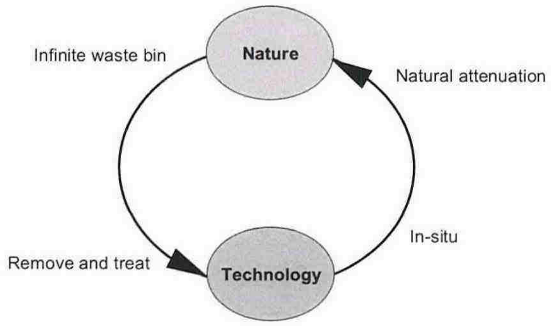

Fig. 20. Historic development of our ways of handling soil contamination.

Initially geotechnical engineers looked at soil contamination problems as an extension of their working field and concentrated largely on containment solutions, focusing on capping constructions and slurry walls. Today we know that solving environmental problems requires a multidisciplinary approach of chemists, biologists, geologists, geotechnical and environmental engineers.

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