Sustainable Use and Management of the Subsurface

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ABSTRACT

The subsurface is and has always been essential to human survival and development. Apart from transport (tunnels) and extraction (mines), the subsurface hosts a myriad of human activities. Increasing land pressures inevitably drives us toward a more intensive use of the subsurface. Sustainable use and management of the subsurface requires forward thinking and planning based on proper geological data. Inadequate legislation and lack of long-term vision together with reluctant public perception still hamper such underground development.

1. INTRODUCTION

Humankind was always more interested in its visible surroundings than in the subsurface. However, the subsurface invariably played a vital role in fulfilling the needs of societies and in sustaining ecosystems. The lack of awareness of the relevance of the subsurface for the inhabitants of this planet points to a distinct knowledge gap.

We know that the Earth is a dynamic system with interactions between the Geosphere, the Hydrosphere, the Biosphere (including humankind) and the Atmosphere, including outer space. Such interactions are often quite complex and occur sometimes over (very) long time scales. Many of these interactions are not yet fully understood challenging reliable predictions for future behaviour of the system, including the ground below our feet. Such knowledge is essential to obtain the necessary Earth resources sustaining our daily lives. We also need such knowledge to predict natural hazards, many of which originate from or are triggered by the subsurface. Reliable hazard predictions reduce risks to society. Finally, we need to know more about where parts of our future cities will be located: in the underground. Chapter 7 shows that all current trends point to higher land pressures, making urban lands extremely precious and making exploitation of the planet's third dimension inevitable: the limited options for ever taller buildings and/or the unlimited dimensions of underground space.

Understand how subsurface development may impact the Earth, at least some knowledge about the composition of the Earth is required. Such knowledge and more in particular about the geotechnical properties significantly grew over the past decades. Uncovering the Earth subsurface is what about 400,000 Earth scientists do by making the underground a little more transparent every day. But relatively little information is available under the world's megacities and very few databases with reliable and detailed subsurface information yet exist. That is rapidly improving now (de Mulder & Jackson, in prep.). Municipal authorities need such information for further and safe urban development, also at surface. Such development is not only hampered by the lack of subsurface information, but by missing or conflicting legislation, regulations and procedures as well. That all may lead to conflicts about land property, liability and management problems, too often resulting in un- or hardly sustainable development. This paper describes past, current and future underground development until 150 metres depth where all current underground activities take place except for oil and gas extraction and mining activities.

2. HISTORIC USE

From the onset of humanity, the Earth almost literally played a mother role, still worshiped in certain cultures. Almost all basic requirements were derived from the subsurface. That changed when farming began, some 10,000 years ago. When that was followed by settlement and urbanisation humans gradually began to lose their dependence of the Earth's subsurface. Modern societies do no longer perceive the Earth as a living 'Mother' but rather as a rigid substratum delivering Earth materials and absorbing wastes. We describe exploitation of Earth materials and the use of underground space from prehistoric times until the time we began to realise, rather suddenly, the relevance of the Earth's subsurface for maintaining our life support systems, by the mid 1970's.

2.1 Resources

The oldest materials mined were rock fragments as construction materials. Traces of 6000 - 7000 years old metal (copper) mining were found in Central Europe. Tin was used for producing bronze and lots were found in SW England that became the world's main supplier. Tin was a target for the Romans who also produced masses of lead. Some authors (Nriagu,1983) relate the decline of the Roman Empire to lead poisoning. Iron mining for weapons was widespread in Europe in Roman Times and peaked again in the Industrial Revolution (since the late 18th century) and the Cultural Revolution in China (1966-1976). Gold mining began at least 5000 years ago but the 'gold rush' occurred in the 16th century.

Energy materials as black coal were already mined for more than 1800 years ago in China, predating such mining in Europe with at least 1500 years. There, coal mining peaked in the mid 20th century but declined since the 1960's when this became uneconomic. The first oil well was drilled in 1859 in Pennsylvania, USA, but it took more than 60 years before oil became the major fossil fuel for vehicles. Until steam powered machines took over in the late 18th century, mining was relatively shallow and mainly by hand or animal power.

Water has always been vital to humans. Groundwater production started when farming began and large volumes were needed for irrigation. Water supply and distribution boomed in Roman Times but large scale underground water mains started only in the 18th century. Mining disrupts balances between Earth processes. In many such processes groundwater is dominant. This also holds for mining as water has to be removed to keep mines dry and if abandoned groundwater levels rise. Groundwater fluxes might impact (underground) mine stability resulting in collapsed roof tops. Mining had major socio-economical consequences as well as local populations do not always benefit from the wealth below their feet.

2.2 Subsurface space and infrastructure

The subsurface has always provided space for storage and shelter. Local geological conditions largely determine if the underground is suitable for such functions. Rock and soil properties, as (thermal and chemical) isolation capacity and bearing capacity, may favour underground storage of food, fuel, strategic or waste materials against limited energy costs. Some 5000 years ago, grain was stored underground in China.

Throughout history, underground constructions were built for two main reasons: to protect against war and extreme climatic conditions. For the latter reason, some 80,000 people still live in caves in Andalusia, Spain and 3,500 people in Central Australia (see chapter 3). A fine example of ancient underground housing can be found under the city of Rome, Italy. But the subsurface has most frequently been used for traffic, transport of water, sewerage and electricity, and for communication lines. Tunnelling began in Europe and followed in North America due to rapid growth of railway and metro systems since the mid 19th century. However, in the 1970's railway tunnelling collapsed in the USA where trains lost competition from the automobile. In Asia, major underground transport tunnels were not built prior to the 1930's in Japan followed by China where the first long train tunnel opened in 1966.

3. CURRENT USE

Public concern about the state of the environment emerged in mid 1970's. That drove governments to act on protecting the environment, including the subsurface. Granting new mining licenses was halted as were other subsurface developments. On the other hand, this concern generated new geological research for permanent storage of hazardous chemical and nuclear waste materials and (later), followed by underground storage of greenhouse gasses.

3.1 Resources and storage

Despite of the gloomy predictions by the Club of Rome, the strongly increased production of Earth materials did not lead to their depletion. Instead, more reserves were found and prices dropped (Crowson, 1998). That could mainly be attributed to the work by a new generation of exploration geologists. Due to strongly increased demands from China and India, commodity prices rose again since 2002. That made lower grade ore bodies economic resulting in expanding extraction sites, more land disturbance and more mine waste products. Production of fossil fuel rose interruptedly since 1975, particularly in South and SE Asia. Oil production increased but the reserves grew faster and since 1990 stabilized at a level of some 40 years. Natural gas production doubled between 1975 and 2000. Large reserves of Uranium were discovered but the Chernobyl accident halted expansion of nuclear power generation since 1986. In 2004, France relied for more than 78% on nuclear energy. Since the 1980's, permanent, geological storage of highly radioactive waste materials was studied extensively for host rocks as granite, clay and rock salt.
In this period geological input in mining increased as shown for example in alluvial diamond mining in Namibia, a country whose economy builds for 21% on diamond production. These diamonds originate from weathered mother rocks in central Southern Africa from where rivers transported them to the west. Detailed geological studies accurately predicted distribution patterns and ever higher yields. More and more geological input is required today for finding construction materials as well. Accurate exploration of these urgently needed materials became increasingly necessary as availability is mainly controlled by environmental and regional political factors today. This approach also applies for groundwater which is an essential component of the life-support system. In this period safe and clean groundwater became an even more important resource as more and more aquifers became contaminated.

3.2 Environmental concern and reclamation

Mining impacts landscapes and disturbs environmental balances making this a more and more unwelcome development since the mid 1970s, regardless of their strong demand. State policies forced mining activities to constrain and, except for the Nordic countries, metal mining got almost extinct in the European Union. Reclamation of abandoned mines and their waste products (tailings) really began to develop in the early 1980's, when the former tin mines in Malaysia were reshaped into residential areas, shopping malls and leisure areas, as were the deep lignite mines in Germany. However, abandoned mining sites might develop into chemical time bombs if rising groundwater levels may mobilize chemical waste products into the biosphere. That may also happen if mine waste is stored in reservoirs that might fail as occurred in Spain, 1998. Another environmental effect of (black coal) mining is related to coal-fires which occur in many of the world's shallow coal belts, in particular in China. These contribute significantly (2-3% by China only) to the world's total annual CO_2output.
Initially, such concerns were politically expressed in environmental protection. The UN Environmental Programme (UNEP) issued guidelines for sustainable mining. UNEP was strongly involved in the Earth Summit (UNCED), in Rio de Janeiro (1992) and in the World Summit in Johannesburg (2002). In this 10-years time span, the UN and many governments moved from environmental protection only towards sustainable development, with a more open attitude towards mining, but under (strict) environmental control.

3.3 Subsurface space and infrastructure

Since 1975, underground infrastructure grew exponentially in length, diameter and volume. Safer and cheaper techniques made tunneling more popular and their numbers grew from 50 longer (> 5 km) train and car tunnels in 1975 to some 160 in 2000 in Europe alone. Norway and Italy currently lead European tunneling. Completion of the Euro Tunnel, connecting Britain with the continent, was a landmark in recent tunnelling history. No such boom occurred in the USA. There, the most prominent (car) tunnelling activities took place in the Boston's Harbor area ('Big Dig'). Today, Japan is the world's leading nation in building longer (train) tunnels: 87 by 2005.

3.4 Can the subsurface be used in a sustainable manner?

Recent, exponential growth of underground activities increased pressure on the environmental conditions of this planet. Since 1975, the global ecological footprint grew from 0.8 to 1.2 Earths in 2001. But, in contrast to 1975, we now know much better how the often slow Earth processes interact mutually and with human activities as underground construction and other activities. If such knowledge would be applied indeed, we can be more confident that subsurface functions can be managed more adequately and sustainably than ever before.

4. SUBSURFACE PROPERTIES & INFORMATION

It is far more difficult to build underground construction than at surface. Underground, one cannot easily collect important rock properties data otherwise than by excavation, by drilling and sampling, by other in-situ testing or geophysical methods. In the subsurface, pressure patterns by constructions are quite different and more complex (mainly three-dimensional) from those at surface. Failure of underground constructions is much different too, often occurring without any warning indications.
Ground properties determine options for underground excavations. Digging and removing Earth materials disturbs existing stress-strain equilibriums in the rock masses while generating new balances. These might require additional support measures to avoid collapse. In addition, excavation may affect the stability of constructions at surface as well. Since the mid 1970s, excavation by conventional drilling and blasting was gradually replaced by tunnel boring machines (TBMs). Support devices changed from steel arches, rigidly poured concrete or concrete segment lining to more flexible types of support, such as bolts with shotcrete. Where initially soft grounds with high water tables remained untouched, since the mid 1970s these are being penetrated by various types of TBMs. Rock tunnel boring machines also improved penetrating even harder and stronger rocks. Alongside, underground worker's expertise improved with such technological developments.
Regardless the much better excavation and support methods failures in underground construction works are still mainly due to sudden and geologically determined changes in underground conditions. Reducing such failures requires more precise knowledge of such conditions. But underground data collection only provides us with samples of reality. To build safely underground we would need to know the composition, structure and properties of the subsurface and all man-made constructions at and around the construction site. Ideally, engineering geologists should produce fully transparent images of the subsurface to serve planners and developers best. 3D engineering geological models come closest to this ideal.
Such models ideally consist of a *boundary model* describing all geotechnical units and their interfaces, and a *property model* describing the properties in such units. Today, very few 3D engineering geological models are operational, most are 2 to 2.5D. Further development of 3D models is seriously hampered by the inhomogeneity of geotechnical units and by uncertainty about how properties are distributed in such units. To cope with this and to produce more reliable models much more (expensive) data would be required. One may question whether the added value of better prediction models would outweigh their much higher cost. Another major challenge in producing more advanced engineering geological models deals with uncertainty in geological interpretation, including discerning

geotechnical units. Such challenges may keep us away from even more advanced (4D) models which would include modifications in geotechnical properties over time.
Engineering geological data are either in vector or in raster formats. Mutual conversion is possible, though more easily from vector to raster format. A myriad of computer programmes for subsurface modelling is currently available, often derived from Computer Aided Design or from 2D Geographical Information System (GIS) software. Relevant data may come from cadastres, small infrastructure, military, topography, public works, archaeology, and from geology and geotechnology (maps, bore holes, in-situ tests, geophysics) sources, most on paper. The rapidly developing information technology and IT literacy by professional users prompted storage of such data and information in digital databases which are more and more feeding engineering geological models. That contributed to yet another challenge: data redundancy and loss of data. This is particularly relevant for complex civil engineering projects where (often the same) data is collected during successive stages of implementation. Development of digital data and information management systems may assist in resolving this problem.

5. LEGAL, POLICY AND MANAGEMENT ASPECTS OF THE SUBSURFACE

This chapter briefly discusses formal relations between the subsurface and society. Time and space play a key role in this respect while this relation is monitored by data and information. In terms of sustainable development, short-term individual interests have to be balanced against long-term (sustainability) societal concerns. As to the subsurface legal aspects, policy and management issues and their mutual linkages are concerned.

5.1 Legal aspects

Legal aspects deal with (written) laws and regulations concerning the subsurface. Most relevant are landownership, mineral rights and environmental aspects, while customary rights should not be ignored. Landownership may be collective or private. Theoretically, a landowner owns the cone-shaped portion of the Earth until the very centre of the planet. This is based on Roman law used as a model for the current English, US and many other laws. In most countries, landowners may not prohibit public use of underground space if that would not obstruct his normal operations at surface. In case of doubt, governmental bodies normally prefer buying the land. They even might chose to expropriate landowners if public interests outweigh those of the landowner. Landownership might be split in more spatial units as is common practice in the USA where the *Condominium law* was developed. Through the *Cooperative Model* ownership may be shared with other parties. Under specific conditions, landowners may allow third parties access to his property by easement. *Leasing* subsurface space may be arranged for obtaining the use (only) of the subsurface. Many legal liability aspects in underground construction concern risks by man-induced geohazards, as unexpected settlement and groundwater contamination. They also deal with the right to access a site in case of emergencies. Liabilities emerging from historic situations and changing property rights are particularly hard to address.
Most nations have a full-fledged mining legislation in place, often recently modernized to include environmental and general underground development and management aspects. Normally, construction materials (stone, sand, clay) are privately owned but metallic and energy material resources often belong to the State. In that case, exploration and exploitation rights may be granted to private parties in return for revenue to the State. Governments may grant *exploration* licenses for limited periods (e.g. in Chile, Japan, and Indonesia) or for infinite time (in Peru and Bolivia). *Exploitation* rights, however, are normally given for a minimum of 25 years (Bastida, 2002). EU member States control their mining operations through their Ministries of Trade, Industry or Economic Affairs. In the USA, this is done by the Bureau of Land Management for their vast areas of federal public lands. For Antarctica, the Antarctic Treaty was signed in 1959 suspending territorial (and mining) claims for 30 years and extended for another 50 years in 1991. Environmental protection and rehabilitation are key elements in mining legislation since the mid 1970s, and Environmental Impact

Assessments became common requirements prior to any mining operation. Unfortunately, plans to harmonize such laws with resource strategies still fail. Legislation on storage of high-level industrial or domestic waste materials is quite recent as well. In OECD countries investments in reclamation of abandoned mines or industrial sites is often part of the permitting process. The strong focus on environmental protection in legislation excluded vast land areas from any development. The 'polluter pays' principle normally applies to environmental liabilities today. Legal aspects of underground activities are quite comparable in most countries, but may differ significantly as to their implementation and enforcement.

5.2 Policy

Policy deals with ambitions and visions, with plans, guidelines and actions as formulated for decision-making by public or private organisations. These might develop into laws, regulations or more informal agreements as covenants between stakeholders, for example between government and industry. In the European Union, policy development on sustainability issues moved from a national to a supranational level. The Malta Treaty on archaeological heritage (1992), the European Framework Directive Water (2000), and the Soil Strategy (2006) relate to the subsurface.

Management

Management concerns the organisational process to implement policy plans and legislation. Managing the subsurface requires specific instruments and tools, as a land and subsurface registration systems of ownership (cadastre), permitting, decontamination of groundwater and soils, data collection and storage and enforcement. With respect to the subsurface, decontamination is still a major management issue in many countries. Public private partnerships might be developed to avoid stagnation and practical measures may work out more effectively than heading for total clean-up.

6. FUTURE USE

To imagine how the subsurface may develop in the course of the 21st century, we may analyse the five drivers of societal pressures on physical space vis-à-vis the availability of such space on this planet. More factors controlling such developments are described later.

1. *Population*: the UN (2005) predicts 9.2 billion people to live on this planet by 2050 (mid-scenario), a figure that will probably remain constant until 2300. This implies a 50% population growth in two generations.
2. *Urbanisation*: the UN (2004) predicts almost all population growth from 2000 (about 2 billion) to be concentrated in cities, adding major pressures on existing urban space. In combination, both trends will cause urban land prices to rise, particularly in the city centres.
3. *Quality of life*: the per capita GDP and life expectancy rose sharply since 1820 in all parts of the world. Simultaneously, the % of poor people roughly halved (Lomborg, 1998). Wealthier people normally demand for better and larger housing and economic growth demands for wider industrial areas and economic zones. Prosperity growth also generated larger volumes of waste products and cities were surrounded by waste disposal sites. Industrial expansion, waste disposal, and increased food and natural resource production have put enormous pressures on physical space. These trends are not likely to be reverted much if at least some global economic growth would be maintained during the next decades.
4. *Environmental awareness* resulted in protection of vulnerable landscapes and conversion of large areas into natural parks or nature reserves. At the same time, vast areas or arable land degraded and became unsuitable for food production and many other functions. In combination, both processes put land development under high pressure and thus to the availability of physical space for growing urban populations.
5. *Technological development* relieved some of these pressures. The green revolution greatly increased food production and re-use of natural resources reduced the size of open-pit mines and volumes of mine tailings. Technology supported land reclamation giving more space to the cities and reduced

waste disposal sites by better incineration techniques. The tunnelling boom in the 1970's and 1980's was partly due to better techniques, making underground construction safer, cheaper and faster. China is becoming the world's first tunnelling nation.
Most likely, the first four drivers will make physical space a more scarce commodity and (especially urban) land more precious. Reclamation of derelict land and parts of the sea may then be more economic, in particular with better technology. Sea-, mountain- or river-facing cities cannot grow horizontally and the need for more urban space will initially be satisfied by more high-rise buildings. But as such constructions have their own intrinsic limitations; the only other way out will be the subsurface. The almost unlimited availability of space will make the underground target for solving space problems at surface. Ongoing technological development will further reduce costs and increase safety of underground construction.
Legislative, knowledge and technological constraints may hamper such developments today but if pressures will become high enough at least some of these will be overcome soon. Psychological constraints may be harder to overcome but by designing pleasant, comfortable and light environments in underground rooms with proper safety and security measures, the public may even like to stay underground as they do in cities as Montreal today (Galipeau & Besner, 2003). In deeper parts of the subsurface (250-700 m) still rather comfortable working and living conditions occur. By exploiting in-situ ground pressures rather big underground rooms may be created once special excavation equipment has been developed (Taselaar, 2002). If successful, exponential growth of such geo-domes may not be excluded, maybe resulting in several thousands of such structures by 2050. These might then be mutually connected and also with other infrastructural elements and might thus serve as kernels of underground networks and, eventually, of underground cities. Such underground activities will impact the delicate balances in and between the myriad of Earth processes. However, geo-experts will then know much more of such processes and how to build underground structures in harmony with them in accordance with the actual societal needs.

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