

GEOENGINEERING CONSIDERATIONS IN THE OPTIMUM USE OF UNDERGROUND SPACE

Raymond L. Sterling

*CEFT Professor of Civil Engineering, Director, Trenchless Technology Center, Louisiana Tech University,
Ruston, LA, USA*

Jean-Paul Godard

*Vice-President of the International Tunnelling Association, Projects Department, Régie Autonome des
Transports Parisiens (RATP), Paris, France*

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

1 INTRODUCTION	3
2 THE DEVELOPMENT OF UNDERGROUND SPACE USE	3
3 REASONS FOR GOING UNDERGROUND	4
3.1 LAND USE AND LOCATION REASONS	4
3.2 ISOLATION CONSIDERATIONS	4
3.2.1 <i>Climate</i>	4
3.2.2 <i>Natural Disasters and Earthquake</i>	4
3.2.3 <i>Protection</i>	5
3.2.4 <i>Containment</i>	5
3.2.5 <i>Security</i>	5
3.3 ENVIRONMENTAL PRESERVATION	5
3.3.1 <i>Aesthetics</i>	5
3.3.2 <i>Ecology</i>	5
3.4 TOPOGRAPHIC REASONS	5
3.5 SOCIETAL BENEFITS	6
4 PLANNING AND DESIGN ISSUES	6
4.1 SAFETY, PSYCHOLOGICAL AND HEALTH ASPECTS	6
4.2 PROTECTION OF THE UNDERGROUND ENVIRONMENT	6
4.3 RELATIONS BETWEEN UNDERGROUND STRUCTURES AND THE GROUND SURFACE	7
4.4 CONSTRUCTION TECHNIQUES	8
4.5 SITE INVESTIGATION	8
4.6 RISK ANALYSIS	9
4.7 ASSESSMENT OF UNDERGROUND STRUCTURES	9
4.7.1 <i>Taking into account life-cycle costs</i>	9
4.7.1.1 Land cost	9
4.7.1.2 Construction cost	10
4.7.1.3 Savings in special design features	10
4.7.1.4 Energy savings	10
4.7.1.5 Maintenance costs	10
4.7.1.6 Replacement costs	10
4.7.2 <i>Taking into account the indirect benefits of underground structures</i>	10
4.8 CRITERIA FOR AN "OPTIMUM USE OF UNDERGROUND SPACE"	11
5 USING GEOLOGICAL FEATURES	11
5.1 THE SITE AND GEOLOGICAL STRUCTURE	11
5.2 SIGNIFICANCE OF GEOLOGICAL FEATURES	12
5.3 GROUNDWATER	12
5.4 GROUND SETTLEMENT AND BUILDING DAMAGE	13
5.5 ARCHAEOLOGY	13
5.6 PLANNING	14
5.7 INFLUENCE OF CONSTRUCTION METHODS	14
6 FUTURE TRENDS	15
7 CONCLUDING REMARKS	17
8 REFERENCES	17

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

1 INTRODUCTION

This paper is organized to first review the history and varied rationales for using underground space, then to review interaction of geology and geoengineering design with the planning and execution of underground works. Those familiar with underground space use and the geotechnical design of underground structures will be well aware of most of the issues raised but it hopefully will provide a good review of the reasons why geological and geotechnical input is critical at all stages of the process. In the last part of the paper, particular attention is paid to the trends in underground technology development as well as urban underground space use and what these trends may provide in terms of opportunities for geology and geoengineering professionals to help optimize the long-term use of underground space in urban areas.

2 THE DEVELOPMENT OF UNDERGROUND SPACE USE

For hundreds of thousands of years, our natural domain has been a principally two-dimensional space: the surface of the ground. Urged by necessity, curiosity, or even by fear, we have tried to escape from the limitations of this space, either by creating new land at waterfronts, or by searching to utilize the third dimension, upwards or downwards.

Underground works have always been difficult but this did not prevent their use at a very early stage of human development, as proved by the discovery of underground excavations that are among the first records of human activity. Of course, nature, and not mankind, is at the origin of the first underground works. Grottos and caves are the result of the action of the rain, the rivers and the sea, and necessity no doubt drove early humans to settle in these natural cavities to find protection from the weather and from attacks. Indeed, it is tempting to think that humanity perhaps owes its survival largely to these natural underground habitats. Cave dwellings were thus an important landmark in the use of underground space by mankind; with them, the use of the underground became intentional and active.

In every age, considerable use has been made of underground structures for mining and defensive purposes. However, the most rapid increase in the use of underground works only appeared in the 19th and particularly the 20th centuries, thanks to the impetus of economic development and the emergence of improved technologies for underground works. During these periods, there was a dramatic increase in underground space use, in mining, in the field of transportation with the development of roads, waterways, and railways, and in other fields such as the development of hydroelectric facilities.

So, since the dawn of human endeavor - more intensively during the recent centuries, and above all during the last several decades - numerous reasons have encouraged mankind to use and develop underground space.

For a good understanding of these reasons, it is necessary to keep in mind certain fundamental characteristics of underground space.

- First, the underground is a space that can provide the setting for activities or infrastructures that are difficult, impossible, environmentally undesirable or less profitable to install above ground.
- Another fundamental characteristic of underground space lies in the natural protection it offers to whatever is placed underground. This protection is simultaneously mechanical, thermal, and acoustic.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

- On the other hand, the containment created by underground structures has the advantage of protecting the surface environment from the risks and/or disturbances inherent in certain types of activities.
- Lastly, another important feature of underground space is its opacity. Thanks to the natural visual screen created by the geological medium, an underground structure is only visible at the point(s) where it connects to the surface.

But what are the main reasons today which justify a more intensive and a better-planned use of the underground space?

3 REASONS FOR GOING UNDERGROUND

3.1 *Land Use and Location Reasons*

In many cases, underground space use results from a lack of surface space. The use of underground space allows a facility to be built in a location where a surface facility is not possible either because of lack of space or because building a surface facility in that location is not acceptable to the community. There are many types of facilities that are best or necessarily placed underground because their physical presence on the surface is unwanted, for example: public utilities, storage of less-desirable materials, and car parks.

Also, there is often the need to separate conflicting transport activities or to provide easy connections among them. The distribution of pedestrians around major train stations and bus/train interchanges are examples of this type of need. Grade separation of various types of transportation corridors is often desired and placing one corridor underground generally impacts far less on the existing community. In urban areas, several levels of transport facilities can be brought together in the important city transport hubs.

The underground solution also allows one to build in close proximity to existing facilities or on otherwise unbuildable sites, thus offering better services to the surrounding community.

3.2 *Isolation Considerations*

The ground is massive and opaque and provides a variety of advantages in terms of isolation which in turn provides an important impetus for placing facilities underground.

3.2.1 *Climate*

The underground provides isolation from the surface climate. The temperature within the soil or rock offers a moderate and uniform thermal environment compared with the extremes of surface temperatures. These moderate temperatures and the slow response of the large thermal mass of the earth provide a wide range of energy conservation and energy storage advantages. Thus, the underground provides both protection from adverse climates and can provide substantial energy savings.

3.2.2 *Natural Disasters and Earthquake*

Underground structures are naturally protected from severe weather (hurricanes, tornadoes, thunderstorms, and other natural phenomena). Underground structures can also resist structural damage due to floodwaters, although special isolation provisions are necessary to prevent flooding of the structure itself. Moreover, underground structures have several intrinsic advantages in resisting earthquake motions. They tend to be less affected by surface seismic waves

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

than surface structures, and, despite some significant failures of underground transportation structures and utilities, underground infrastructure has survived well in recent earthquakes in Kobe in 1995, and previously in San Francisco and in Mexico City.

3.2.3 *Protection*

Underground structures offer advantages in terms of preservation of objects or products stored within the structure. For example, food preservation is enhanced by the moderate and constant underground temperature conditions and the ability to maintain a sealed environment. Small amounts of earth cover are very effective at protecting from the transmission of airborne noise. Similarly, if the vibration sources are at or near the ground surface, levels of vibration will diminish rapidly with depth below ground and distance of the source. As with noise and vibration, the earth provides protection by absorbing the shock and vibrational energy of an explosion. In cases of explosion, radioactive fallout, and industrial accident, underground structures can be valuable emergency shelter facilities, if provided with the ability to exclude or filter contaminated outside air.

3.2.4 *Containment*

Containment is the inverse function of protection. This is very important for protecting the surface from the nuisances and dangers generated by some facilities like hazardous material storage and hazardous processes. Examples include the storage of nuclear waste far from human activity and the isolation of hazardous industrial plants.

3.2.5 *Security*

The principal security advantage for underground facilities is that access points are generally limited and easily secured.

3.3 *Environmental Preservation*

The ground also provides a variety of advantages in terms of protection of the environment. These are notably important aspects in designing facilities with a low environmental impact.

3.3.1 *Aesthetics*

A fully or partially underground structure has less visual impact than an equivalent surface structure. This may be important to hide unattractive technical facilities in sensitive locations or when industrial facilities must be sited adjacent to residential areas. This is also important for the preservation of natural landscapes. The increasing requirement for all utility services to be placed underground stems essentially from visual impact considerations and concerns about protection against the elements.

3.3.2 *Ecology*

In some cases, underground structures help preserve natural vegetation. Less damage is thus inflicted on the local and global ecological cycle. Plant life, animal habitat and passages, and plant transpiration and respiration are maintained to a greater extent than with surface construction.

3.4 *Topographic Reasons*

In hilly or mountainous areas, the use of tunnels improves or makes feasible various transport options such as roads, railways, canals, etc. Tunnels are also an important option in river, straits and harbour crossings. Generally speaking, underground space use offers many advantages with

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

regard to the layout of facilities and infrastructures. These advantages derive essentially from the freedom (within geological, cost, and land ownership limitations) to plan a facility in three dimensions and from the removal of physical barriers on the land.

3.5 Societal Benefits

Cities that are capable of functioning economically, socially and ecologically provide the prerequisite for a decent life in built-up areas. Underground space has an important role to play in this respect, i.e. in the achievement of environmentally-friendly development, whether it be in the reduction of pollution or noise nuisance, the efficient use of space, economic development, the preservation of the living environment, public health or safety. In these fields, it offers numerous advantages:

- Tunnels play a vital environmental role by conveying clean water to and by conveying wastewater out from urban areas;
- Tunnels provide safe, environmentally sound, fast, and unobtrusive urban mass transit systems;
- City traffic tunnels clear vehicles from surface streets, traffic noise is reduced, air becomes less polluted and the surface street areas may partially be used for other purposes;
- Underground car parks and shopping malls in city centres leave room for recreation areas and playgrounds above ground;
- Multipurpose utility tunnels are less vulnerable to external conditions than surface installations and will cause only insignificant disturbance above ground when installed equipment is repaired or maintained;
- Last, but probably not least, the safest location to store nuclear waste and other hazardous or undesirable materials is in a properly designed underground facility.

4 PLANNING AND DESIGN ISSUES

This section of the paper gives a general overview of the various problems to be taken into account when developing urban underground space.

4.1 Safety, Psychological and Health Aspects

There remains a natural reluctance to go underground among a large proportion of the population, and many people claim to have feelings of apprehension and even anxiety when they descend into a subway or an underground car park. This suggests that human factors should always be an important criterion when looking for underground technical solutions and systems that involve significant human occupancy. When discussing use of the underground with planners and the public, the health, safety and psychological aspects of the planned structures should be given a high priority to avoid unneeded negative views on the utilization of underground facilities.

4.2 Protection of the Underground Environment

Although we use underground space as a means of reducing surface environmental impact, it is necessary to remember that underground space also is part of the environment and must also be protected. It is vulnerable in several ways:

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

- The use of underground space is irreversible. Unlike structures aboveground, which can be demolished and rebuilt differently, underground works cannot be demolished. This irreversible aspect of using underground space is a major consideration when developing this space. It is therefore important to avoid “consuming” it in an uncontrolled and unplanned manner.
- The vulnerability of ground water tables is the most characteristic aspect of the fragility of underground space. Any use of underground space that affects formations located below the ground water level can have an impact on the quality of underground water tables or their flow, or on both.
- The geological environment is permanently changed by developments made in it, and there is no way of re-establishing its initial conditions. Poor ground control in one project can have harmful consequences for the stability of adjacent structures.
- Underground space in many locations holds archaeological treasures that either are or should be protected. The constraints on construction methods and time schedule must be taken into account in planning projects in such areas.

It is therefore important that local authorities control the use of the underground space of their cities through appropriate laws and regulations. The major aim of these laws and regulations should be to achieve the best possible use of urban underground space in connection to surface town planning, in the interest of the whole urban community. Thus, it would be desirable if underground space use were taken into account when drawing up large-scale outline plans for cities and when making major policy decisions in town planning. In this way, its intended use could be recorded in documents dealing with urbanization at both the local and regional level.

4.3 *Relations between Underground Structures and the Ground Surface*

All underground structures must have some junctions with the ground surface. But developing structures that require such junctions, and especially determining the location of their outlets at ground level, is particularly difficult, especially in urban areas. This issue must not be neglected, as it often represents a major difficulty in designing, building, and even operating underground works. For example:

- Transitional structures between aerial or surface and underground sections of a transportation network require special handling from a structural, functional, and aesthetic perspective. With road tunnels, these problems of aesthetics and integration combine with that of the pollution created by the release of exhaust fumes at the tunnel portals.
- Access points to underground works during construction are another type of junction consideration. The difficulties in implementing such access points, especially in an urban area, are well known. Since such structures are a major part of the design of underground projects, they must be carefully studied and evaluated from the earliest stages of the design process.
- Another type of junction between underground and surface works occurs as part of technical structures, which are sometimes called “*ancillary works*”, but which are absolutely indispensable to the operation of underground facilities. One of the most characteristic examples of this type of structure is a road tunnel ventilation system. Such a system can pose serious problems regarding location, due to the pollution and the disturbances it engenders in its vicinity in terms of noise, atmospheric pollution, air speed, and aesthetics.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

4.4 Construction Techniques

A widespread use of underground space requires efficient and reliable construction techniques. This is especially true in built-up areas, where careful precautions must be taken for avoiding damages to the surrounding structures and special measures must be taken to reduce the effects on urban life during the construction phase. The elaborate construction techniques necessary in urban areas have long been (and in many cases remain) an obstacle to adopting underground solutions.

Considerable progress has been made over the past 20 or 30 years in underground construction techniques:

- The problem of damage to adjacent structures from ground movements caused by the construction is increasingly well controlled.
- The cost and duration of underground construction continue to decrease relative to above-ground construction.
- Technology improvements have led to high levels of safety in underground civil engineering projects.
- Pressure-balanced shields (slurry or earth pressure) are resulting in the mechanization of an increasing number of applications.
- Progress has also been made in cut and cover construction methods, especially in the area of ground support (slurry or precast walls, grouting, and anchors). But the efficiency of these construction methods is significantly reduced by the constraints resulting from underground congestion due to the presence of numerous utility networks and the more and more severe environmental requirements, such as, for example, maintaining trees during the construction phase. In addition, cut and cover methods are encountering growing resistance from local inhabitants, because of the disturbances and nuisances caused by major excavations undertaken in such congested areas.

4.5 Site Investigation

For all subsurface construction, it is particularly important to predict the properties of the ground accurately, because errors can have serious consequences for a project as regards completion dates and additional costs. Geological surveys are therefore vital and include the development of systems for the interpreting of expected geological, hydrological and seismic conditions, and the preparation of plans for on-site investigations.

It also is important to have reliable information concerning the location and the features of the existing underground structures, facilities and public utilities, in order to be able to determine the most suitable location of the planned structure, the most appropriate construction methods and the precautions to be taken towards the works in the vicinity.

The development of a better knowledge and representation of the geological medium and of existing underground structures is a critical need in urban areas. The upgrading of the quality of data on existing structures and geological conditions needs to be undertaken by urban authorities. Integration and visualization of this data also is important and significant advances in the use of three-dimensional Geographical Information Systems (GIS) for underground planning and construction monitoring are being made around the world.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

4.6 Risk Analysis

As the demand for underground facilities has increased, risk considerations have taken on greater importance. In spite of the progress that has occurred in underground construction during the last several decades, decision-makers still express concern for the risks encountered in underground construction.

Feasibility studies and, even more important, tenders and contracts, must deal with the following categories of risks and potential hazards:

- Financial risks, such as cost overruns, or lower (than projected) rates of capital return;
- Risks that public facilities will not be accepted and used by the public to the degree anticipated;
- Changed ground conditions, such as unexpected geological or geomechanical features or more water leakage than expected;
- Other construction risks, such as tunnel boring machine failures, cutting tools wearing out too fast, face collapses, or sealing leaks;
- Contractual risks resulting from construction problems as well as other issues such as additional work, time delays, disputes and claims;
- Environmental risks such as impacts on groundwater quality, damage to surrounding buildings, and air or noise pollution;
- Risks in operation, notably for transport tunnels.

These factors are of great importance in order to gain or maintain public acceptance of underground solutions.

4.7 Assessment of Underground Structures

Economic aspects remain a major barrier to the development of the use of the underground space. Since the initial construction cost of underground structures is generally higher than for building in the open air but the advantages of underground structures in terms of improved environment over the life of the facility are very hard to quantify, underground structures are in a sense “penalized” when compared to open air construction on this restricted basis.

The economic benefits of an underground facility need to be calculated over the full life cycle of the facility and should take into account the various indirect advantages they offer – notably with regard to the environment.

4.7.1 Taking into account life-cycle costs

Some of the key issues are listed below:

4.7.1.1 Land cost

The most obvious initial cost saving related to an underground facility is in a reduced cost for the land purchase or easement necessary to carry out the project. In areas with extremely high land costs, the cost of land purchase can dominate all the initial cost decisions, especially in the heart of the major cities. But one of the main advantages of placing a facility underground is that one can significantly increase the usefulness, and thus the value, of the surface land. Construction underground increases the useable value of the land in the same way as the value of the land is enhanced by construction of multi-story facilities. Underground infrastructure also makes possible the utility service and user accessibility for a densely developed area whether above or below ground. In many cases, all three options: surface, underground, and air-rights are used to

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

maximize the value of the land. Properly taking into account the initial land cost savings due to underground construction and the preservation or increase of land value in its vicinity (for example, compared to an elevated rail or transit line) is perhaps the key problem in the proper assessment of life cycle benefit-cost ratio.

4.7.1.2 Construction cost

Despite the progress in site investigation, geotechnical engineering and construction methods, underground structures as a rule cost more to construct than equivalent aboveground structures. Some combinations of geological environment, scale and type of facility may provide direct savings in construction cost but this is not normally the case. While the efficiency of underground construction continues to increase, the cost gains are often offset by higher design standards, higher construction safety standards, and environmental mitigation efforts for new facilities.

4.7.1.3 Savings in special design features

The physical characteristics of underground facilities can provide direct cost benefits when compared with a surface facility. For example, thermal isolation reduces peak load demands for a facility's air conditioning system, enabling a smaller and thus less expensive system to be installed. The partial costs for providing low vibration, constant temperature, or clean room space may also be less underground than at the surface. For aboveground buildings that would require an expensive exterior finish, significant savings can be made underground where such special design features are unnecessary.

4.7.1.4 Energy savings

The thermal advantages of underground buildings usually translate into reduced energy costs to operate them. Although ventilation and lighting costs may increase, thermal benefits outweigh these in moderate to severe climates.

4.7.1.5 Maintenance costs

The physical isolation of underground structures from the external environmental effects that deteriorate building components can result in low maintenance costs for underground structures.

4.7.1.6 Replacement costs

Underground structures last significantly longer than their surface counterparts. Aboveground structures are generally much more susceptible to damage and deterioration. Good examples of the longevity of underground structures include the numerous railroad tunnels that have been in service for over 100 years.

4.7.2 *Taking into account the indirect benefits of underground structures*

The assessment of underground structures is strongly related to the community valuation of drawbacks of surface or aerial structures in terms of environmental degradation. Unfortunately, most of the numerous advantages of underground structures, especially those concerning the protection of the environment, cannot be assessed easily in terms of monetary value. As a consequence of the mixing of well-defined and poorly-defined but important costs and/or benefits, the decision making process concerning the realization of an underground structure (especially when it is compared to an aerial or surface solution) is flawed. Thus, cost comparisons should not only refer to the well-defined life-cycle costs, but must take into account the various advantages offered by the underground alternative, particularly the environmental benefits. The International Tunnelling Association is working to help find means of quantifying these advantages

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

with the cooperation of all the professions concerned (engineers, economists, planners, architects, ecologists, etc.).

4.8 *Criteria for an “Optimum Use of Underground Space”*

From the viewpoint of the whole community and not necessarily from the viewpoint of one particular owner, the above discussion can be summarized in terms of the principal criteria that should guide the development of underground space:

- Take into account the needs of the Community;
- Maximize the benefits from the use of the underground as developable space;
- Reinforce the positive features of the surface urban environment;
- Make the most effective use of the features and properties of the geologic setting;
- Design for “sustainability” in the use of the subsurface space.

5 USING GEOLOGICAL FEATURES

5.1 *The Site and Geological Structure*

Topography determines many aspects of what are favourable sites for urban development and national infrastructure. Transportation corridors, land for housing, storage/delivery of water and removal of sewage are all strongly influenced by topography especially during the developmental stages of a city. In the same manner, the internal structure of the ground, provides natural sites that are more or less favourable to particular types of underground developments.

Such underground sites are comparable to an orebody, the economic value of which depends on the ore concentration, the size of the orebody, and the ease of recovery - from mining issues to processing and transportation of the ores.

Surface sites of particular interest (e.g. archaeological, historical, architectural, cultural, or of outstanding natural beauty) are likely to be well defined, documented, protected and/or regulated. This is seldom true for underground sites with particular characteristics that make them of special interest for historical reasons or for future development.

Some natural caves, disused tunnels and underground quarries may be catalogued and have been used as civilian shelters in time of war or for storage of military equipment or strategic products. Some special geologic features of national importance may receive special attention as important underground sites (e.g. sites for radioactive waste isolation, anticlines for aquifer storage of fuel gases, and salt deposits for large scale cavern construction and storage uses). Very little has been done, however, in terms of identifying urban geological features that have special characteristics regarding future urban development.

Properties and structures of underground geological bodies clearly are of paramount importance to underground works. The stratum of London clay provided a favourable site for the London metro, the limestone stratum of “calcaire grossier” under Paris for the Banque de France safe room and the “blue chalk” stratum for the Channel Tunnel.

In relation to surface topology, underground space in hills or near slopes offers many advantages : there is no need to go down to enter, no need for energy to go out, gravity drainage of the structure is possible, etc. Good examples of such spaces are the car parks under the Salzburg Castle hill, the Gjøvik sport halls and, on a larger scale, the Kansas City industrial space within limestone mines.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

5.2 Significance of Geological Features

Geology is the first basis for land use and town planning. Geology controls the landforms and hence the geometry of any site, from a wide plain to a narrow valley or a mountain slope. Together with climate, geology controls the flow and actions of surficial water, the extent and location of groundwater resources, and the designs for foundations of buildings and other structures.

City sites can be classified in a table indicating both the morphology and the rock or soil materials (see Table 1). Typically, cities lying directly on bedrock provide better foundations together with better opportunities for the use of underground space. The best example is Kansas City (Missouri) lying upon a flat plateau between the valleys of the Missouri and Kansas rivers. The bedrock is made of horizontal limestone where the mined space has been reused for industrial purposes. On the contrary, low plains often provide both poor foundations and bad conditions for underground works due to a groundwater level too close to the surface. The depth to the bedrock also has to be considered: under the Chicago clay lies a sound dolomite where very large tunnels and reservoirs have been bored as part of the “TARP” project to intercept sewer overflows and avoid the pollution of Lake Michigan.

Table 1 Classification of cities by nature and morphology of their soil (After Duffaut, 1982)

	Low plain	High terrace	Plateau	Rugged hill	Slope
Sound rock			Kansas City	Oslo	
Soft rock or weathered rock	Lille	Orleans	Madrid	Limoges	Algiers (partly)
Gravels	Strasbourg Lyons (partly)	Toulouse	La Paz (Altiplano)		La Paz (partly)
Fine soils	Chicago Bangkok	Winnipeg			

Of course, many cities do not fit any one classification. For example, one part may lie upon a low plain, another over or around some hills. In such a case, the space inside the hills is of special value for city planning, as it is at road level and easy to dewater by gravity.

Beyond a description of the subsoil conditions and morphology, local geologic features are of great importance for the location, orientation and design of underground works. For example, in the case of stratified rocks, the orientation and dip of bedding planes is important together with the thickness of the layers. In horizontally bedded rock formations, convenient flat roofed caverns can be readily constructed with their span controlled by the thickness and competency of the rock beds immediately above the roof.

5.3 Groundwater

In any underground project, groundwater is a prime factor in its successful development and use:

- Groundwater pressures and inflow affect the stability of excavation faces and the strength of the permanent support structure required.
- Leakage of groundwater into a finished underground structure severely affects the quality of the space and is very difficult to correct.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

- Underground construction may have to deal with existing groundwater pollution affecting personnel safety and raising costs.
- Groundwater chemistry affects the rate of corrosion of underground structures.
- The excavation and use of the underground structure can cause pollution of the groundwater.
- Groundwater movement can affect the settlement of the surrounding ground.
- Groundwater can provide the sealing mechanism for storage of certain products underground, e.g. oil and gas.

There is increasing concern about the effect of underground construction on the environment and particularly its effect on groundwater quality and groundwater table. This affects the length of the approval process for the project, the type of underground construction method used, the types of products used (e.g. grouts), and the extent of monitoring required. Underground projects also are being required to clean up existing pollution when it is encountered.

5.4 *Ground Settlement and Building Damage*

As traffic congestion and environmental issues force the construction of more urban tunnels, more tunnels are being constructed in very difficult ground conditions and close to structures of great historic importance. Limiting ground movement around tunnels, underground caverns and open cut excavations is critical in these situations and public scrutiny and regulation have increased greatly in recent years. Managing the risk of damage to existing buildings affects many aspects of the project process. In planning for new tunnel projects in the Netherlands, for example, such considerations have resulted in:

- Extensive geometrical and condition surveys of buildings that may be affected along the route;
- Comprehensive three-dimensional finite element analyses including progressive tunnel excavation, ground response and structural response that predict the movements and structural distress expected with various construction procedures;
- Establishment of survey control points that define the vertical, tilt and rotational movements of the buildings;
- Linking all survey and predictive data into a GIS system for real-time comparisons and warnings;
- Using risk management issues and planning for risk avoidance as criteria in contractor selection.

While these techniques are a part of many underground projects around the world, the level of integration, modeling and planning for real-time response being used is very impressive. It is expected that this level of preplanning for settlement risk issues will become more widespread in the coming years.

5.5 *Archaeology*

The shallow layers of soil, especially in older urban areas, may be rich in archaeological remnants. These sites and artifacts would normally not be discovered without an excavation. For example, the excavation for a car park in front of a Paris cathedral exposed city walls from the Middle Ages and excavation for the Mexico City metro exposed the foundations of ancient structures. These finds then can be preserved and made accessible to the public as part of the

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

new structure. The use of underground space opens this opportunity but often at a significant increase in project cost and project timetable for the careful excavation, cataloguing and project redesign to preserve the site. As with environmental concerns, expectations and regulations regarding the conduct of underground works in archaeologically rich areas are increasing and require archaeological, geological, and geoengineering input into identifying potential sites, choosing appropriate methods of working that will reduce damage to the sites, and adapting designs to preserve and display the sites.

5.6 *Planning*

Miners call “virgin ground” the ground that nobody has touched. On the surface, any construction can be demolished, and the site turned again to almost its original state; underground, re-filling an underground excavation cannot restore the original properties of the strata. The development of a mine is carefully planned in terms of access ways, maximum recovery of the orebody consistent with economical working, and the control of stress conditions in the ground as the excavated areas increase. On the surface, the layout of roads and interchanges often are changed, bridges are widened, and buildings are enlarged. Underground, it is rarely possible to move an existing underground structure, and it is difficult to modify or enlarge it unless special provisions have been taken from the very beginning of the works.

For these reasons, it is important to forecast the near-term and long-term uses of any underground project, and to plan them with more care than for surface projects. This responsibility often exceeds the concerns of the current owner of the underground space and calls for regional planning by the State or Local authorities. In particular, it is critical not to preclude economical later access to deeper or more remote underground spaces especially to those areas with favorable geological conditions. It is also important to provide corridor reservation for major tunnels. Such long, linear works are very difficult to design and locate because of the need for the tunnels to find the most favorable geologic conditions, avoid existing underground plant, maintain the alignment and grade constraints for operations, and yet provide appropriate and economical interchanges with the surface (e.g. at metro stations).

As cities grow and traffic congestion worsens, so does the congestion of the underground – particularly at the important transportation nodes of a city. At these locations, three, four, or even five underground metro lines may come together and interface with rail stations, bus stations, and concentrated traffic and business development. In these areas, planning for future underground developments in terms of circulation patterns and geotechnical/structural design is particularly critical. Underground transportation corridors and stations should be designed to overlap as closely as possible in the vertical dimension to avoid very deep structures in later developments.

5.7 *Influence of Construction Methods*

Aboveground, the availability of various construction methods can strongly influence the design of a structure, say a bridge, but rarely its location. Underground structure design is more dependent on the methods of construction and often the location and geometry of the structure is adjusted to best accommodate the method chosen. For example:

- The cross section of a tunnel normally will be circular if it is bored by a full-face tunnel boring machine. It will have vertical walls if it is constructed between slurry walls.
- The design of the lining (thickness and reinforcement) depends on the movements of the surrounding ground during excavation: tunnel support methods such as steel ribs and lag-

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

ging can allow the ground to loosen and increase the eventual support whereas early support methods (e.g. rock bolts and/or shotcrete) can reduce the final support loads that need to be carried.

- The depth of a tunnel below grade may depend on the construction method to be used. In the case of cut and cover, the shallower the better. In the case of a bored tunnel, a minimum cover is desired in order to benefit from the natural arching effect in the ground.
- When a rock stratum is very suitable for a particular construction method, the tunnel profile may be adjusted to remain within this layer – provided this is permitted by the use constraints of the final tunnel. A good example is given by the RER metro line in Paris between “Gare de Lyon” and “Châtelet Les Halles.” This section was bored by a full-face tunnelling machine inside a soft limestone stratum. Because of the limited thickness and the diameter of TBM available, two single track tunnels were designed instead of one double track.

6 FUTURE TRENDS

What can we expect in the future in terms of underground space development, the technologies used to create and maintain such structures, and, in turn, the demands of these on professionals involved in geology and geoengineering related professions?

In terms of underground space use, we can expect that this will continue to increase and moreover that it will increase in relative importance to other forms of construction especially in the major urban areas of world, in areas of special environmental significance, and along major transportation routes through difficult topography. The long tunnels being constructed through the Swiss Alps to ease the traffic impacts of freight movement between Italy and the rest of Europe are one example. The rapid expansion of tunnel projects in the Netherlands is another – as it struggles to balance its economic position as the port of Europe with its high population density and lack of open space. Probably the greatest increases will come however in the rapidly growing megalopolises in developing countries around the world. These are developing into cities of unprecedented size, with extremely poor access to clean water and sanitation and with extreme traffic congestion due to a poor existing road infrastructure and high-density development.

Intense development of the urban underground will lead to pressure to change the laws of ownership of the underground. For example, the public ownership of the deep underground beneath urban areas has been explored extensively in Japan over the past 15 years. One solution will be to allow subdivision of underground space in the same way that ownership of air rights parcels can be recorded and sold. While such a division of ownership of the underground would have many benefits, it would also raise some interesting geoengineering issues. For example, significant ground movements or settlements associated with underground construction would shift the location of underground tunnels or cavern relative to fixed spatial boundaries in the vertical direction and could create a new breed of legal dispute. Underground space boundaries described relative to strata boundaries would address some of this concern but introduce additional problems in defining such boundaries in terms of location and continuity.

In terms of the technologies used, we can expect the continued development of current trends and, hopefully, the resolution of problems that continue to plague underground construction. Some thoughts from the authors in these regards are:

- For reasons of safety, economy and speed increasing amounts of underground work will be done by remotely operated machinery and by providing full support to the surrounding ground during excavation (for example using slurry or earth-pressure balance type shield

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

tunneling machines). Such machines will increasingly have to deal with a greater variety of ground conditions as part of their “normal” operation.

- The use of such equipment means that there is less opportunity to visually observe the ground conditions, obstacles or artifacts in the path of the excavation, and the ground response. This means that less is learned about the geologic environment during a current project that could be of use in designing a future project.
- Underground utility systems and building structures will increasingly be handled in an integrated manner over their life cycle from planning to design and construction followed by operation, maintenance and decommissioning. This will require greater integration of urban databases for underground structures and urban geologic conditions.
- The loss of visual contact with the ground will be compensated for by greater use of “see ahead” ground investigation techniques and obstacle detection techniques and by greater levels of monitoring of the excavation system and the surrounding ground. This in turn will probably require that expected responses of the detection and monitoring systems based on expected geological conditions be calculated and that feedback loops will be created to compare expected and actual conditions and adjust geological models, and machine operation appropriately.
- The development of low cost wireless microsensors for geotechnical and structural monitoring will allow frequent enough deployment to allow the creation of “smart” underground structures and pipes that monitor their own performance and deterioration and provide this information to asset management programs that guide the maintenance of these expensive and poorly accessible assets.
- There will be an increasing use of the developments in trenchless technologies as part of the site investigation and construction methodologies in large underground projects. For example, continuous directional drilling and coring along tunnel alignments for preinvestigation (compared to less satisfactory intermittent vertical borings), greater use of pilot holes and reaming operations for tunneling and greater use of microtunnelling and directional drilling for presupport of large excavations.

For the geology and geoengineering related professions, the trends discussed above offer the following possibilities:

- An increased market for underground construction
- An increased imperative for the “geo” professions to become more involved in making underground space use planning a normal part of city planning
- New geotechnical problems and opportunities created by the use of trenchless technologies (for example, 80 years of buried pipe design development have been related to its installation in a trench – far less work has been done on the loads to be expected when installed by microtunnelling or directional drilling)
- A reality that an increasing proportion of geotechnical investigations and analysis will have to rely on remotely-gathered or non-invasive data. Increasing amounts of such data will be available but the need for management of these data will increase. The data will need to be used to ensure that a project conforms to contractual expectations of efficiency and financial risk as well as societal expectations of safety and environmental risk.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

7 CONCLUDING REMARKS

Underground space use will increase and, since its creation is usually an expensive and difficult endeavor, actions encouraging and/or contributing to advances in tunnelling and underground construction techniques will provide an important public benefit. Much has been already done in this respect but this action must be combined with the strong support of local and regional authorities in terms of planning for effective underground space use and national and international authorities in terms of advancing the technologies available.

Within the scope of its general objective: Towards an improved use of underground space, the International Tunnelling Association forms international working groups to study and report on specific topics, gathering a wide range of information – from scientific, technical, planning, statistical, legal, administrative, economic and social fields – and then evaluates them in order to define research and development objectives, or simply spread the results of recommendations to decision-makers and planners. All these studies relate to one or several of the main issues examined in this article and are especially aimed at reducing the various risks of underground construction. The results of these studies can be found on the website of the International Tunnelling Association which is <http://www.ita-aites.org>.

8 REFERENCES

- Carmody, J. and R. Sterling, 1993. *Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces*, Van Nostrand Reinhold, New York.
- Duffaut, P., 1982. "Subsurface townplanning and underground engineering with reference to geology and working methods," *Proc. Regional Symposium on Underground Works and Special Foundations*, Singapore.
- Duffaut, P., 1992. "Mining technologies for underground space in France," *Proc. World Mining Congress*, Madrid.
- Duffaut, P. & M. Labbé, 1994. "Underground utilities and other uses of urban subsurface space," *City Tec 94*, Seminar on advanced urban technologies, Barcelona.
- Godard, J.P., 1999. "Sub-Surface Development in the Urban Environment," *Proc. 10th Australian Tunnelling Conference*, "The race for space", Melbourne.
- ITA, 1987. "Examples of Benefits of Underground Urban Public Transportation Systems," Report of the Working Group on Costs-Benefits of Underground Urban Public Transportation, *Tunnelling and Underground Space Technology*, Vol. 2, No. 1, Pergamon Press, Oxford, U.K., pp 5-54.
- ITA, 1990. *Legal and Administrative Issues in Underground Space Use: A Preliminary Survey of ITA Member Nations*, Report of the Working Group on Subsurface Planning, International Tunnelling Association, Bron, France.
- ITA, 1995. Report of the Working Group on Direct and Indirect Advantages of Underground Structures, J.P. Godard, Animateur, "General Considerations about the Advantages in Using Underground Space," *Tunnelling and Underground Space Technology*, Vol. 10, No. 3, Pergamon, Oxford, U.K.
- ITA, 1998. *Underground Works and the Environment*, Report of the Working Group on Underground Works and the Environment, International Tunnelling Association.
- ITA, 1999. *Overview of Planning and Mapping of Subsurface Space*, G. Landahl (Ed.), Report of the Working Group on Subsurface Planning, International Tunnelling Association, Bron, France.
- ITA, 2000. *Why Go Underground?*, Tunnelling Technologies for the 3rd Millenium.
- Sterling, R.L., S. Nelson and M. Jaffe, *Planning for Underground Space*, Planning Service Advisory Report No. 375, American Planning Association, April 1983.
- Sterling, R.L. and J. Carmody, 1992. "Merging Geological and Human Use Considerations in Underground Transit Station Design," *Proc. 5th Intl. Conf. on Underground Space and Earth Sheltered Structures*, Delft University of Technology, Aug. 2-5, 1992.

Geoengineering Considerations in the Optimum Use of Underground Space

Raymond L. Sterling • Jean-Paul Godard

- Sterling, R.L., *Indirect Costs of Utility Placement and Repair Beneath Streets*, Report to the Minnesota Dept. of Transportation, Aug. 1994.
- Sterling, R. 1996. *Down Under Down Under: Towards a 4 Dimensional City*. Project Report for the Underground Space Project, The Warren Centre, University of Sydney, Australia.
- Sterling, R.L., 1996. "Going Under to Stay on Top, Revisited: Results of a Colloquium on Underground Space Utilization," *Tunnelling and Underground Space Technology*, Vol. 11, No. 3, July 1996, Pergamon Press, Oxford, U.K., pp. 263-270.
- Sterling, R., 1998. "The Value of Land Beneath Public Rights-of-Way," *Proc. Intl. No-Dig '98*, Lausanne, Switzerland, Jun 8-11, 1998, ISTT, London.
- Sterling, R.L., 2000. "Planning, Design and Management of Future Underground Space Use," *Geocology and Computers: Proc. 3rd Intl. Conf. Advances of Computer Methods in Geotechnical and Geoenvironmental Engineering*, Moscow, Feb.1-4, 2000, S. Yufin (Ed.), A.A. Balkema, Rotterdam, pp. 57-60.