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USE, PLANNING AND DESIGN OF UNDERGROUND STRUCTURES

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Abstract

This key note lecture gives a survey of the different ways the underground have been taken into use. Examples show caverns used for living, for storing of food, drinking water, hot water, oil and other liquid hydrocarbons, pressurized gas and air and nuclear and industrial waste. Also the use of the underground for industrial and municipal installations like powerhouses, water and sewage treatment plants and car parks are described, as well as caverns for entertainment and recreation like sportshalls and swimmingpools. A final chapter outlines the geotechnical engineering related to planning and design of rock caverns.

1. INTRODUCTION.

It is well known that there is a number of natural caves or caverns around the world. Some of these were probably man's first dwellings. In a geotechnical society it is, however, natural to define a cavern as a room excavated in rock.

During the last two - three decades there has been a rapid development in excavation techniques for rock masses. Simultaneously there has also been a rapid growth of our cities, and an increasing awareness of the quality of our evironment. This has led to an almost exponential increase in the use of the underground. This is clearly demonstrated by the facts that during the twenty years from 1967 to 1987 the number of cities with underground metros increased from 30 to more than 80, and that the number of long highway tunnels (longer than 3 km) has doubled from 28 in the period 1970-80 to 56 in 1980-90.

Going underground is today an everyday experience to a large number of people. Thus there is a huge potential for taking the underground, or the subsurface as it is often referred to, into use. This paper will concentrate on caverns. It will show examples of the varied use of caverns which already can be found in different parts of the world. It will also briefly outline an approach to the planning and design of caverns which the author will recommend.

A cavern may be used for:

1. Living
2. Storing
3. Industrial installations
4. Municipal installations
5. Entertainment and recreation
6. War protection

and a combination of these different purposes. In the succeeding chapters examples of the different uses will be described.

2. CAVERNS FOR LIVING.

The cavern or the cave is often described as man's first "house". If it was not the first, there are certainly plenty of proofs that some of our predecessors lived in caverns, some natural made, but the majority excavated with simple tools. And for good reasons there are still a lot of people living quite happily in excavated caverns. There are in fact good reasons to believe that there is more people living in caverns today than ever before in history.

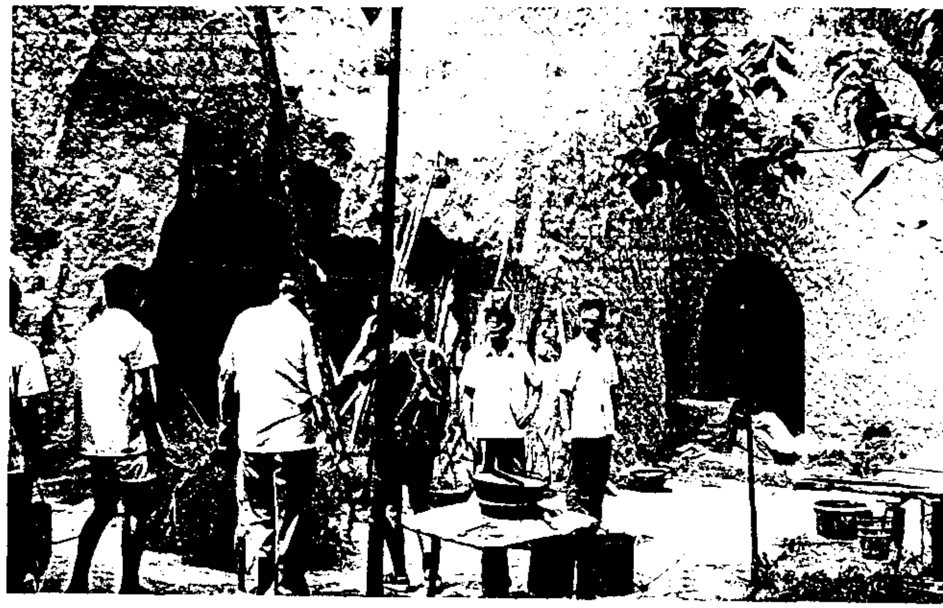

Fig. 1 Cave dwelling in the loess in China.

Figure 1 is a picture from the Shanxi province in China where the Yellow River is eroding actively in a loess formation. This rock is easy to excavate even with hand tools, yet at the same time it is strong enough to give stable roofs and walls with dimensions that give good sized living rooms. The picture shows several rooms around an outdoor patio. The total complex makes a good "family house" with cool rooms in summer and warm in winter. According to local information it is assumed that more than 50 millions are living in caverns of similar types in China. And China is not the only place in the world where people are living in caverns.

In modern society there is an increasing interest in utilizing the subsurface for accommodation, partly by digging the house into the ground and cover it up, and partly by using "semicaverns" with a front towards the open air. One good reason for the renewed interest is the low energy consumption. These techniques are excellently described in a new and very comprehensive book by John Carmody and Raymond Sterling called "Underground Space Design".

3. CAVERNS FOR STORING.

Caverns are being used to store:

- Food
  - Grains and vegetables at rock or refrigerator temperatures.
  - Fish, meat, icecream, etc., at deep freezer temperatures.
- Water
  - For general supply.
  - Hot water for energy supply.
- Oil and other liquid hydrocarbons
- Pressurized gas and air
- Industrial waste
- Nuclear waste
- Others
  - Coal, sand, archivals, art, wine, beer, etc. etc.

Not all aspects of storage in caverns can be dealt with in this paper. Only a few selected items will be described in some detail.

Man has for centuries used the underground for storage purposes. Good protection and a constant climate have been important factors. Today some additional factors may favour the choice. It may be desirable to get for instance large tank farms for oil and other hydrocarbon products out of sight. There may also simply be a lack of land in built up areas. But the most important factor is, of course, the cost of the storage.

Excavation techniques for large rock caverns have been constantly improved over the last decades, and hence the costs have decreased. Cost comparisons carried out in Scandinavia between rock caverns and concrete or steel tanks for storage of liquids, indicate that when the volume to be stored exceeds 5.000 - 10.000 m^3, the cavern gives the cheapest solution. Cost curves also show that the cost per m^3 of cavern is reduced by 50% when the volume increases from 10.000 m^3 to 100.000 m^3.

3.1. Cold store caverns for food.

Favourable temperature conditions are one reason for choosing the subsurface alternative. Another reason can be the favourable insulation that rock masses around a cavern can provide. The "walls" can, in many cases, be regarded as being of infinite thickness. Thus rock caverns have for some time been used as cold stores where, for instance, fruits and vegetables have been stored at normal refrigerator temperature, +(2 - 5)°C, and frozen food like fish, meat and icecream have been stored at so-called deep freezer temperatures -(25 - 30)°C.

In Scandinavia the energy consumption for deep freezer storages is 75% and for refrigerator storage only 25% of similar surface stores. The peak energy requirements, and thus the installations, are even more favourable. The deep freezer storage will need 50% and the refrigerator storage only 20% capacity of similar surface stores.

Strongly reduced insurance rates are also favouring the subsurface solution for cold stores. This is due to the fact that the rock mass surrounding the storage caverns contain a big cold reservoir. In case of a breakdown in the cooling machinery, this will act as a reserve. Experience have shown that with cooling machinery out of function for a couple of weeks, an increase in the temperature of only 2 - 3°C is measured.

3.2. Drinking water.

Next to the storage of oil and gas in caverns the most important is the storage of drinking water. Figure 2 shows the lay-out of an unlined rock cavern tank in the author's home city of Trondheim. The capacity of the tank, 20.000 m^3, was obtained by the excavation of two caverns with a width of 12 m, a height of 10 m and length 85 m and 110 m respectively. Also the service section is put underground. This is well accepted, but is not in daily use as the operation is remotely controlled.

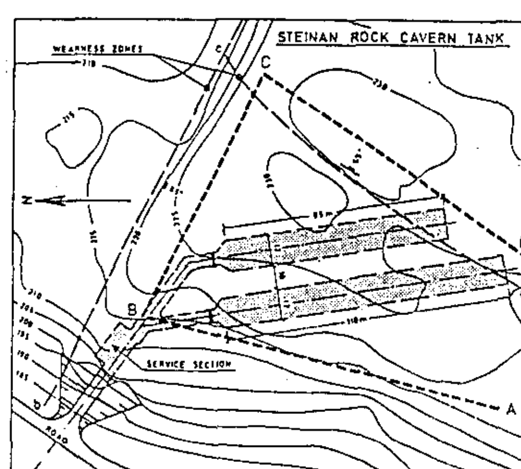

Fig. 2 The Steinan rock cavern tank in Trondheim. Total capacity 20.000 m^3 (from Broch and Ødegaard, 1983).

Additional factors which may favour an underground solution for drinking water tanks:

- High degree of safety, also against war hazards, sabbotage and pollution.
- Constant and low water temperature.
- Low or no addition in price for a two chamber solution.
- The excavated rock masses may be used for other purposes.
- Low maintenance costs.

3.3. Hot water.

Development work on methods of bedrock utilization in heat storage has been actively pursued in Sweden for more than a decade. The following three techniques realize the practical application of heat storage technology:

- Water filled rock caverns.
- Water filled in-rock pit.
- Bedrock activated through piped boreholes.

Two heat storages in water filled rock caverns have been put into operation in Sweden, Avesta, with a capacity of 15.000 m^3 and Lyckebo with a capacity of 100.000 m^3. The Lyckebo cavern is used for seasonal storage of solar energy in a solar heating system for 550 accommodation units. The store operates in the temperature range +40 to 90°C. It is charged from solar collectors, and in the initial stages by an electric boiler.

3.4. Oil and other liquid hydrocarbons.

Storing large quantities of oil in unlined rock caverns is a fully accepted technique all over the world today, and will thus not be described in this report. The interested reader can easily find related literature. A recently published general report on the subjet is Lindblom (1989). Let it only be briefly mentioned that oil caverns in reasonably good rocks normally has a span of 17 - 20 m, a height of 25 - 30 m and lengths from 200 to 500 m. Two to five parallel caverns is quite common. To prevent leakage of oil and/or gas through the rock mass, a socalled water curtain is usually established above and around the caverns.

3.5. Pressurized gas and air.

There are basically two ways of storing large quantities of natural gas economically; either by compressing the gas, or by cooling down the gas,- in the ultimate case down to -160 - 170°C where the gas turns into liquified natural gas, LNG.

So far storage of LNG in rock caverns has not been successful. There is some very challenging research ahead which has to be done. Our basic knowledge about how rock masses behave when exposed to these extreme temperatures, needs to be improved. Such research can only partly be done in the laboratory, and even then with great difficulties. Reliable design parametres can only be obtained after testing done at a reasonable scale in the field. Also better knowledge about heat transfer in and around LNG caverns is needed.

Storing gas in a compressed condition has for some time been done, but so far only for pressures up to approximately 10 bars. If natural gas shall be stored in rock caverns, pressures in the order of 100 bars (or perhaps 200 bars) will be needed to give economical solutions.

In Norway socalled air cushions have been used to replace surge shafts and surge towers at several underground powerhouses for 20 years. The system is schematically shown in Figure 3. Caverns with volumes of more than 100.000 m^3 and pressures of 78 bars are successfully operating without any airloss through the rock mass. Three out of ten air cushions have been equipped with a water curtain (or water umbrella).

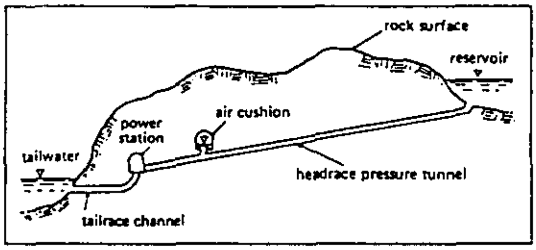

Fig. 3 Concept of powerplant with air cushion surge chamber (from Goodall & al., 1988).

Based on quite comprehensive studies of the behaviour of the air cushions it has been concluded that storing of gas with pressure of 100 bars or even more in large rock caverns is fully possible provided certain design rules are followed, Goodall et al. (1989).

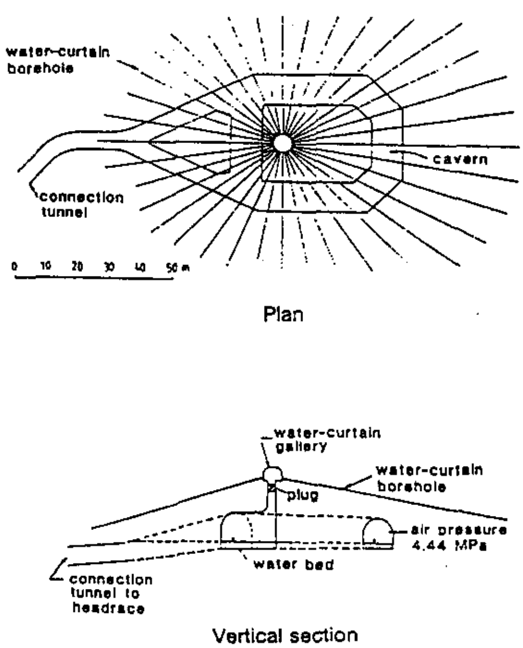

Fig. 4 Geometry of Torpa air cushion surge chamber with water curtain (from Kjørholt and Goodall, 1989).

One particular question of great economical importance is how deep should a pressurized gas cavern be put. A safe answer is that the water pressure in the rock mass should be greater than the gas pressure in the cavern. This will under normal conditions mean that for a gas pressure of 100 bars the depth to the cavern should be more than 1000 m. It has, however, been shown in the air cushion study that lack of natural groundwater pressure in the rock mass can be compensated for by the use of water curtain, Kjørholt and Broch (1992). A water curtain with a water head twice as high as the rock mass overburden has been successfully operating at the Torpa hydropower station since 1989. The doughnut shaped air cushion and the water curtain is shown in Figure 4.

Pressurized air caverns are also an important part of the socalled CAES-concept (Compressed Air Energy Storage) for production of peak hour electric energy, Goodall et al. (1990).

3.6. Nuclear and industrial waste.

Subsurface storage of radioactive or nuclear waste has been much discussed during the last decade. From the Nordic countries the Swedes have in particular been active in this field. The first construction phase has recently been completed for a final disposal of reactor waste. The repository is situated in the bedrock under the Baltic sea, with a rock cover of about 60 m. The high-level waste will be deposited in large concrete silos situated in cylindrical rock caverns 70 m high, entirely surrounded by a clay barrier with very low permeability, see Figure 5. The lower-level waste will be stored in several 160 m long rock caverns. The first construction phase included the excavation of 430.000 m^3 of rock and has given a total storing capacity of 60.000 m^3.

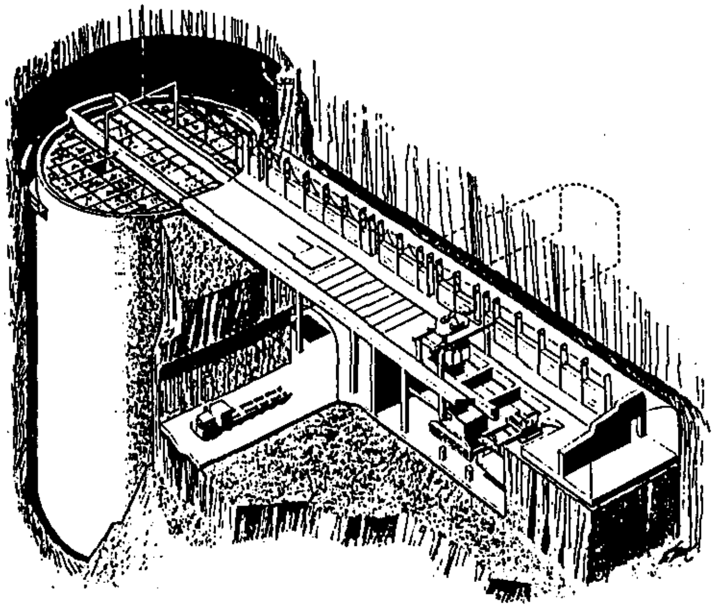

Fig. 5 The inside of the silo is divided into 2.5 m square cells running from top to bottom. Waste package are placed in the cells, which are then backfilled with concrete. Handling is totally automatic using remotely controlled lifting equipment.

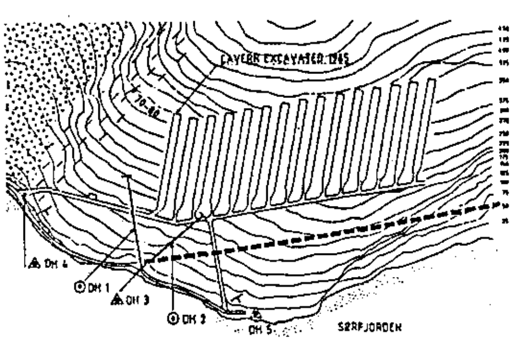

Fig. 6 Lay-out of the cavern system for storage of industrial waste at Odda (from Aarvoll et al., 1986).

In Odda, the Norzink company, a major producer of zinc has by the Norwegian environmental authorities been instructed to deposit the residues from the production in a pollutionsafe place. The nearby steep mountain were considered to be the ideal place for the construction of rock caverns for storing of the annual production of 50 - 60.000 m^3 of residues. A series of parallel caverns are being excavated, one cavern approximately each year, see Figure 6. The first one was completed in 1985.

There is no doubt in this author's mind that underground storage of waste is one of the best ways of saving our environment for future generations.

4. CAVERNS FOR INDUSTRIAL INSTALLATIONS.

Caverns housing industrial activities or other activities related to industry may roughly be divided into the following categories:

- Powerhouses

  - Hydro power

  - Thermal power

  - Nuclear power

- Factories

- Laboratories

- Telecommunication centres

Floor area is often more important than volume when caverns are designed for industrial installations. The shape may therefore be different from caverns which are typically designed for bulk storage (oil, gas, water). Low, wide and often relatively short caverns may be preferred by the planners. The exception is the modern powerhouse with vertical axis for the turbine/generator where caverns with heights of more than 50 m may be needed.

4.1. Powerhouses.

There are probably between 400 and 500 underground powerhouses around the world today. Only a handful of these were constructed before World War II. Since 1950 no less than 200 underground powerhouses have been constructed in the author's home country. In mountainous regions, like in Norway, this means that practically all hydropower schemes include caverns. A considerable part of the existing rock mechanics and rock engineering literature is therefore describing and discussing different aspects of the planning, design and construction of underground powerhouses.

This author had the pleasure of writing a general report on underground power plants for the ISRM symposium "Rock mechanics and power plants" in Madrid five years ago, Broch (1988). At that time it was only possible to find one underground powerhouse for thermal power (Stenungsund in Sweden) and two underground plants for nuclear energy (Halden in Norway and Chooz in France). All three plants were built more than 25 years ago, and the author raised the questions: What have we done wrong? Why are not more thermal and nuclear powerhouses put underground? It is difficult to reach a clear answer when one sees how the hydropower industry has taken the underground into use.

4.2. Factories.

As early as in 1954 an ammunition factory at Raufoss in Norway took into use nine big underground production halls with a total floor area of 25.000 m^2. An undergrond locomotive repair shop has also been used for a long time in Oslo.

In Finland the Valmet company has utilized rock caverns for machine assembly workshops for a long period. In fact, the construction of such caverns started already during World War II.

4.3. Laboratories.

A particularly interesting subsurface structure is the research caverns at Otaniemi in Finland They have a volume of 125.000 m^3 and a floor area of 15.000 m^2. The caverns are built to be easily converted to bomb shelters. The daily operation is, however, taken care of by the Technical Research Centre of Finland. Väätäinen et al. (1991) describe the thermal balance around these caverns. The investigations consisted of computer simulations and measurements taken over a two-year period, and good agreements between simulations and investigations were found. After approximately two years the heat loss is stabilized and is in the order of 60 - 80% of the initial heat loss.

4.4. Telecommunication centres.

Such centres are really the nerve centres of modern society, and should therefore be protected as good as possible. The use of the underground is thus the evident solution. Excellent possibilities for climate conditioning are also favouring this solution. Today a number of underground telecommunication centres can be found in Scandinavia.

5. CAVERNS FOR MUNICIPAL INSTALLATIONS.

Several municipal activities may be put underground. Today the following types of installtations are found in rock caverns:

- Water treatment plants
- Sewage treatment plants
- Car parks

5.1. Water treatment plants.

In 1970 Oslo took in use a new plant for treatment of drinking water with a capacity of supplying half a million persons. The entire plant is situated underground close to the shore of the lake Maridalsvannet 5 km north of the city centre at an elevation of 150 m above sea level. Figure 7 and 8 show the general lay-out and a vertical cross-section through the Oset Water Treatment and Pumping Plant.

The nomical capacity of the plant is 6 m^3/sec and the retention time for the water is approximately 5 hours. 350.000 m^3 of solid rock (syenite) was excavated for the different basins and tunnels. This gave a total floor area of 30.000 m^2 of which one half is paved and one half is wet.

5.2. Sewage treatment plants.

Also the sewage treatment plants have been put underground in many of the Nordic cities and towns. In the Stockholm area six plants which are partly put underground, can be found. The oldest parts of the Henriksdal Sewage Treatment Plant date back to 1941. This plant has today a capacity to serve a population of 725.000 and can treat up to 370.000 m^3 of sewage and storm water per day. 630.000 m^3 of solid rock has been excavated, all by the drill and blast method.

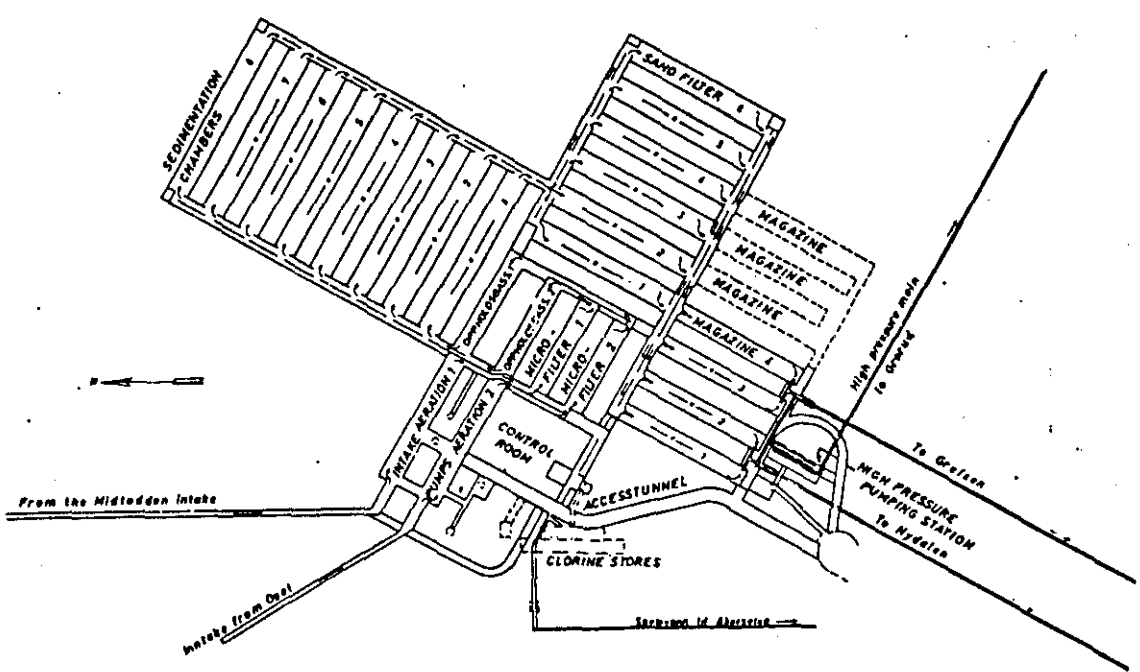

Fig. 7 Lay-out of the Oset Water Treatment and Pumping Plant.

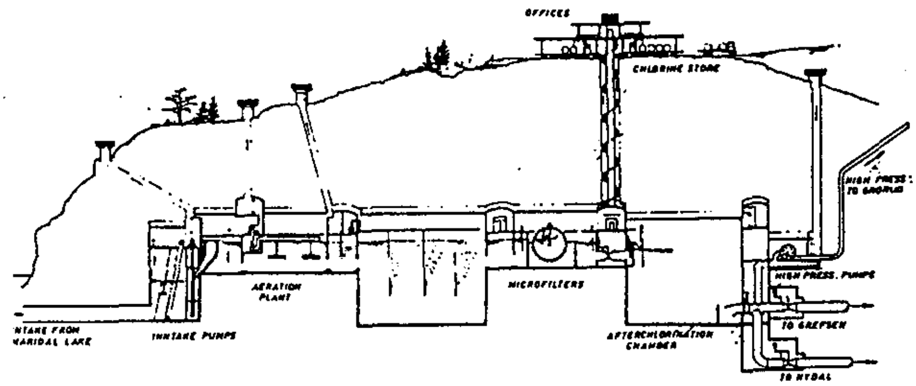

Fig. 8 A vertical cross-section through the Oset Water Treatment and Pumping Plant.

The Nordic ountries contain today in the order of 15 - 20 underground sewage treatment plants of various sizes. Figure 9 shows the interior of a treatment plant in Trondheim. The rock surfaces are only supported locally where needed by rock bolts and shotcrete. Even though cost estimations may have shown that construction costs for underground treatment plants are higher than for similar on-the-ground plants, the underground solutions have been chosen. Favouring this choice is first of all the wish to avoid the impact such big installations may have on the environment. For the drinking water treatment plant the safety aspect has also been taken into consideration. A valuable additional benefit is the produced rock masses which there always is a need for in an urban area.

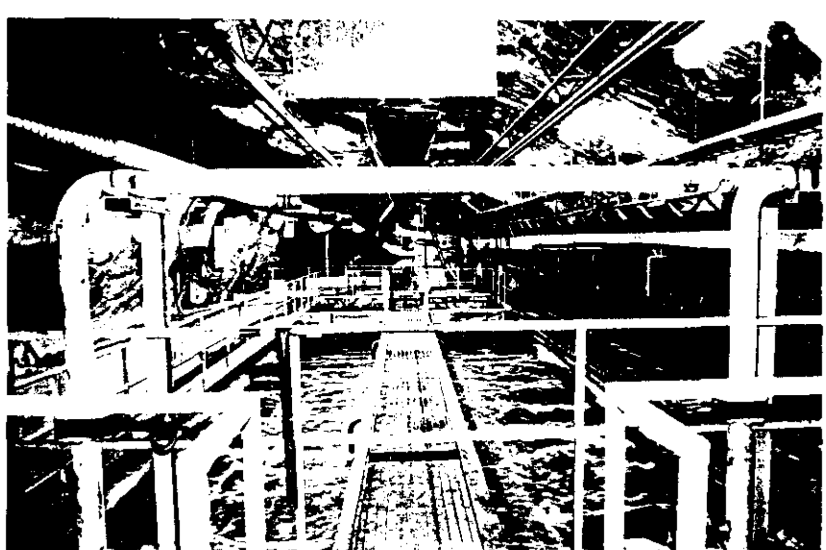

Fig. 9 The interior of a sewage treatment plant in Trondheim.

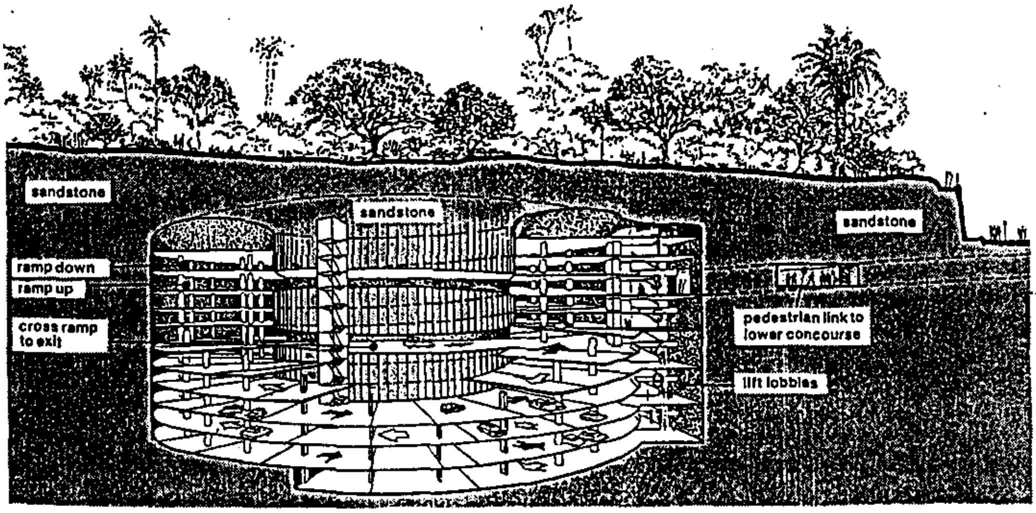

Fig. 10 Car park structure in Sidney (from Pells et al., 1991).

5.3. Car parks.

In several cities around the world where bed-rock of a reasonable quality is easily accessable, caverns have been excavated for car parking. One of the newest is in Sidney, Australia, Pells et al. (1991). Close to the famous Opera house and under the Royal Botanic Gardens a car park consisting of a twin spiral road wrapped around a central intact core containing linking drives and sevice tunnels is constructed, see Figure 10. During construction a toroidal shaped cavern is being created with an outer diameter of 71.2 m and inner diameter of 36.4 m and a height of 32 m. Only 4 m cover of Sidney Sandstone exists over the roof of the cavern. The largest unsupported span is 17.4 m.

6. CAVERNS FOR ENTERTAINMENT AND RECREATION.

A particularly interesting development the last twenty years with regard to the use of the underground, is the many rock caverns which have been excavated for entertainment and recreation. Many of them are dual purpose caverns, which means that they in case of warfear are quickly converted to air-raid shelters. Thus part of the construction costs is covered by the National Civil Defence Authorities. In the Nordic countries one will today find caverens for:

- Theatre and cinema
- Consert halls
- Sports halls and gymnasiums
- Swimming pools
- Ice hockey rinks
- Restaurants

Some examples will be briefly described in this chapter. Others are described in Broch and Rygh (1988), Saari (1988) and Winquist and Mellgren (1988).

6.1. The Odda sports center.

In the small industrial town of Odda suitable conditions for the construction of a rock cavern were found close to the outdoor sports stadium and the junior college. Here the first underground sports center in rock was completed in 1972.

Figure 11 shows the general lay-out with two entrances, A and B. A leads to four wardrobe/shower sections, while B leads to a 100 m sprint track and a jumping ground. This long tunnel is also used for shooting.

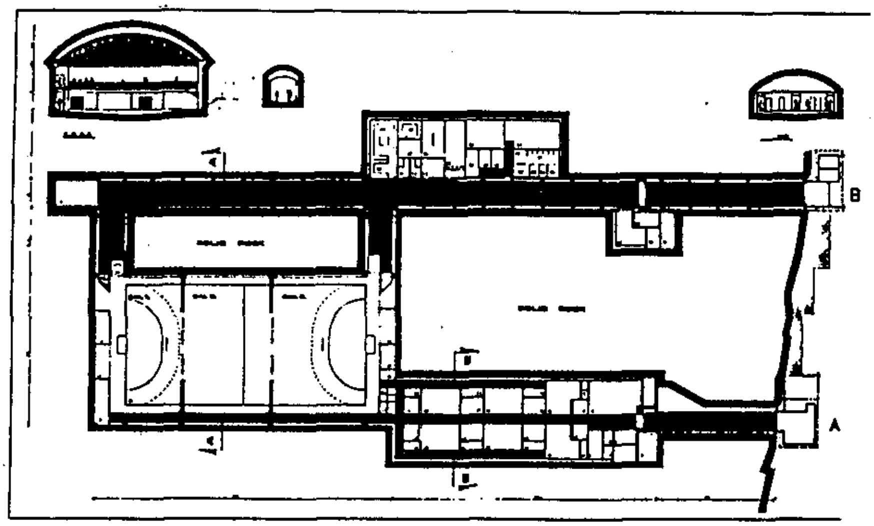

Fig. 11 Lay-out of the Odda Sports Center (from Broch and Rygh, 1976).

The main hall is 25 x 60 m which makes it adequate for international handball games. It can be divided into three gymnasiums by curtain walls. The hall has a gallery stand for 500 persons. 25.000 m^3 of solid rock was excavated, giving an available floor area of 2.700 m^2.

6.2. The Gjøvik underground complex.

In 1975 the first underground swimming pool with international standards was opened in Gjøvik, Norway. This swimming pool was part of an underground scheme which also included a telecommunication center and headquarters for the local civil defence. As Figure 12 shows, the entrances to these subsurface installations are close to the main street of Gjøvik.

From the entrance lobby with ticket office and cloakrooms, traffic is divided into two wardrobe/shower sections for men and women respectively. Toilets and saunas make parts of these sections.

In the main hall with a span of 20 m are the swimming pool with 6 lanes of 25 m and children's playing pool of 4 x 8 m. Separated by a class wall is a small gymnasium (also used as a meeting room).

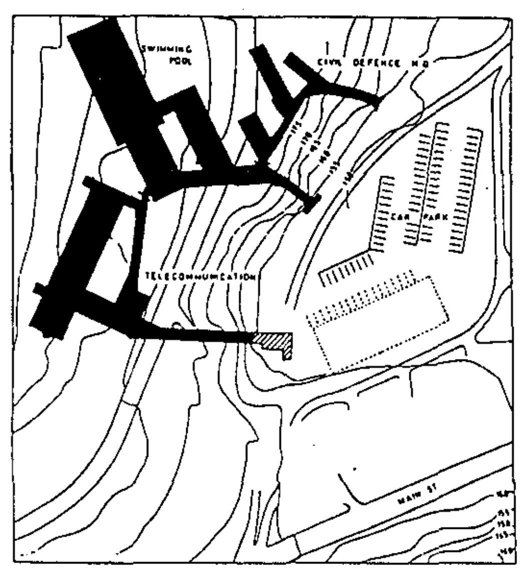

Fig. 12 Lay-out of the subsurface installations in Gjøvik (from Broch & Rygh, 1976).

Of special interest is the fact that the energy consumption for running this underground public bath and swimming pool has been cut down to approximately 50% of what would have been necessary for a similar building on the surface. Both this and the fact that there were limited areas for building in the center of the town, were important factors when the decision to put the swimming pool underground was made. 11.000 m^3 of solid rock was excavated and transported to a nearby marina under construction.

The very latest development in Gjøvik is, of course, the construction of the Gjøvik Olympic Cavern Arena. The cavern is 91 m long, has a maximum height of 25 m and the enormous span of 61 m, by far the largest span in the world for an excavated cavern which is going to be used by the public. A special session of this symposium is devoted to the description of the planning, design and construction of his cavern.

6.3. Holmlia sportshall and swimming pool.

In 1983 a combined underground sportshall and swimming pool was taken into use at Holmlia, a new suburban area in Oslo. During the planning of the area it was decided that a modern center for varied sports activities should be built. In accordance with Norwegian civil defence regulations, blast and gas tight shelters for approximately 7000 people were needed near the center of the new development area. Furthermore, large amounts of rock material were needed for the construction of roads and parking lots in the area.

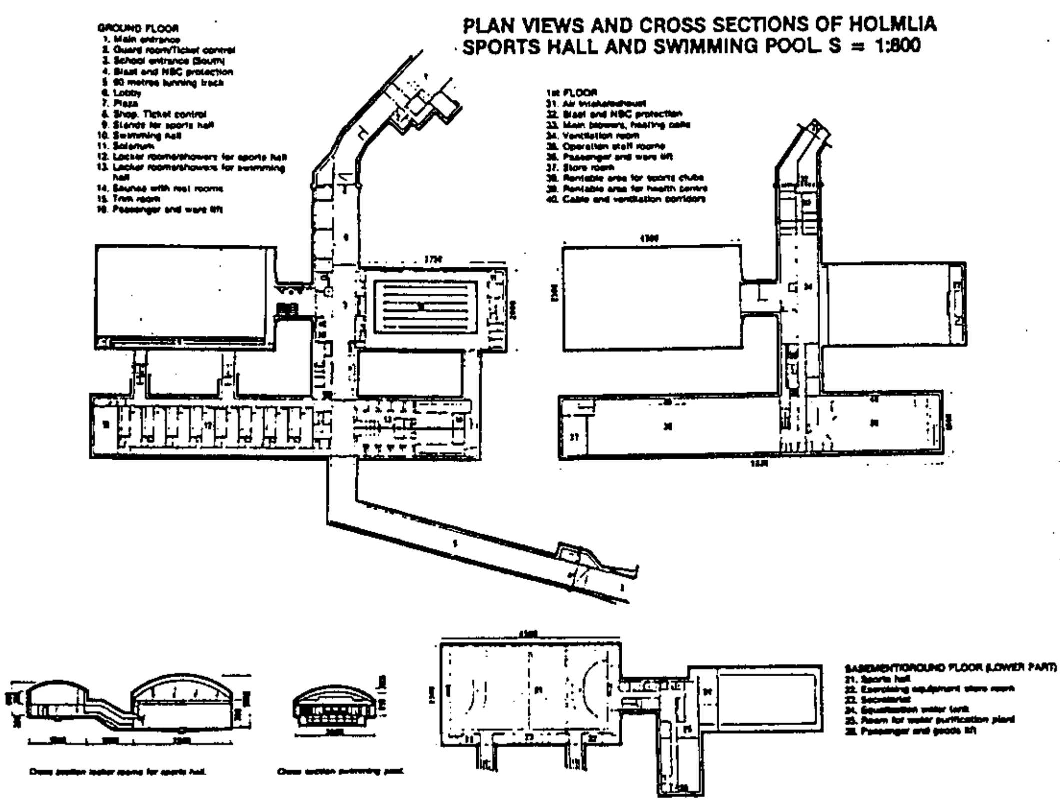

Fig. 13 Plan view and cross-section of Holmlia sportshall and swimming pool.

Within easy walking distance from the Holmlia railway station and a shopping center, a small hill of gneissic rock was the obvious place for an underground sports center. The rock cover was rather small, in certain places only 20 m above the roof of the sportshall, but was accepted by the Civil Defence Authorities.

Figure 13 shows the general lay-out of the Holmlia Sportshall and swimming pool as well as the main dimensions. The spsortshall is 25 x 45 m and is equipped for different ball games. The swimming pool has 6 lanes of 25 m. 53.000 m^3 of rock was excavated and the total floor area, including the swimming pool, stands, gallery and first floor above entrances, is 7.550 m^2.

When completed in 1983 the total costs (including civil defence installations) added up to 54 million NOK (7.5 mill. USD). 8% was design, supervision and administration, 67% civil engineering works, and 25% heating, sanitary, ventilation and electrical installations.

7. GEOTECHNICAL ENGINERING RELATED TO CAVERN DESIGN.

The design and construction of a cavern is a multidiciplinary task where engineers of different professions are involved. To this audience the problems related to geotechnical and rock engineering, are of particular interest. The geotechnical engineer is involved at different stages in the process and for different purposes.

During the feasibility study and the preinvestigations he/she will take responsibility for all geotechnical investigations and for giving advice on where ground conditions are favourable and where not for the cavern or the underground complex.

In the design process the geotechnical engineer will, based on the interpretation of the results from the previnvestigations, have to:

1. find the optimum place and orientation for the caverns,

2. find the best shape and dimensions of the different caverns and tunnels,

3. plan supporting, lining, rock improvement and treatment for the different parts of the cavern complex.

Parallel with the designing it is also important to make plans for further investigations which have to be carried out during the construction, for instance rock stress measurements, convergency measurements, sampling of gouge material from joints and faults, etc.

Like for all other construction work the successful construction of a cavern is to a large extent the result of a thoroughly conducted design. However, as underground construction work always will contain a fair amount of the unknown, flexibility in the contracting system is equally important. When unforeseen or changed ground conditions are encountered, it is necessary to change or revise the design and the excavation procedure. This is normally accepted when conditions get worse than anticipated, but it should, of course, also be used when conditions are better than the preinvestigations may have indicated. This is the only way to obtain the minimum costs. During the construction the rock engineer should therefore continuously evaluate the rock condition so that at any time design improvements can be made and the supporting systems revised to fit the actual conditions and not the assumed conditions.

A look through geotechnical literature quickly reveals that a majority of the papers related to the design of underground structures are discussing the shaping and the dimensioning of caverns. One may therefore be tempted to draw the conclusion that this is the field where the contribution from the geotechnical engineer is most important. This is, however, not necessarily true.

If one carefuly evaluates all steps in the design procedure and tries to estimate where the most crucial mistakes can be made, there is no doubt in this author's mind that it is when the place and the orientation for the caverns are decided. The cost reductions in improving shape and dimensions of the caverns are in general just marginal as compared with improving the location and orientation.

A comprehensive paper discussing the different design steps for underground power plants was published some years ago in "Water Power & Dam Construction" (Broch, 1982). Excerpts of this will be presented in the next four sections.

7.1. Location of the cavern.

As already stated the greatest risk for technical and economic disasters in connection with underground structures lies in a wrong or unwise choice of place. It should be remembered that when the location is decided, also the quality of the construction material, i.e. the rock mass, has been selected. When designing caverns, it is often possible to choose between several locations. This possibility should always be fully appreciated and exploited.

First of all certain types of rock are less favourable than others for the construction of large caverns and should therefore be avoided when possible. Such rocks may be porous, friable sandstones, heavily sheared shales and phyllites, karstic limestones, jointed and/or porous volcanic rocks, serpentinites, peridotites and other rocks that have been exposed to high tectonic activity.

Secondly, faults and other weakness zones should preferbly not intersect larger underground openings. The geological map must therefore in addition to the different rock types also include all weakness zones in the actual area. Strikes and dips for these have to be measured or calculated so that their location at the cavern level can be found. This is often a difficult and uncertain task. It is therefore advisable to have a construction contract that allows for certain adjustments of the final location of the cavern. Much money and time can be saved in this way.

Too high or too low stresses may have an adverse influence on the stability of a cavern. Under very low stresses the interlocking effect between the blocks that make up the rock mass is reduced. This may lead to difficulties in establishing the necessary arching effect for selfsupporting roofs. A cavern should therefore not be located too close to the surface. Some tens of metres of overburden is preferable.

Caverns are often located in valley sides. In steep and deep valleys the stresses inside the rock mass are high and uneven. Thus high tangential stresses may develop along unfavourably oriented areas of the underground openings. In extreme cases they may cause slabbing and rock bursting along roof or walls which again calls for extra scaling and support. During the locationing procedure one should therefore try to find areas where the stresses locally may be reduced. Such places could be in protruding noses along a valley side or in areas which have been cut off or isolated from the rest of the rock mass by major faults.

7.2. Orientation of the cavern.

If high stresses are unavoidable at the selected location, it is imperative that the caverns get a proper orientation. The least slabbing and rock bursting is normally obtained when the caverns are given a direction which is subparallel to the direction of the major principal stress. In a valley side the major principal stress is commonly oriented perpendicularly to the length axis of the valley and often with a dip subparallel to the valley side. The worst possible orientation of a cavern in a steep valley side is therefore with the length axis parallel to the valley, an orientation which is unfortunately not uncommonly seen.

The jointing of the rock mass is the key factor to take into consideration in addition to the stress situation when the best orientation for an underground opening is to be found. With only one clearly developed set of discontinuities, as in some shales and shists, the least stability problems are experienced when the length axis of the cavern is normal to the strike of this. Most rocks will, however, have two or three sets of discontinuities like a bedding or foliation plane and one or two sets of cross joints. Most stable walls are obtained when the length axis is oriented approximately along the bisection line of the two major steeply dipping joint sets, see Figure 14. Parallelity with a possible third set should be avoided.

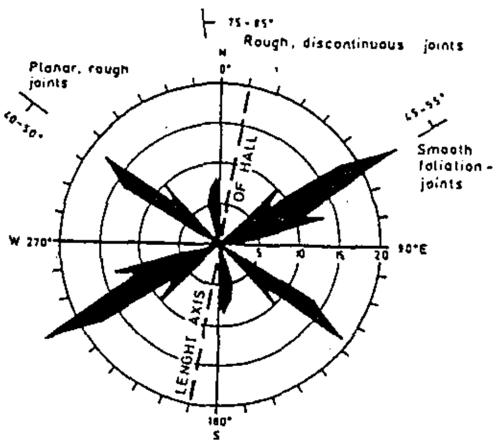

Fig. 14 Joint rosette with brief descriptions. The dotted line indicates the orientation of the length axis of the cavern that will give least stability problems.

7.3. Shape of caverns.

When designing a rock structure, it is important to keep in mind the fact that a rock mass is a discontinuous material. Hence its ability to withstand tensile stresses is very low. Furthermore the stability is dependent on the shear strength of the discontinuities, which may be mobilized on these. A basic design concept for underground openings is therefore not only to find a favourable orientation, but also to aim at evenly distributed compressive stresses by giving the room a simple form with an arched roof. It is important that intruding corners are avoided. The rock masses in such corners will be in a destressed state, resulting in over-break during blasting or unstable conditions after blasting.

The shape of the roof of an opening at a shallow or intermediate depth is designed taking into consideration the orientation, the number and the character of the joints, and foliation or bedding partings.

In deeper underground openings, the tangential stresses may locally exceed the strength of the rock, thus resulting in spalling or rock bursts. If the stress level is not too high or anisotropic, it is advisable during the design to avoid small curvation radii, as these will lead to unnecessary stress concentrations. If, however, the stress level and the anisotrophy is so high that rock bursts or spalling may be expected, it will usually be economical to design the opening to concentrate the stability problems, and in this way reduce the areas which have to be supported.

The design concepts based on these two different principles are shown schematically in Figure 15. Note that the principles in the table imply that a stable situation for an opening with high walls is obtained when the opening is in rock masses dominated by moderate horizontal stresses, and the length axis of the opening is oriented normally to the direction of the major principle stress. This is also a favourable combination of level and direction of stresses when a large span for an opening is required.

7.4. Dimensions for caverns.

Dimensioning of underground openings based on detailed static calculations is usually not carried out. This is partly because of the problem of obtaining reliable parameters for the material, and partly that transforming the problem from three to two dimensions is not always either easy or accurate when the, materials are as complicated as rock masses. Dimensioning is therefore, to a large extent, based on rules of experience from the numerous openings in varying types of rock masses under varying stress conditions. Such experience may be quasiquantitatively expressed in the form of a rock mass classification system such as for instance the Q-method introduced by the Norwegian Geotechnical Institute, Barton et al. 1974.

Typical dimensions for caverns for powerhouses, oil, gas and water storage are:

Span : 15 - 25 m

Height: 20 - 50 m

Length: 50 - 500 m

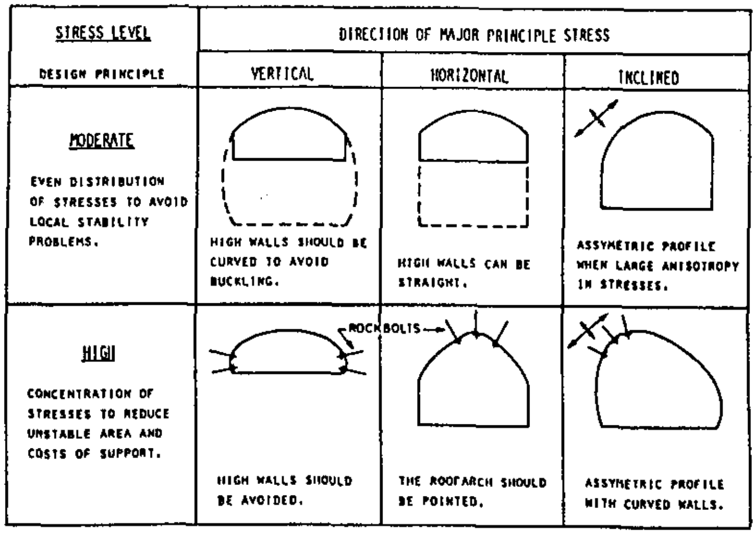

Fig. 15 Design principles for underground openings in rock at varying stress levels, and varying directions of the major principle stress when this is normal to the length axis of the opening.

It is the height of the underground opening together with the quality of the rock mass and the local stress conditions that decide the thickness of walls between adjacent rooms. Under reasonable conditions with properly oriented rooms and normal demans for stability, it is a rough rule that the thickness of the walls should be equal to the height of the rooms. For low rooms, it is preferable to have somewhat thicker walls (minimum thickness 5 m) while somewhat thinner walls may be accepted for high rooms.

For stability of walls, horizontal bedding or jointing is favourable. On the other hand, this has a unfavourable influence on the stability of the roof. As is often the case during the design of underground openings, different conditions may have contradictory influences on various parts of the whole structures. It is the designer's task, using a thorough collection of all relevant data, and recalling all his experience, to balance carefully all these contradictory aspects, in his effort to find the best and most economical solution.

8. CONCLUDING REMARKS.

This paper has hopefully given the reader an idea of the great potential for the use of the underground. The list of examples could easily have been extended. For the interested reader there are several excellently illustrated books published in recent years available. Two of them are already referred to, namely the Finnish "The rock engineering alternative", Saari (1988) and the Swedish "Going Underground", Winquist and Mellgren (1988). The Norwegian Soil and rock Engineering Association has since 1982 published 9 books on tunnelling and different aspects of the use of the underground. One of the latest book on the market is the American "The global review of underground space '91/92" edited by S. Nelson of the American Underground-Space Association. The very latest is probably "Underground Space Design" by John Carmody and Raymond Sterling from the Underground Space Center in Minnesota.

The use of the underground is a major item for the International Tunnelling Association (ITA). This is therefore exposed in the name of the Association's quaterly journal "Tunnelling and Underground Space Technology". ITA and many of its national member societies are actively pursuing the use of the underground by organizing national and international meetings and symposia on this and related topics and publishing proceedings from these events. It is thus in good ITA-tradition that the Tunnelling Committee of Korea is a co-organizator of this symposium.

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