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The significance of weakness zones in rock tunnelling

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ABSTRACT: Although weakness zones normally occur along only 1 - 15% of a tunnel, they form an important feature in rock tunnelling since they can be vital for the safe completion of a project. Low stability and short stand-up time, sometimes associated with water ingress are the main challenges that may arise in such rock masses. The main types of weakness zones and how they can be traced during field investigations are shortly described. It is important to know the pattern of the regional and larger weakness zones in an area for evaluation of the optimum tunnel alignment. Risk sharing contract provisions where the possible variations in the rock mass conditions are described, afford the freedom to choose the best excavation and rock support method, which often results in large cost savings. Some examples of methods used in Norway for tunnelling through weakness zones of very low stand-up time are illustrated.

1. INTRODUCTION

Weakness zones play an important part in hard rock tunnelling. They not only cause increased tunnelling and project cost, but in many cases are of vital importance for the safe completion of a project, and can at times cause substantial delays.

A weakness zone is a layer, zone or vein where the rock mass properties are significantly poorer than in the surrounding materials.

An understanding of the geological development and the occurrence of such weakness zones features is important in the planning and construction of a project. Close cooperation between the engineering geologists, the design engineers and the contractor can often give large savings of costs and time.

2. FORMATION AND DEVELOPMENT OF WEAKNESS ZONES

Weakness zones, as all materials in the Earth's crust, are formed as a result of particular geological processes. Knowledge of the geological history of a region is necessary in understanding the mode of occurrence and extent of the zones.
There are three main groups of weakness zone formations:

1) tectonic fracture zones
2) layers or lenses of weak rocks
3) altered zones of 1) and 2)

The many types of rock formation and varied tectonic histories cause a corresponding variety in occurrence and structures of the weakness zones. The number and the intensity of the orogenetic and faulting periods that the bedrock in an area has been subjected to, are perhaps the most important factors for the development of weakness zones.

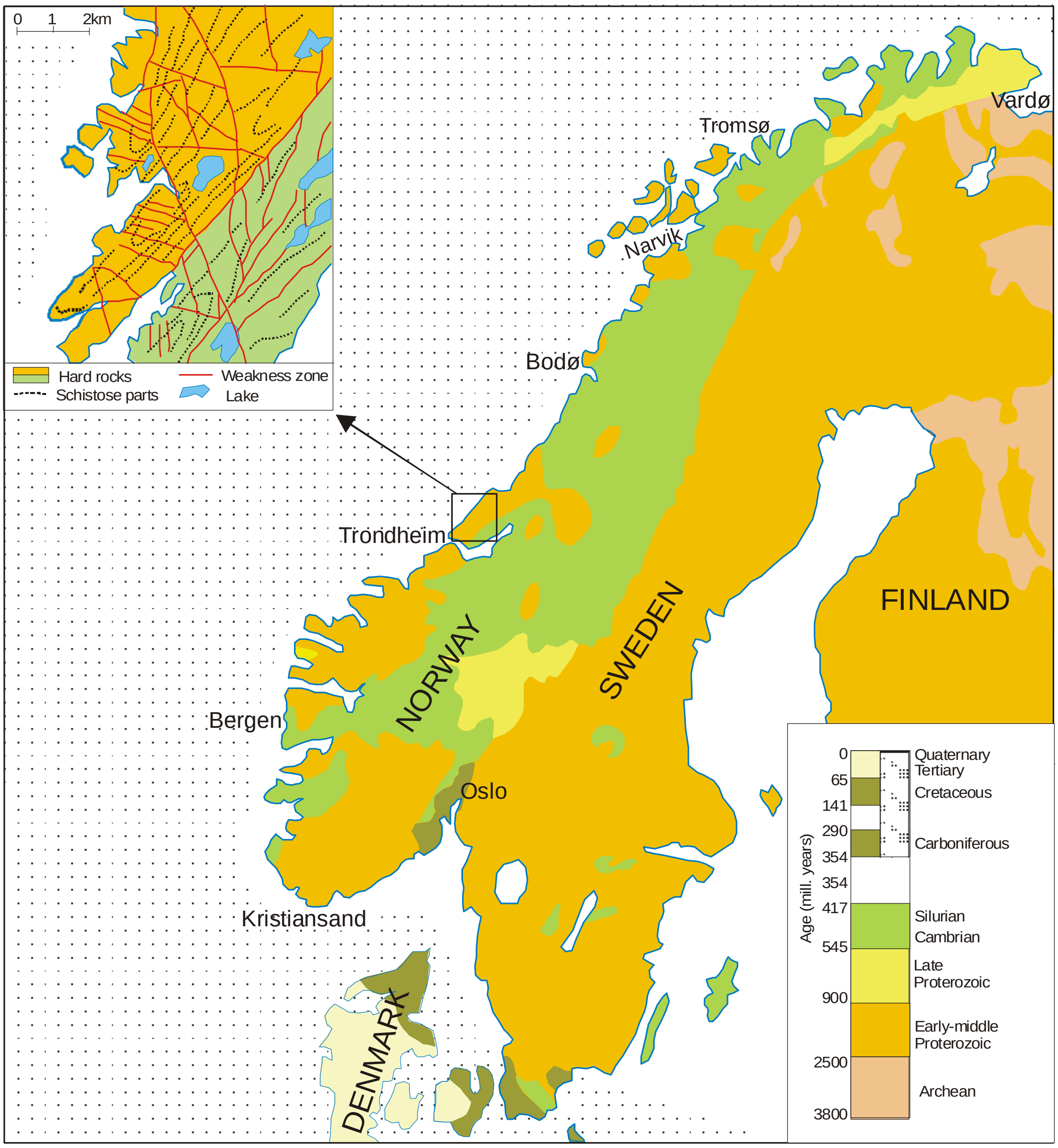

Figure 1. A simplified geological map of Scandinavia and a lineament map interpreted from satellite photographs (Norwegian Rock and Soil Association, 1988)

An example of this is the difference in the geology between Sweden and Norway shown in figure 1. Most of Sweden is made up of old basement rocks which were faulted mainly in Precambrian time, while the Norwegian bedrock has been exposed, not only to the Precambrian orogenies, but also to faulting in the Caledonian (in the Devonian period) and the Alpine orogeny. During the latter orogeny, faulting occurred along the Norwegian coast in connection with the westward continental drift of Greenland.

Figure 1 shows also that the Norwegian bedrocks do not only consist of Precambrian igneous and highly metamorphic rocks, but also of Mesozoic low to medium metamorphic rooks of sedimentary origin, where weak layers and zones are likely to be found.

3. OCCURRENCE AND TYPES OF WEAKNESS ZONES

The structure and composition of weakness zones as they occur today are of predominant engineering importance, whereas origin is of secondary interest. For tunnelling purposes, the weakness zones therefore have been divided into the following groups and subgroups:

TECTONIC FRACTURE ZONES

Tension faults
- feather joints
- clay filled zones
- zones filled with lamellar calcite (chlorite, silt etc.)

Shear faults
- coarsely fragmented crushed zones
- finely fragmented crushed zones
- simple, clay-rich crushed zones
- complex, clay-rich crushed zones
- larger fractures or joint zones

LAYERS OF WEAK ROCKS
- layers of mica
- layers/veins/lenses of talc, soapstone, gypsum or chlorite
- dykes/veins (e.g. highly jointed dolerite or breccia etc.)

ALTERED ZONES
- layers, zones or lenses of altered rocks
- altered crushed zones

Some of the weakness zones are shown schematically in Figure 2.

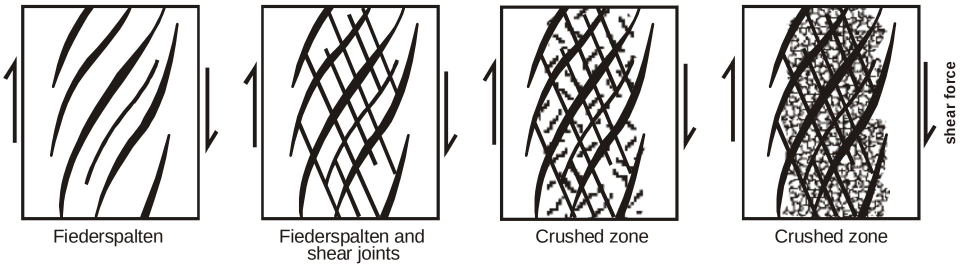

Figure 2. Some types of weakness zones, (modified after Rock Mechanics Group 1985).

4. INVESTIGATIONS AND DETECTION OF WEAKNESS ZONES

Weakness zones can often be traced on the surface. Where erosion has been effective in outcropping rocks, even minor weakness zones can often be observed in the surface. Because of the reduced mechanical properties in such zones, they form valleys or similar smaller depression in the topography creating identifiable lineaments on aerial photographs. From the shape of the valley it is also possible to find the dip of the zones, refer to Figure 3. Estimates can frequently be made of the width of the zone.

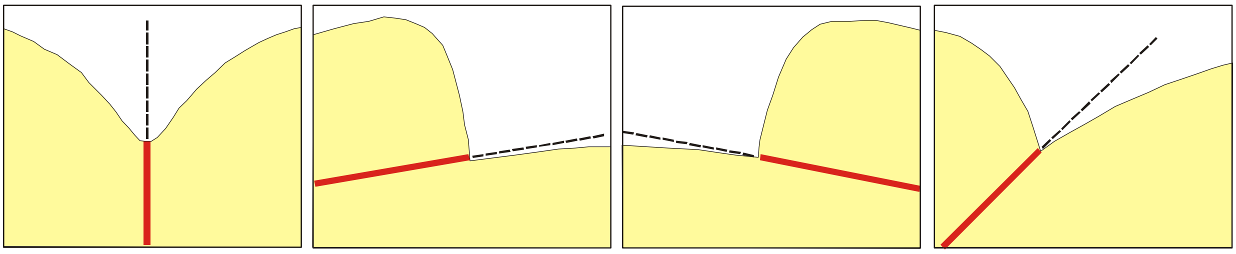

Figure 3. From the shape of the eroded valley the dip of the zone can often be estimated. (Selmer-Olsen, 1976)

In areas with deeply weathered rocks or with larger parts of rocks hidden by soil, tracing of weakness zones require often far more investigations. In many cases a combination of geophysical measurements with core drillings and regional geological surface mapping are applied with good results.

In Norway, ice erosion during Quaternary time has left a surface of unweathered, mostly bare rocks. Because most geological features can be traced on the surface, it has been possible to produce a general map of regional weakness zones from satellite photographs, Figure 1. This information is useful for the overall understanding of the main lineaments and tectonic features.

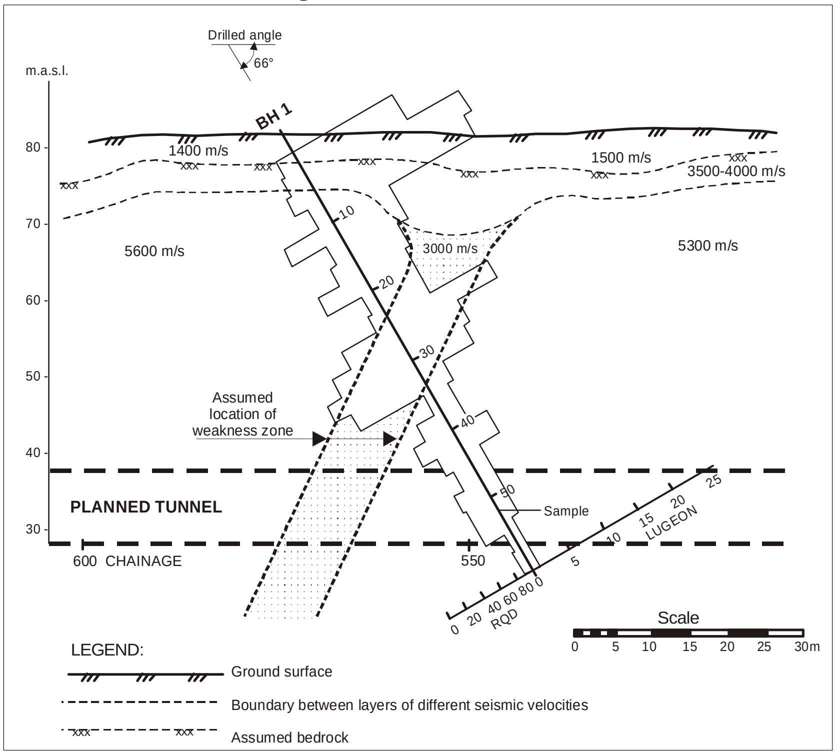

Figure 4. Weakness zone traced from refraction seismic measurements and core drilling (Rock Mechanics Group, 1985).

Interpretation of aerial photographs is an important step in the studies of weakness zones, and from these results a map of the major zones can be worked out, Figure 5. The occurence of the zones found are then verified in the field during the geological mapping for the project. Many zones important for the project may require further detailed study. Refraction seismic measurements and core drilling are common methods of investigation. Results from such a investigation often are shown in Figure 4.

Particular problems are often associated with detecting zones of low dip, and the occasional steeply dipping zones that have a poor surface expression. Detailed knowledge of the regional and local tectonics can solve this problem in part; the risk of encountering undetected weakness zones at depth cannot be entirely removed. Adequate investigations can, however, give reasonable assurance that major zone of weakness, that might affect the economics of a scheme, will not be encountered.

5. DESIGN AND TENDER SPECIFICATIONS

The general design rule is to avoid weakness zones whenever possible. For many rock facilities there is considerable latitude in determining its location, as for example, underground power houses and storage caverns. Engineering geological input at the planning stage is advantageous in obtaining the optimum scheme. When a map of the weakness zones has been made, this can be used in working out the most favourable alignment for the tunnel. For instance, the location of the tunnel between predetermined portals can be adjusted to avoid driving the tunnel along weakness zones and to cross them in the shortest practicable distance, refer to Figure 5.

Considerable importance must be given to providing contract documents that allow for variations in tunnel alignment after the work has commenced, should zones with unfavourable direction to the tunnel be met. This can be used to reduce costs for water tunnels and other tunnels where alignment is of secondary importance. Rail and road tunnels, however, have strict limitations on allowed curvatures and present a particular problem. The savings in cost by varying the alignment after work has started, can yield considerable savings in cost compared with adhering to the original design. This is only achievable if the consulting geologist is closely involved with the tunnelling work and has experience in assessing the economic consequences of various courses of action. Figure 6 shows that the length of a zone along the tunnel is highly dependent on the zone's orientation with respect to the tunnel.

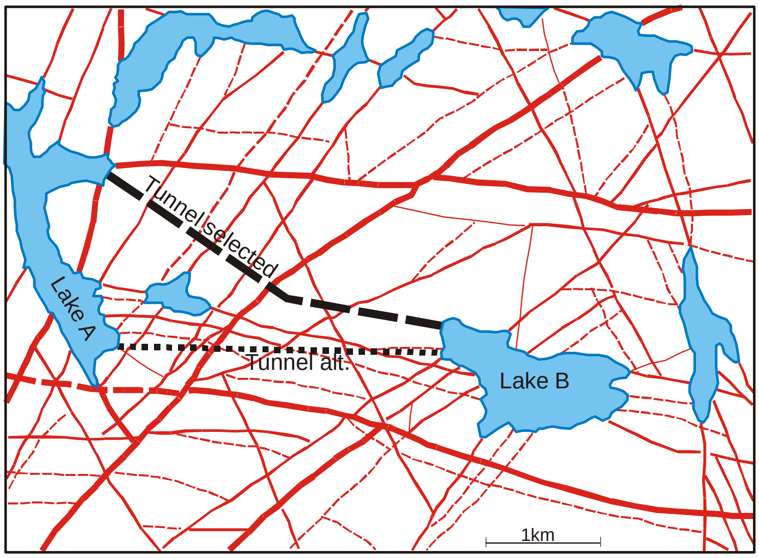

Figure 5. The pattern of weakness zones found from aerial photo interpretation and geological mapping. The shortest tunnel, 2.8km, would be along the dotted line between I and II. By making the tunnel 300m longer it will pass through 70 - 100m of weakness zones instead of 500 - 600m.

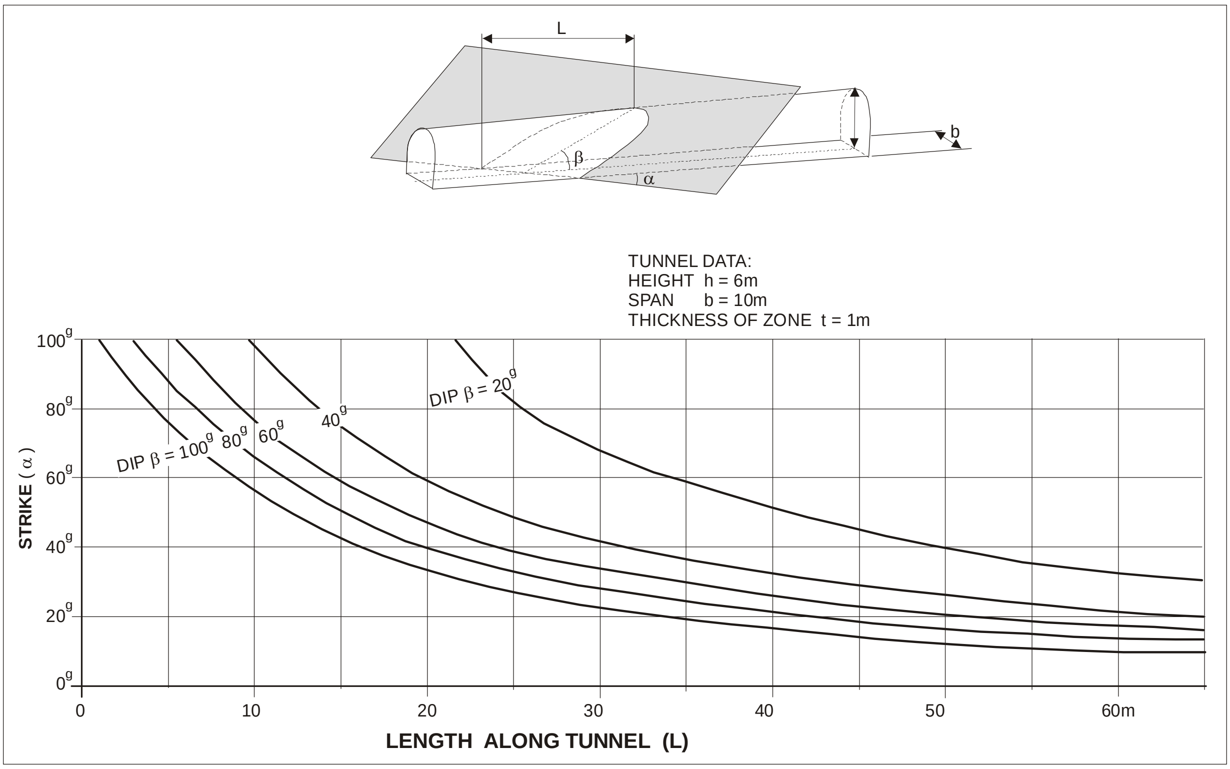

Figure 6. A zone with strike 40^g and dip 60^g with respect to the tunnel will cut the tunnel along 25m (instead of 1m when passed at a right angle).

From a strictly technical point of view, the investigations carried out prior to construction should give sufficient information on all weakness zone for the engineer to determine:

– how the tunnel should be excavated;
– how and when the rock support should be carried out; and
– what safety precautions should be taken.

This would involve a high expenditure on investigative work without, however, giving any guaranty of not encountering all unforeseen difficulties.

In contract provisions made for tackling difficulties caused by unforeseen geological features, many of the investigations can be omitted or reduced. The specifications in the contract take care of the effect of changing rock mass conditions, within reasonable limits, on tunnel excavation, rock support and the allowable construction time. This risk sharing contract concept, NoTCoS (Norwegian Tunnelling Contract System), has been in successful use in Norwegian tunnelling for more than 15 years.

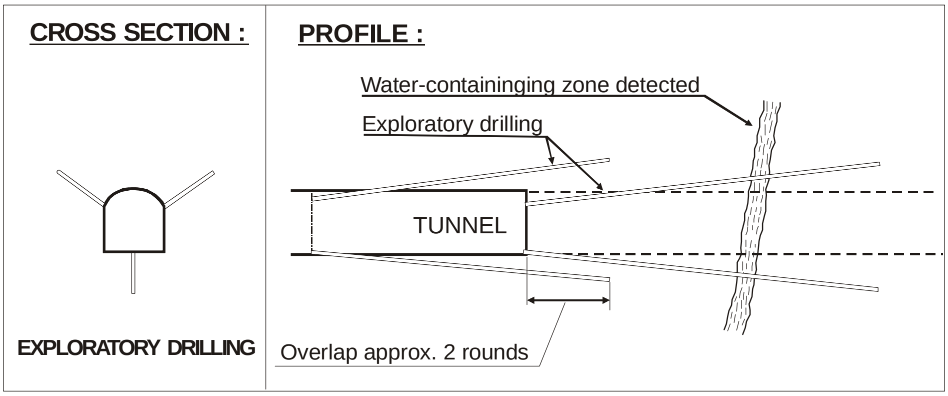

Figure 7. Exploratory drilling is an important measure in tunnelling to detect possible weakness zones

6. TUNNELLING AND ROCK SUPPORT IN WEAKNESS ZONES

There can be considerable changes in excavation and rock support methods when tunnelling into a major weakness zone. An experienced contractor, who knows the possible methods and their applicability under varying circumstances, will succeed in tunnelling efficiently. This is fare more important than detailed knowledge and analysis of the physical circumstances as time is of the essence: short stand-up times are frequently encountered in many of the larger weakness zones. Of prime importance is the prevention of the development of cave-ins, and secondarily the treatment of cave-ins should they occur. A geological understanding of the structure of the zone combined with rapid excavation and installation of the rock support are in all cases the main answer.

Developments both in excavation techniques and in rock support methods have made it much easier to tackle low stability conditions. Among these developments, fibre reinforced shotcrete (fibrecrete) is important, because it can be applied rapidly and provides quickly good stability. The use of prefabricated formwork modules has extended the possibilities of passing through larger zones of low stability safely and rapidly.

As an example, a sub-sea tunnel encountered a 400m thick weakness zone near its deepest point some 170m below sea level where the rock cover up to sea bottom was 60m. The zone consisted of consolidated sand, probably a zone of tuff, which was penetrated with a combination of:

- short blasting rounds
- rapid application of fibrecrete
- concrete lining of each round

This is illustrated in Figure 8.

At Vardo subsea tunnel another method, shown in Figure 9 was used. Also in this case there was a potential risk of cave-ins some 40m below sea bottom, and rapid execution of the works was essential. Spiling bolts ahead of the tunnel face have in many cases been found useful during tunnel-ling through low stability zones.

There have been occasional problems with cave-ins. The Norwegian experience is that the slipped material should not be touched. In cases when materials has been mucked out, the slide has developed further up above the tunnel and it has become difficult or even impossible to support the mass and to tunnel through the zone. In such cases a bypass tunnels have been made in which the zone has been passed by using reduced blast rounds and rapid rock supporting works.

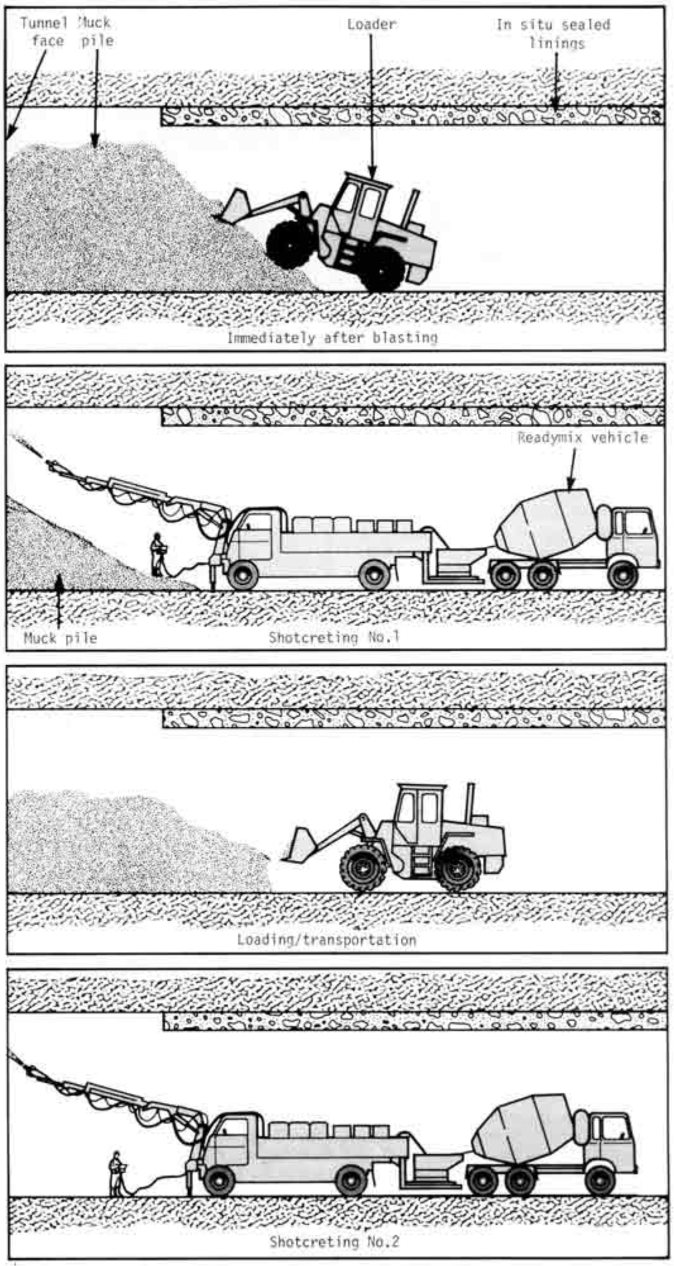

Figure 8. The excavation and rock supporting technique applied in the Karmsund subsea tunnel (modified after Martin 1983).

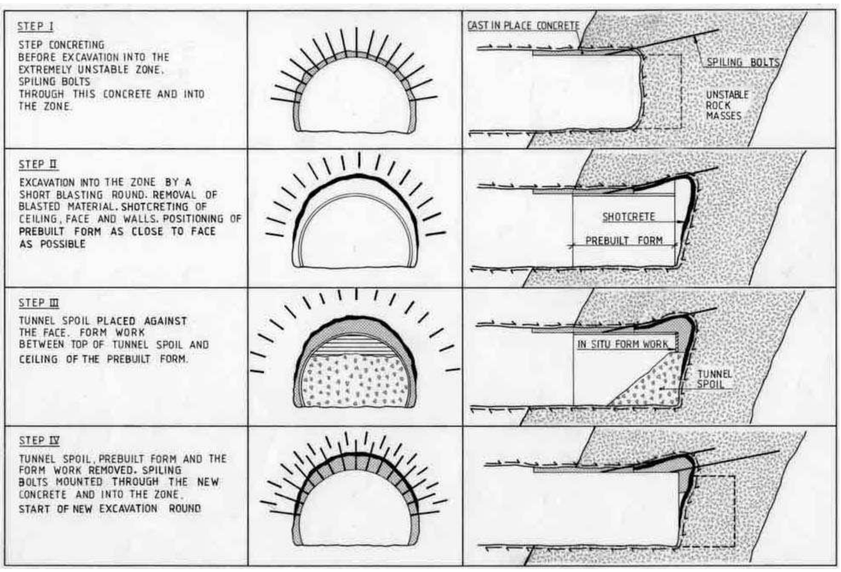

Figure 9. The excavation and rock support system applied in the Vardo tunnel under extreme low stability rock mass conditions (Palmstrom, 1984).

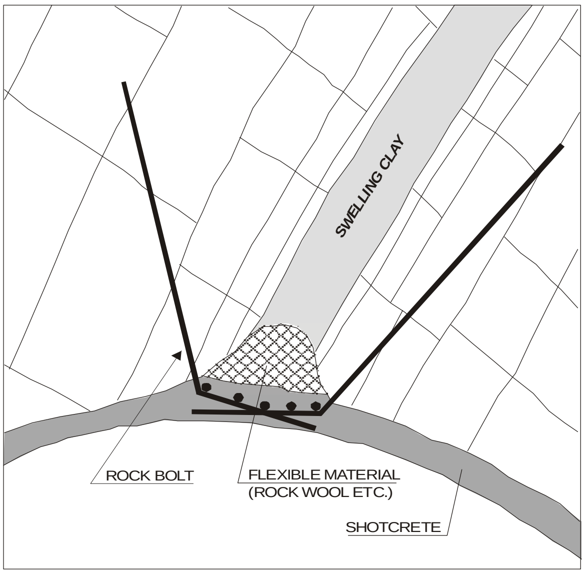

Figure 10. Method often used for support of swelling clay zones with thickness less than 1m.

7. EXPERIENCE

The amount of weakness zones in Norwegian tunnels varies from about 1% of the length to more than 20%. In some cases the amount could have been less if a closer following-up of the tunnelling works had been done by experienced engineering geologists, so that the tunnel alignment could have been changed in time.

It is, however, as mentioned earlier most important to thoroughly evaluate the tunnel alignment during the planning stage to avoid or to pass through the weakness zones at a favourable (great) angle. The experience from Norwegian tunnels is that the costs of the rock supporting works amounts from less than 5% to more than 200% of the costs for the excavation and mucking out. Of these costs rock support of weakness zones normally constitute from 30 - 60%.

In Norway the expected variations are taken into account in the tunnelling contracts as provisions in the choice of excavation and support methods to suit the varying rock conditions as they are revealed. This means that the final decision is taken after the rock masses can be studied and described in the tunnel, so that the real, existing conditions are used in the rock support evaluations.

REFERENCES

Martin, D., 1983. Fibrecrete gives face a lift in delicate undersea tunnel blasting job. Tunnels & Tunnelling, July 1983.

Norwegian Rock Mechanics Group, 1985.
Handbook of engineering geology rock (in Norwegian). Trondheim, Tapir.

Norwegian Soil and Rock Engineering Association, 1988. Norwegian tunnelling today. Publ. no. 5, Trondheim, Tapir.

Palmstrom, A., 1984. Geo-investigations and advanced tunnel excavation technique important for the Vardø sub-sea road tunnel. Symp. on Low cost road tunnels. Trondheim, Tapir.

Selmer-Olsen, R. 1976. Engineering geology (in Norwegian). Trondheim, Tapir