Influence of Geological Conditions on Design and Construction of Tunnels
Lecture 4 & 5

Dr. Muhammad Zubair Abu Bakar

The Geological Environment

- Tunnels are driven in virtually all the main rock types:
  - Igneous Rocks
  - Sedimentary Rocks
  - Metamorphic Rocks

Igneous Rocks

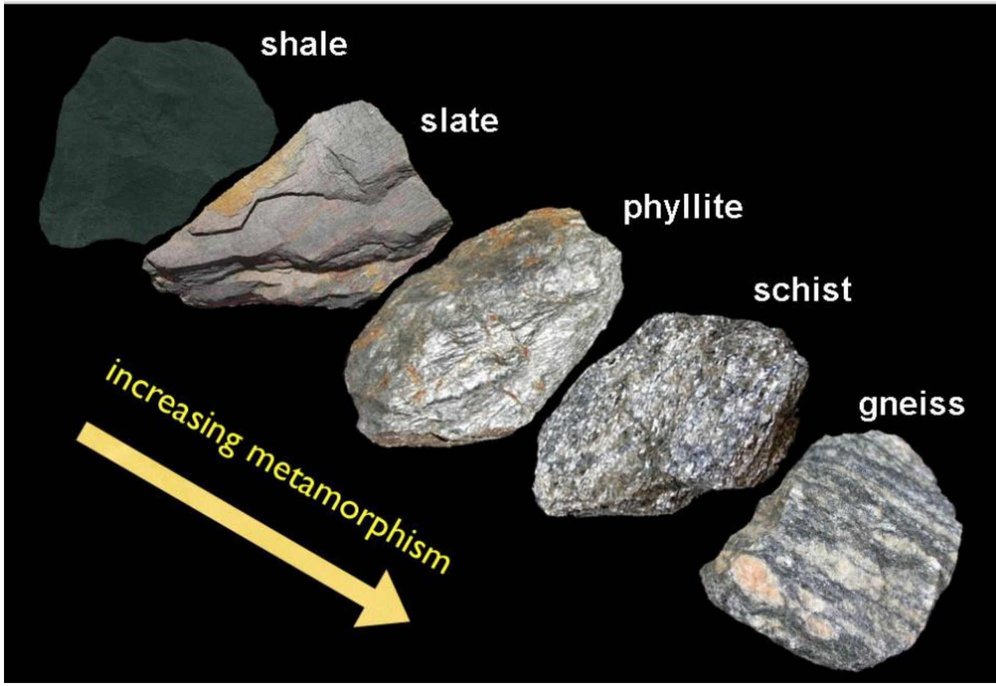
- Crystalline nature of igneous rocks signifies high compressive strength with potential difficulties in excavation processes.
- High strength offers the advantage of marked competence which leads to decreased support requirements.
- The crystal or grain size of these rocks is dependent on the size and geological history of the igneous body.
  - Localized and relatively thin intrusives are usually fine-grained and possess high strength and significant resistance to weathering by comparison to coarse grained types with similar mineral contents..
  - Intrusive igneous bodies can range from granitic batholiths exhibiting surface exposures in excess of 100 km^2, to dykes, sills and structurally controlled intrusions of localized nature.
  - The intrusives can act as a means of directing water into the path of the tunnel.
  - Extrusives like rhyolite and basalt have cooled relatively rapidly producing a fine grained structure.
  - Igneous rocks such as volcanic tuff and pumice, can be particularly weak and porous allowing easy excavation, they can be subject to rapid weathering and can give rise to significant groundwater problems.

Sedimentary Rocks

- Clastic types (adhered together as a compacted matrix or by chemical cement actions): sandtsones and other silica constituted sediments, carbonates, iron oxides.
- Crystalline types: rock salt, gypsum, anhydrite, certain crystalline limestones.
- Sedimentary rocks are generally weaker in strength than majority of igneous and metamorphics. Consequently, they do not generally pose difficulty by machine excavation methods.
- Effects of stress and advanced weathering, weakening by the action of water can give rise to problems especially where such rocks contain appreciable amount of clay minerals.
- Wide ranging values of permeability occur in such rocks with some clay beds being impervious to water, while other sedimentary types act as significant aquifers.
- The banded/layered nature of these rocks needs special consideration in tunnelling operations. Such bands exhibit marked differentials in strength and competence. This is of importance in allowing free spanning to occur together with appreciable standup times.

Metamorphic Rocks

- Formed due to partial or complete recrystallization as a geological process at high temperatures/pressures.
- Exhibit foliation and schistosity.



- Rocks such as quartzite, marble, dolomitic marble and hornfels generally exhibit random distribution of mineral components, with minor, if any, foliation, and consequently display competent properties.
- Metamorphics containing abundant micaceous minerals result in well-defined planes of weakness allowing easy splitting , such as slate, phyllite, schists.

- Micaceous layers can be of significance in influencing the vulnerability of certain metamorphic rocks to weathering processes.

Rock Alteration

- Weathering produce rock alteration which is of major importance to tunneling.
- Weathering reduces the strength of the rocks and can extend to considerable depths by the action of groundwater movement.
- Biological activity and time are also important to the depth of weathering.
- Erosion removes weathered material, but deep channels and narrow valleys remain with weathered materials being well concealed from surface observation.
- Buried zones of weathered rocks may exist under glacial drift materials.
- Pockets of highly weathered rocks usually contain water and can be under appreciable hydrostatic pressure head.
- Consequently they can possess the ability to rapidly flow into an excavation if disturbed by underlying or adjacent tunneling activities.

General Influence of Geological Conditions

- When a tunnel is excavated, three types of geological conditions may be found that cause loss of strength and stability problems in a rock mass:
  - ➢Unfavorable orientation of discontinuities.
  - ➢Unfavorable orientation of stress with respect to the tunnel orientation.
  - ➢Water flowing inside the excavation along fractures, aquifers or karstified rocks.

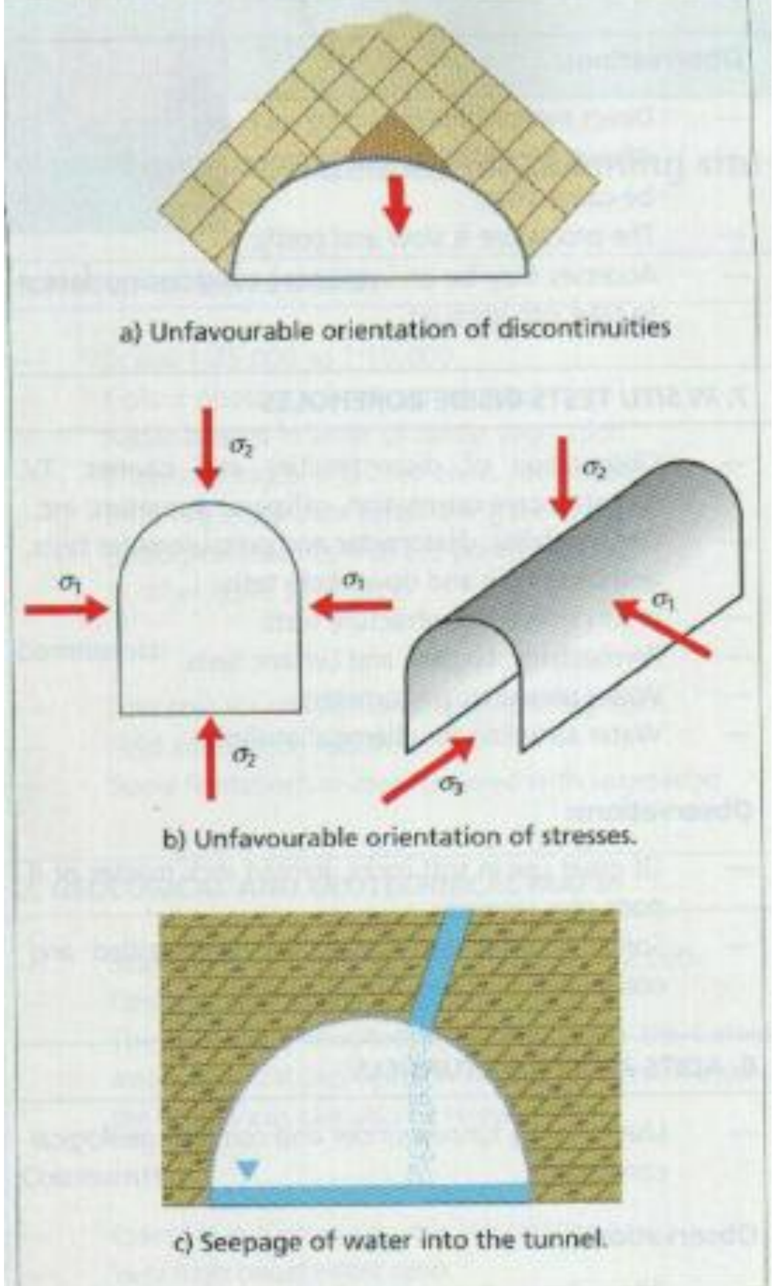
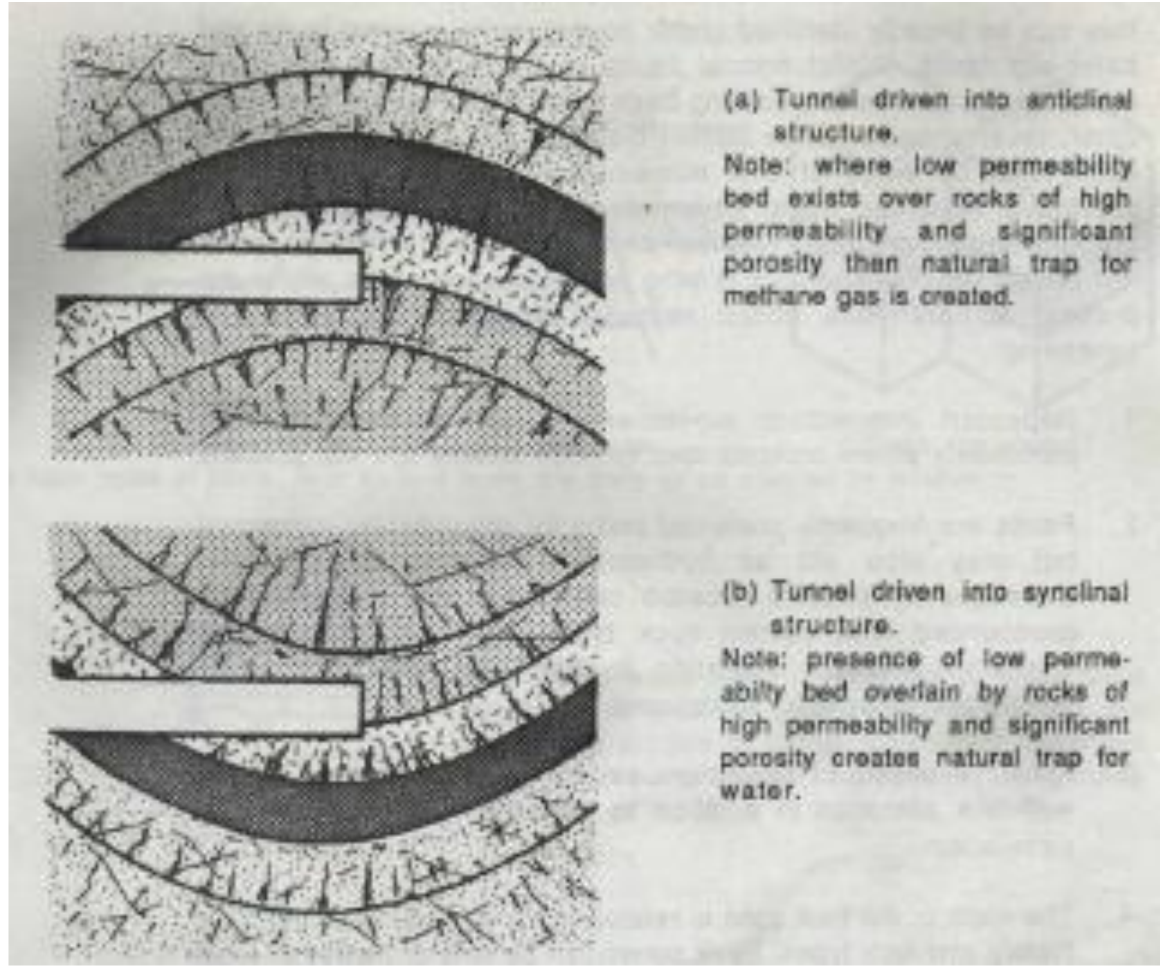


Figure 10.4 Geological conditions affecting the stability of rock tunnel excavations.

Rock Mass Deformation by Folding Action

- Folded strata allow natural traps to form which attract accumulation in significant quantities of natural gas, petroleum and water.
- Severely distorted folds are frequently accompanied by plastic behavior of rocks especially in the softer sediments and in metamorphic rocks.
- Relative sliding between layers also occurs in flexural folding in strongly stratified structures.



•Opening of tension gashes or cracks in stronger rock formations in addition to shear development in the compressive zones of folds also occur.

- Localized stress concentrations occur in association with folded rocks, and such stresses can cause <u>bursting action during excavation of stronger and brittle rocks</u>.
- Folded rocks represent zones of decreased competence with zones of intense fracturing and stress relief causing dislodgement of rocks in freshly exposed tunnel excavations.

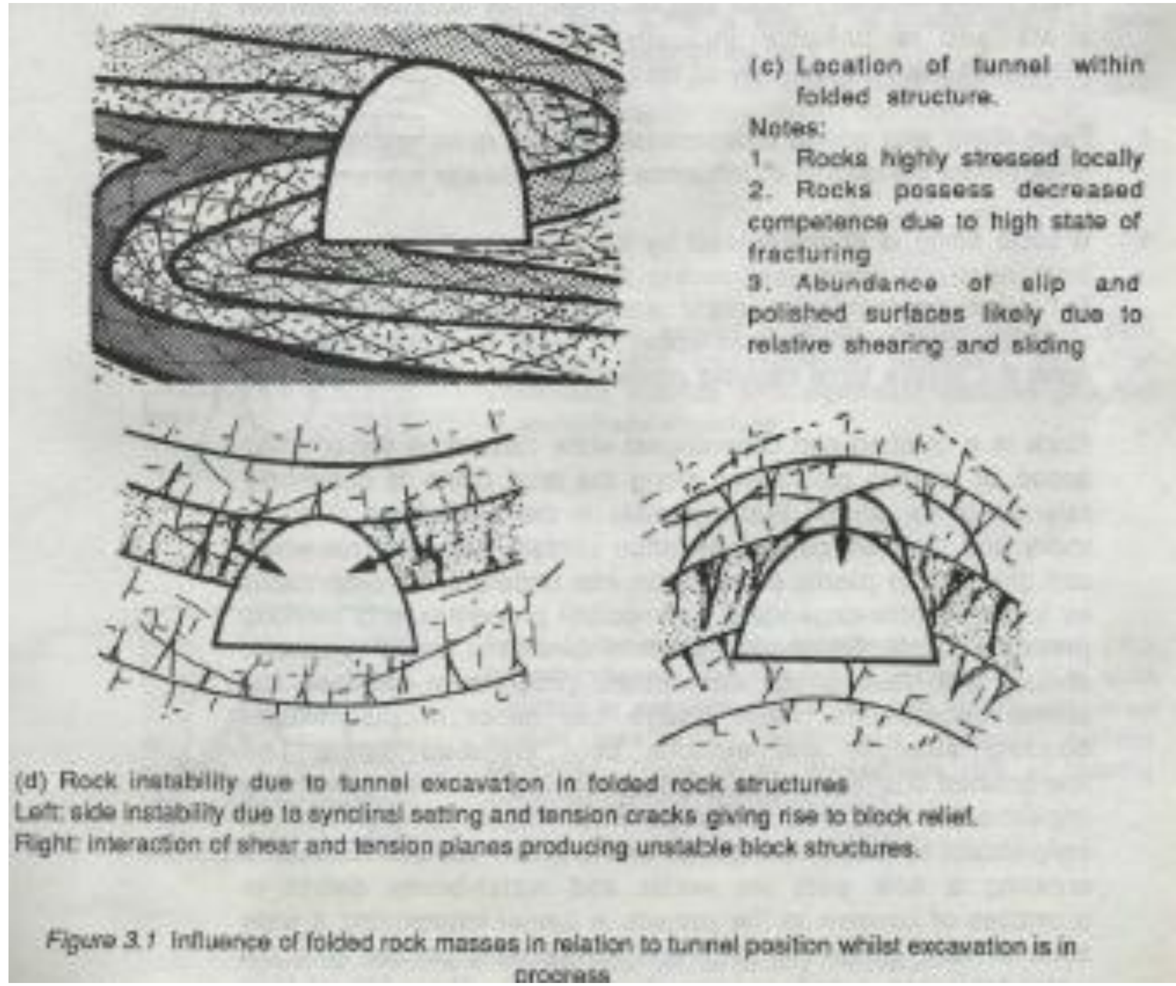


Figure 3.1 Influence of folded rock masses in relation to tunnel position whilst excavation is in process

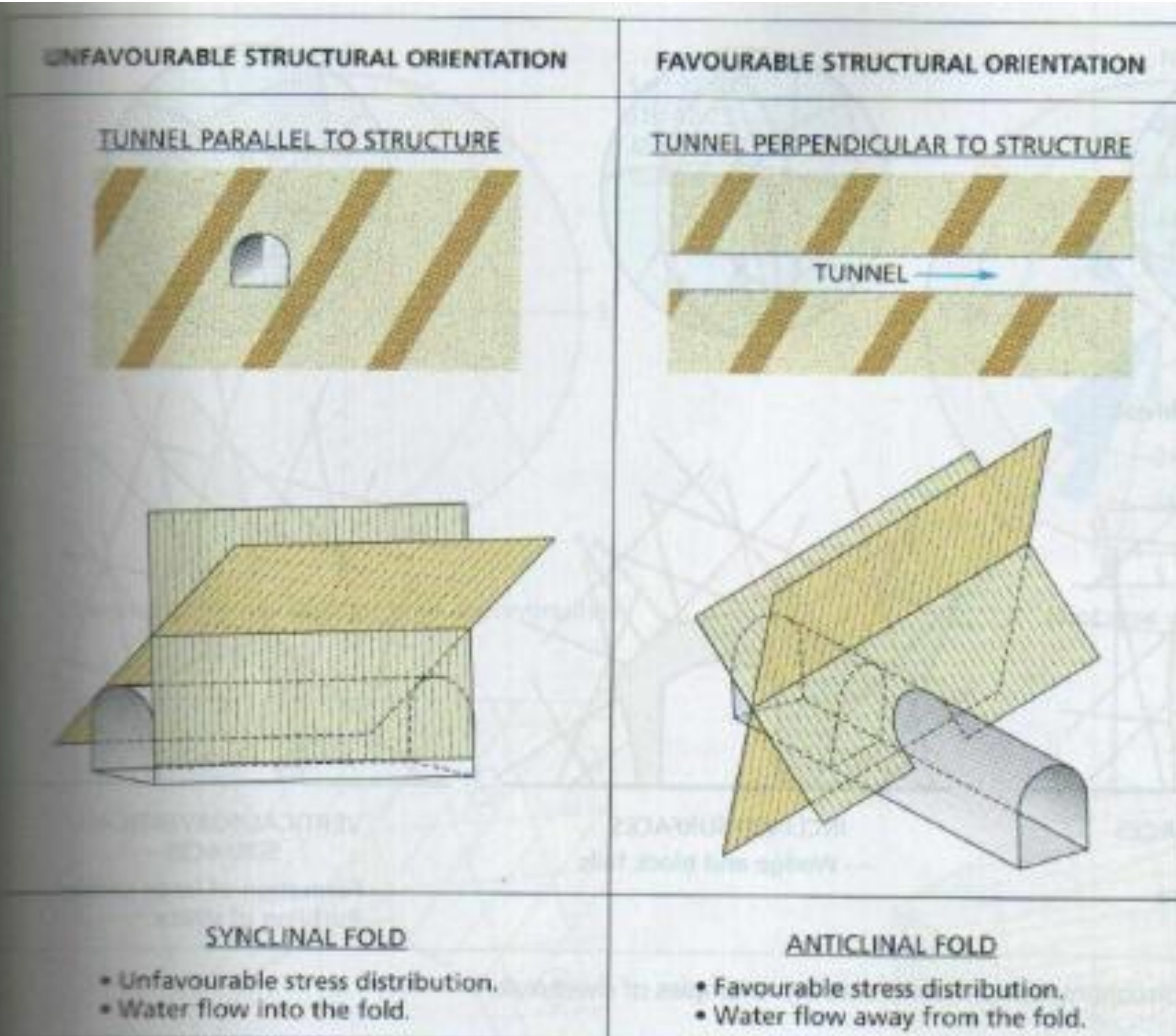
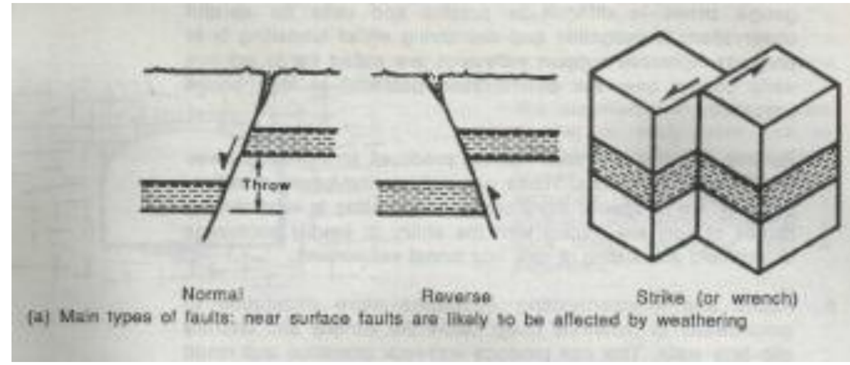


Figure 10.5 Influence of geological structure on tunnel stability.

Faults: Chracteristics and Influence on Tunnelling

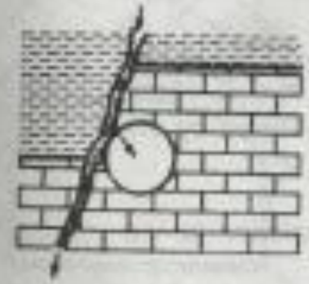
- Repeated intermittent movements occur at several sites, particularly where tectonic and igneous activity are still present.
- Faults are preferred paths for groundwater movement but also act as hydrological barriers.
- Frictional effects of movement along the fault plane can induce wall-rock alteration in addition to chemical reaction from water circulation.
- Fault zones can be tens of meters in width even where relatively minor displacement has occurred between strata.
- Fault filling and gouge properties differ quite markedly and often reflect the degree of influence of groundwater movement.



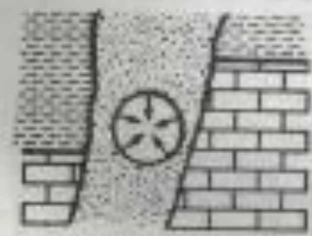
(a) Main types of faults: near surface faults are likely to be affected by weathering

- Breccia filling is characterized by its fragmented nature derived from relatively competent rocks; such filling can exhibit voids but often contains fine materials.
- Water assists in the breakdown of some rocks and the fault gouge can often contain clay minerals which can give rise to plastic deformation into U/G excavations due to creep and swelling pressure effects.

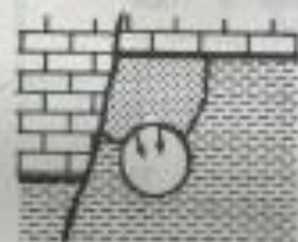
- Relative movement of rock masses produces scratches, grooves and polished interfaces. These can indicate movement direction, but are of special significance to tunneling in representing planes of very low friction with the ability to encourage detachment and sliding of rock into tunnel excavations.
- Faults allow circulation of groundwater to penetrate deep below the surface and laterally into side walls. This can produce wall-rock alteration and result in deep seated weathering.
- Orientation of faults in relation to the tunnel line is vitally important, since this governs the length of tunnel affected by the fault and its accompanying fault zone.



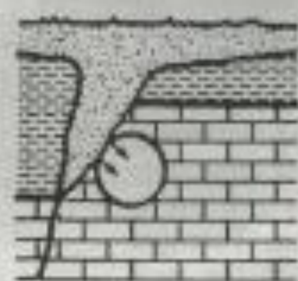
Likelihood of water being encountered as many faults are a preferred path for groundwater. Additionally the fault maybe subject to further intermittent movement and thus require special consideration regarding support.



Fault zone width is difficult to predict and can vary along the length of the fault.
Fault gouge is of low competence and exhibits poor stand-up time.



Fault planes exhibit relatively low friction with poor cohesion and consequently represent zones of decreased stability with significant collapse potential in under-hade situations.



Fault zones frequently represent the preferred path for groundwater transmission. Consequently it is quite common to encounter localised and significantly deep seated weathering particularly in near surface situations. There is an appreciable risk of tapping saturated unconsolidated deposits.

Figure 3.2 Faults and their influence on the stability of tunnels

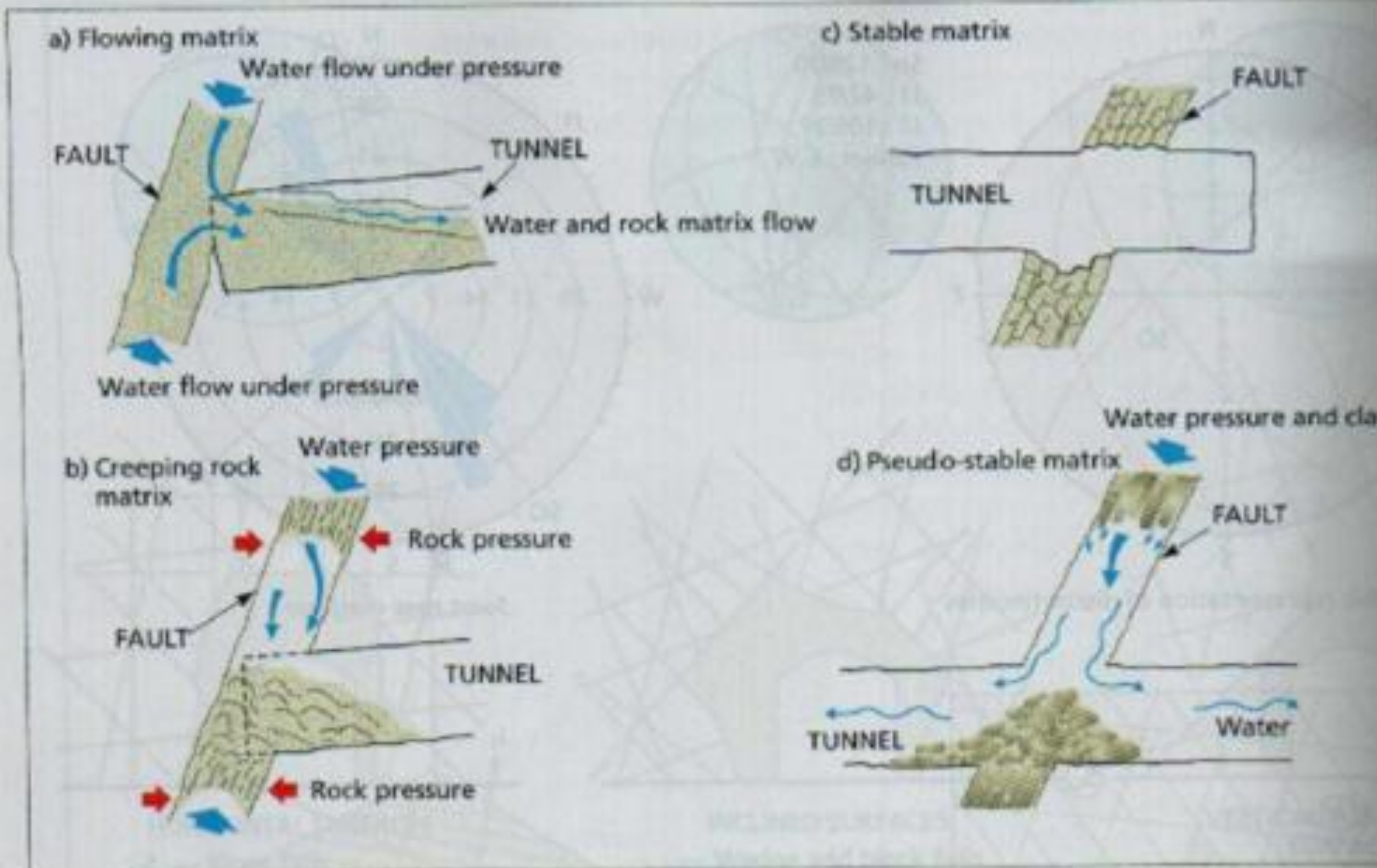


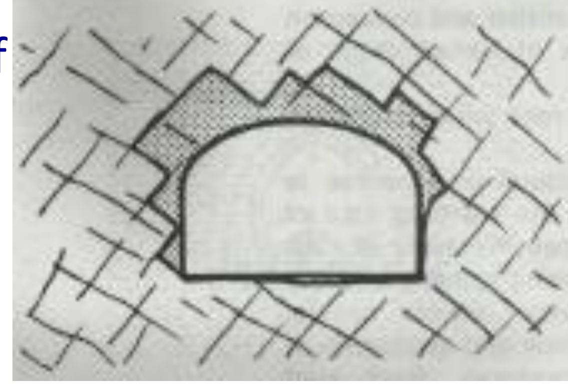
Figure 10.8 Stability of faulted rocks in a tunnel (Hansen and Martna, 1988).

Figure 10.34 Faults intersecting the tunnel excavation front in RMR Class IV shales.

Joints and Their Relevance to Tunnelling

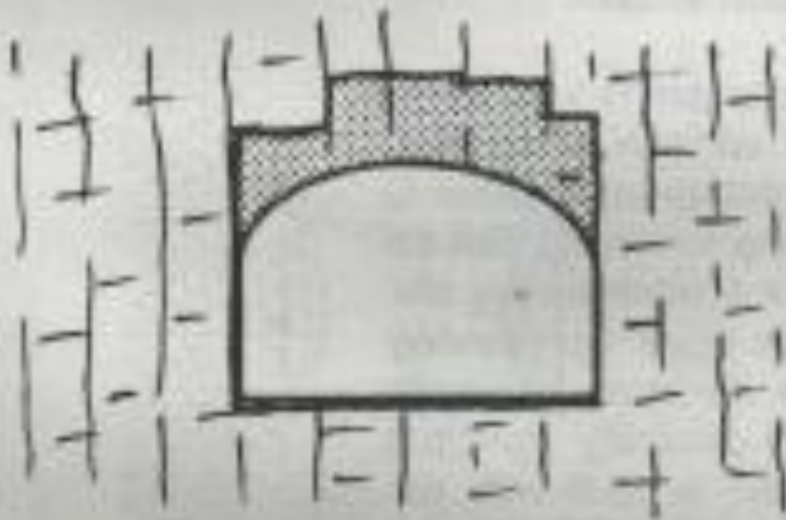
- Joints occur in sets. Multiple joints run essentially parallel to each other; two further sets of joints commonly exist and are often at consistent angles to each other.
- Joint systems in coarse grained igneous rocks (granite) commonly exhibit three sets of joints.
- Sedimentary rocks also exhibit three sets of joints with one usually parallel to the bedding planes, while others intersect the planes approx. at right angles.
- Joint spacings in limestone and sandstone beds are commonly meters apart while in shale they are usually closer.

The occurrence of joints in sets parallel to each other and at consistent angles is a common feature. The pronounced block formation shown represents a situation with appreciable risk of such blocks dislodging into the excavation.



Where the joint sets are orientated with their main planes of weakness inclined so as to encourage blocks to slide into the excavation, this situation can give rise to instability predominantly on one side and above the excavation. This form of instability is gravity controlled.

- Two or more sets of joints also exist in metamorphic rocks and often one set is approx. at right angles to the cleavage planes.
- Joint spacing increases with depth below surface while the width of the joints decreases with depth.



Where predominantly vertical stratification exists the joint sets can give rise to situations where blocks can readily become detached and fall into the excavation. Such situations call for special attention to be given to effective temporary support measures aimed at giving immediate control over the risk of such blocks becoming unstable.

A commonly encountered situation in pronounced horizontally stratified sediments is that of bedded structures with weak interfaces and joints almost at right angles to the bedding plane. Consequently rock detachment in the form of slabs frequently gives rise to flat top roof situations whose span is usually governed by the thickness of beds and their general strength characteristics.

Figure 3.3 Illustrating the influence of rock joints in relation to stability of tunnel excavations

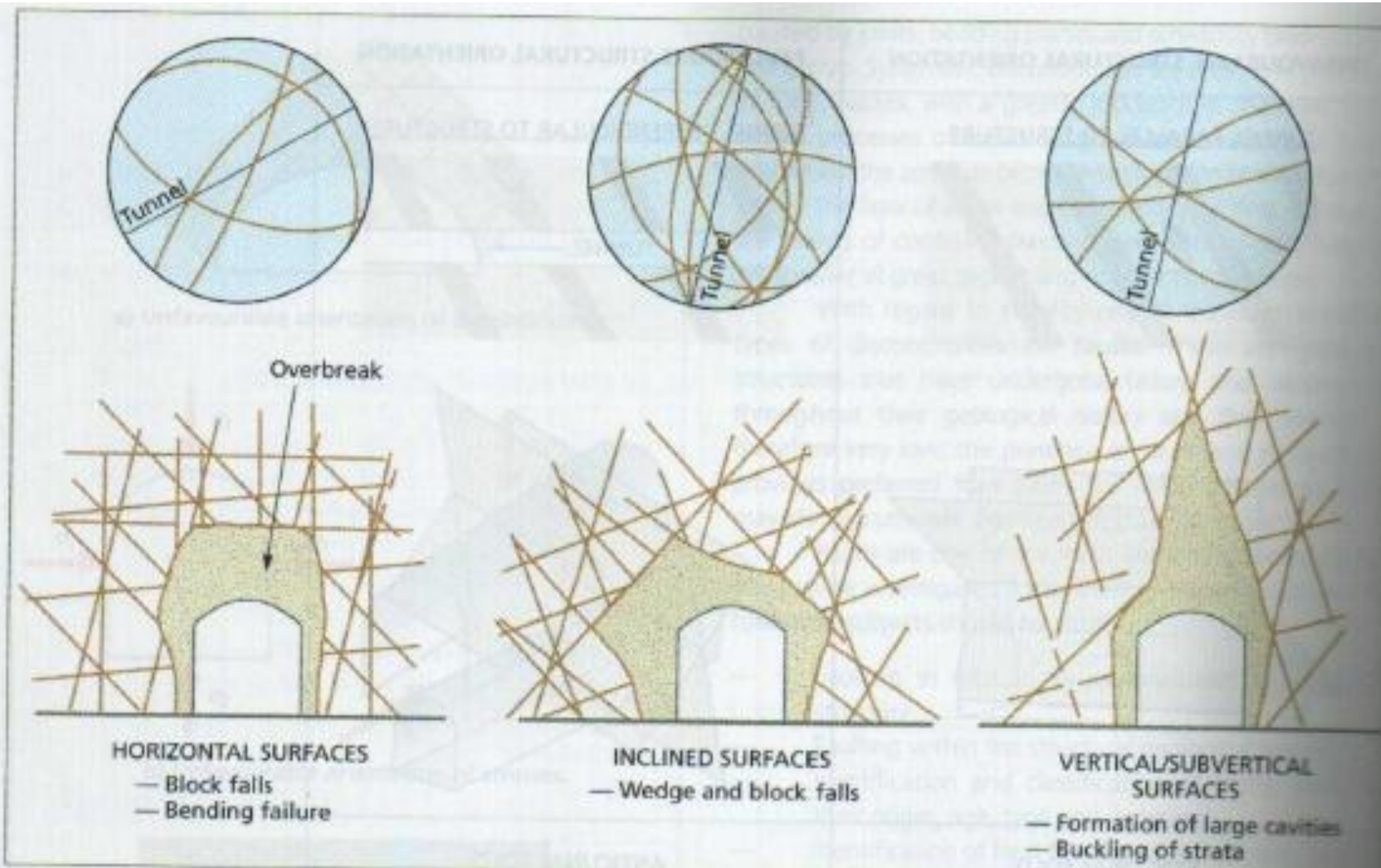


Figure 10.6 Influence of discontinuities on tunnel stability: examples of overbreak.

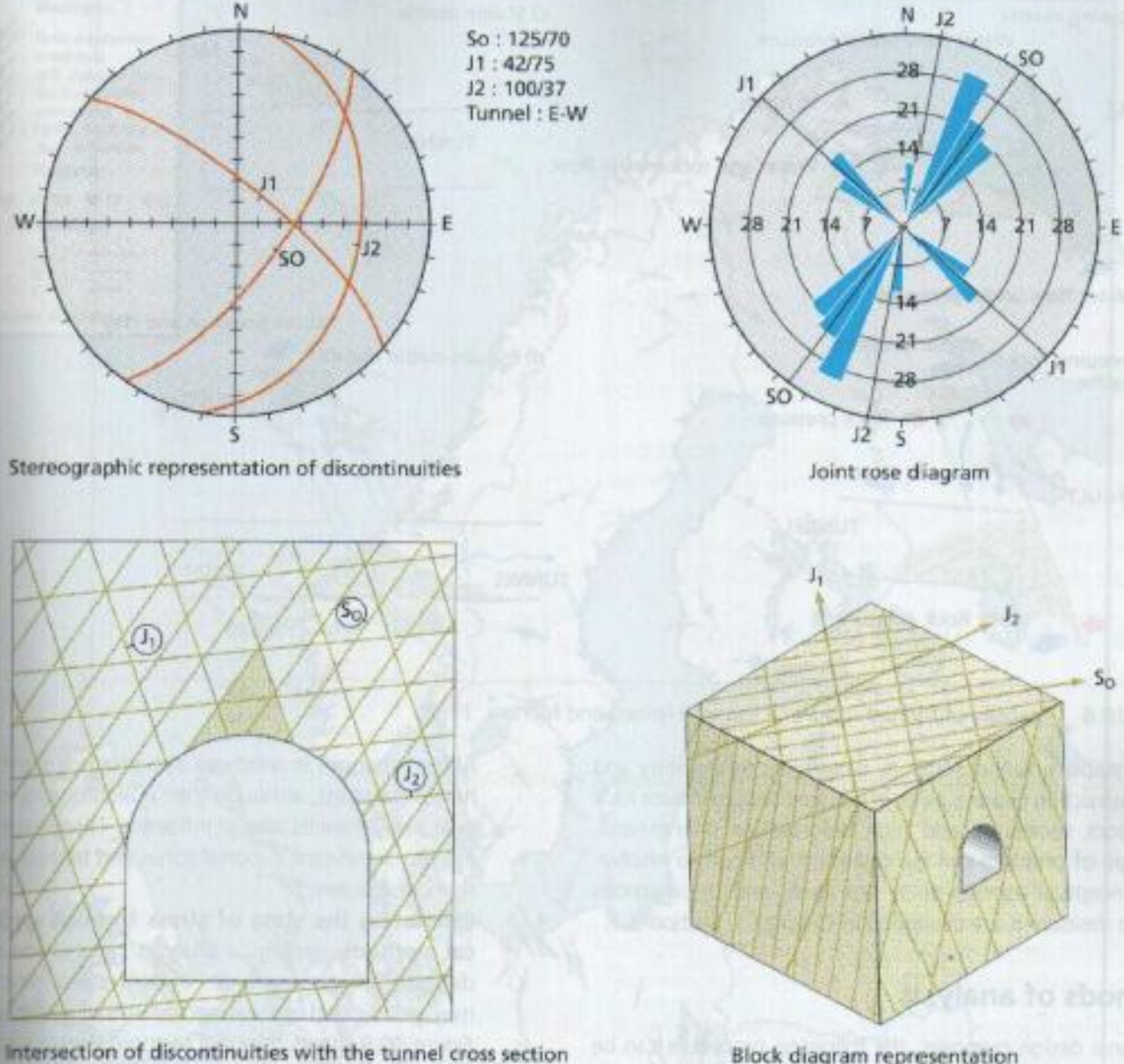


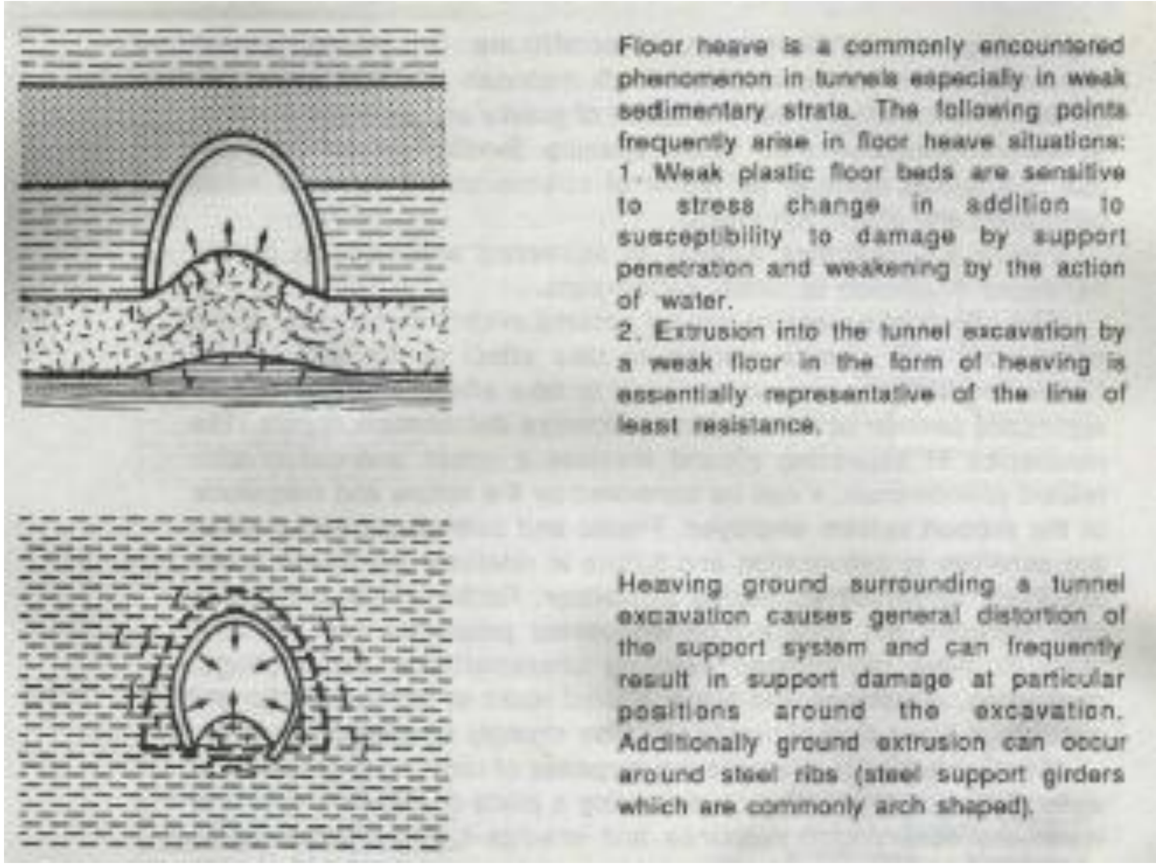
Figure 10.7 Graphical analysis of discontinuities.

Groundwater Aspects

- Presence of groundwater in very large quantities is a major hazard in addition to causing operational difficulties in tunneling activities.
- Groundwater presence, quantity, quality, formations having water all must be identified at site investigation stage.
- Large quantities of water in weak ground conditions can lead to rapid formation of cavities around the tunnel excavation.
- Tunneling projects can experience relatively warm water (> 30-35 C) which can impair the environmental conditions within the tunnel.
- Groundwater could be a carrier of dissolved gases into the tunnel excavation.

Squeezing and Swelling Ground Conditions

- Squeezing ground commonly refers to weak, plastic rock material which displaces into the tunnel excavation under the action of gravity and from the effect of stress gradients around the tunnel opening.
- Swelling ground displaces into the tunnel opening as result of volume change due to water adsorption and absorption effects.

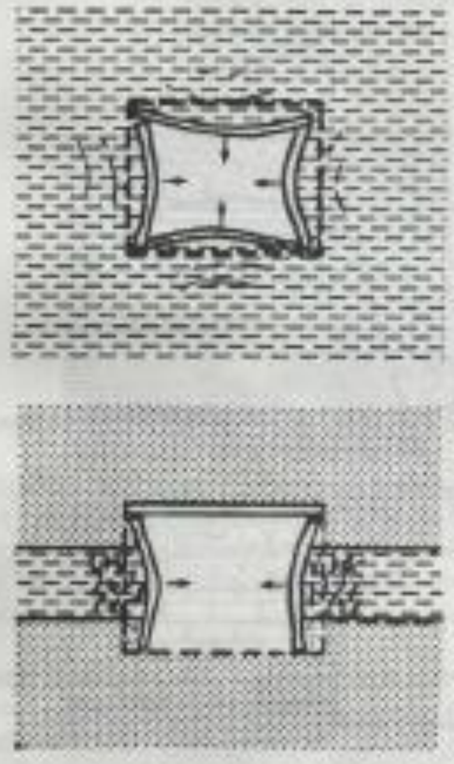


Floor heave is a commonly encountered phenomenon in tunnels especially in weak sedimentary strata. The following points frequently arise in floor heave situations:
1. Weak plastic floor beds are sensitive to stress change in addition to susceptibility to damage by support penetration and weakening by the action of water.
2. Extrusion into the tunnel excavation by a weak floor in the form of heaving is essentially representative of the line of least resistance.

Heaving ground surrounding a tunnel excavation causes general distortion of the support system and can frequently result in support damage at particular positions around the excavation. Additionally ground extrusion can occur around steel ribs (steel support girders which are commonly arch shaped).

- Effects of squeezing ground become evident immediately during excavation, with closure starting to take effect at the tunnel face.
- Swelling ground is slower to take effect.

- Plastic and semi-plastic rocks which are sensitive to deformation at relatively low stress levels are likely to exhibit squeezing behavior.
- Rocks which are rich in clay minerals not only have squeezing properties but are also have pronounced swelling properties e.g. fault gouge, mudstones, claystones and highly altered rocks of pyroclastic and micaceous types.



Heaving and swelling ground effects on rectangular tunnel profiles commonly result in significant bending of the roof and invert support girders in addition to inward deflection of the side support members. The general bowing of the girder supports can eventually result in becoming unstable especially when the joints become distorted, sheared or twisted during the deformation process.

Where a localised band within strata is sensitive to stress and/or water, then extrusion into the tunnel can induce localised damage to the support system. This form of localised extrusion can cause considerable disruption to the tunnel support system.

Figure 3.4 Aspects of squeezing and swelling ground behaviour in relation to tunnel excavations

•Some claystones disintegrate fairly quickly and increase their volume by more than 25%, generating a swelling pressure of up to 5.75 bar.

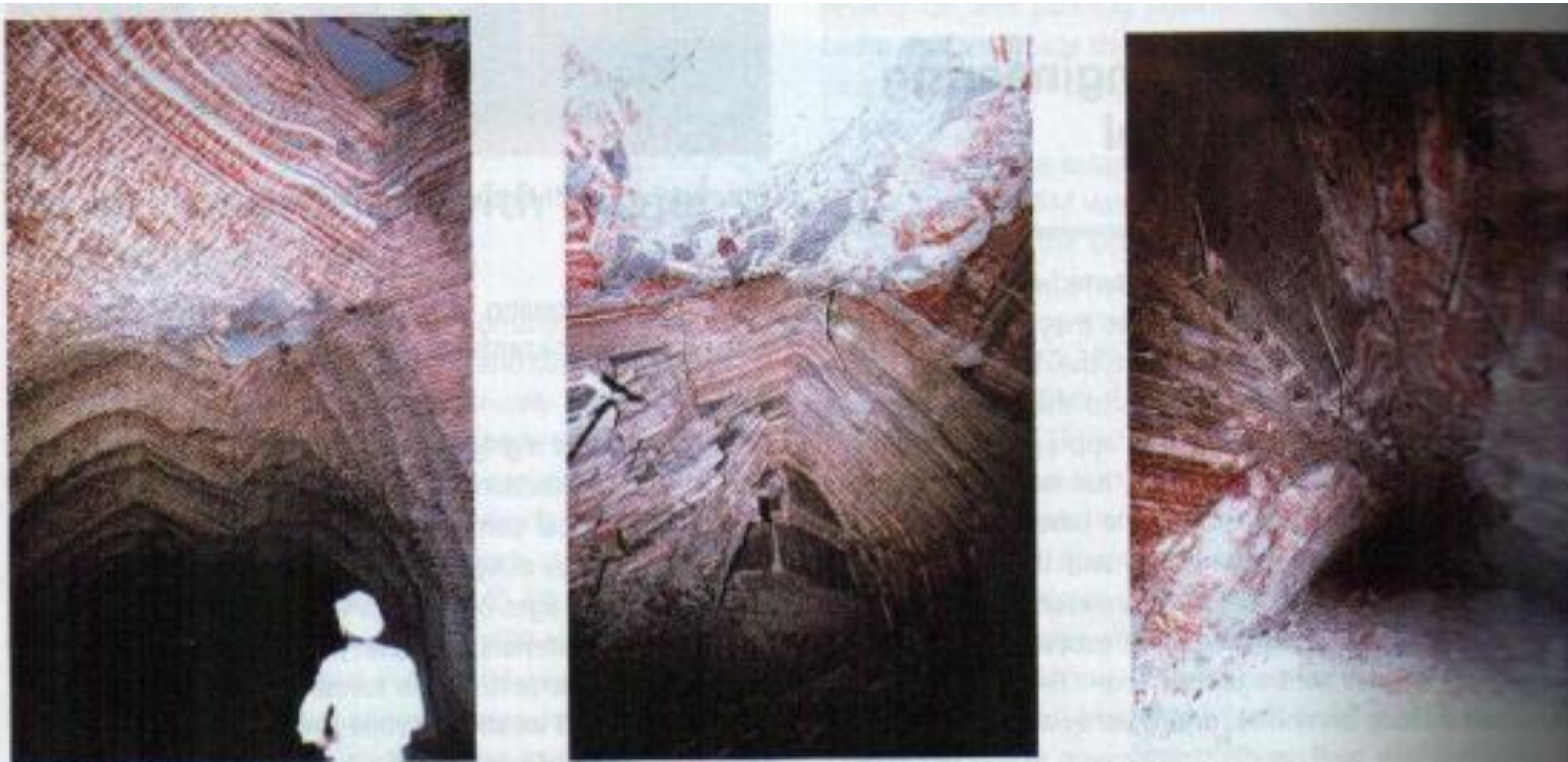
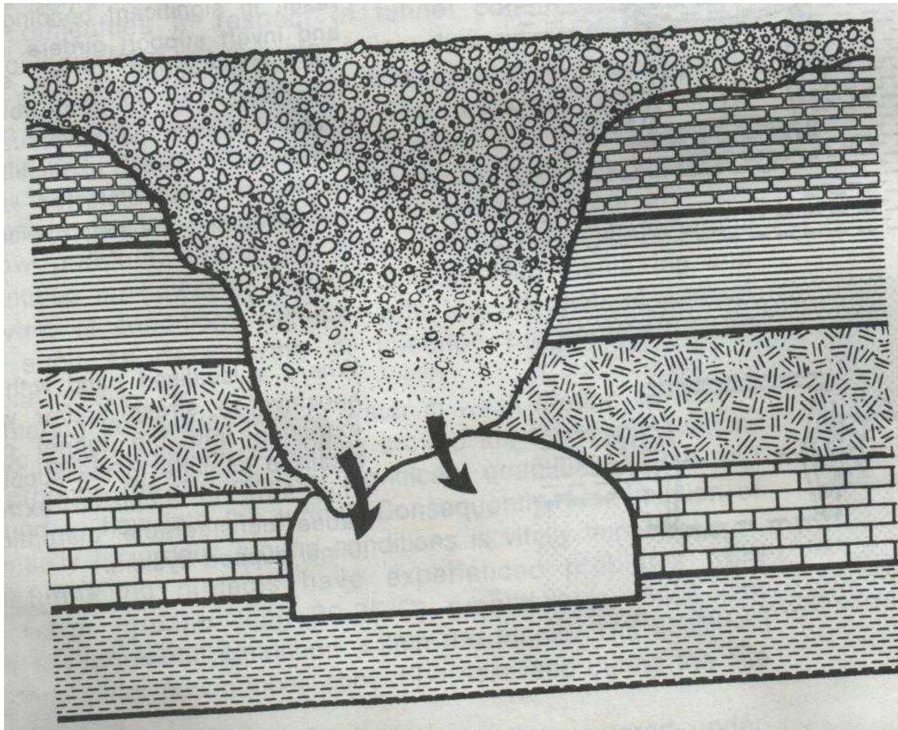


Figure 10.35 Large deformations in mudstones and rock salt: a) initial roof failure; b) large failures with high deformation the side walls; c) excavation is almost closed due to ground deformation and bolt support failure.

http://www.ifb.ethz.ch/pcbm/people/twangler/research

Running Ground

- Running ground (which has the ability to flow freely e.g. loose sand) requires special support.
- Running ground in relatively dry state can be encountered in arid/hot countries where tunnel excavations tap unconsolidated deposits lying close to the surface.
- Generally running ground is saturated with water and presence of water can encourage liquefaction when disturbed by tunnelling activities.



ure 3.5 Common form of inrush condition where a tunnel taps an ancient river bed consisting of unconsolidated materials and in a saturated state

•Progressive collapse and formation of cavities can tap major aquifers or overlying unconsolidated and saturated deposits (**chimney collapse**).

Stage 1: A major collapse of ground is shown to have occurred.

Stage 2: Temporary support has been erected to control ground falling into the tunnel excavation but as is shown here the collapse chimney is continuing to progress upwards; the collapse chimney would naturally become choked by virtue of the bulking properties of the broken ground but as is shown here the collapse chimney is likely to reach the overlying aquifer before becoming choked.

Stage 3: The condition shown here is that of the collapse chimney having reached the aquifer. This has resulted in the broken material within the chimney becoming saturated and possibly under a hydrostatic pressure head; consequently the increased pressure acting on the temporary support system gives rise to a potential inrush condition should the support fail.

Stage 4: In the event of an inrush occurring and the aquifer bed breaking down, the collapse chimney could progress through to the surface and cause the formation of a sinkhole.

An enormous sinkhole in Guatemala

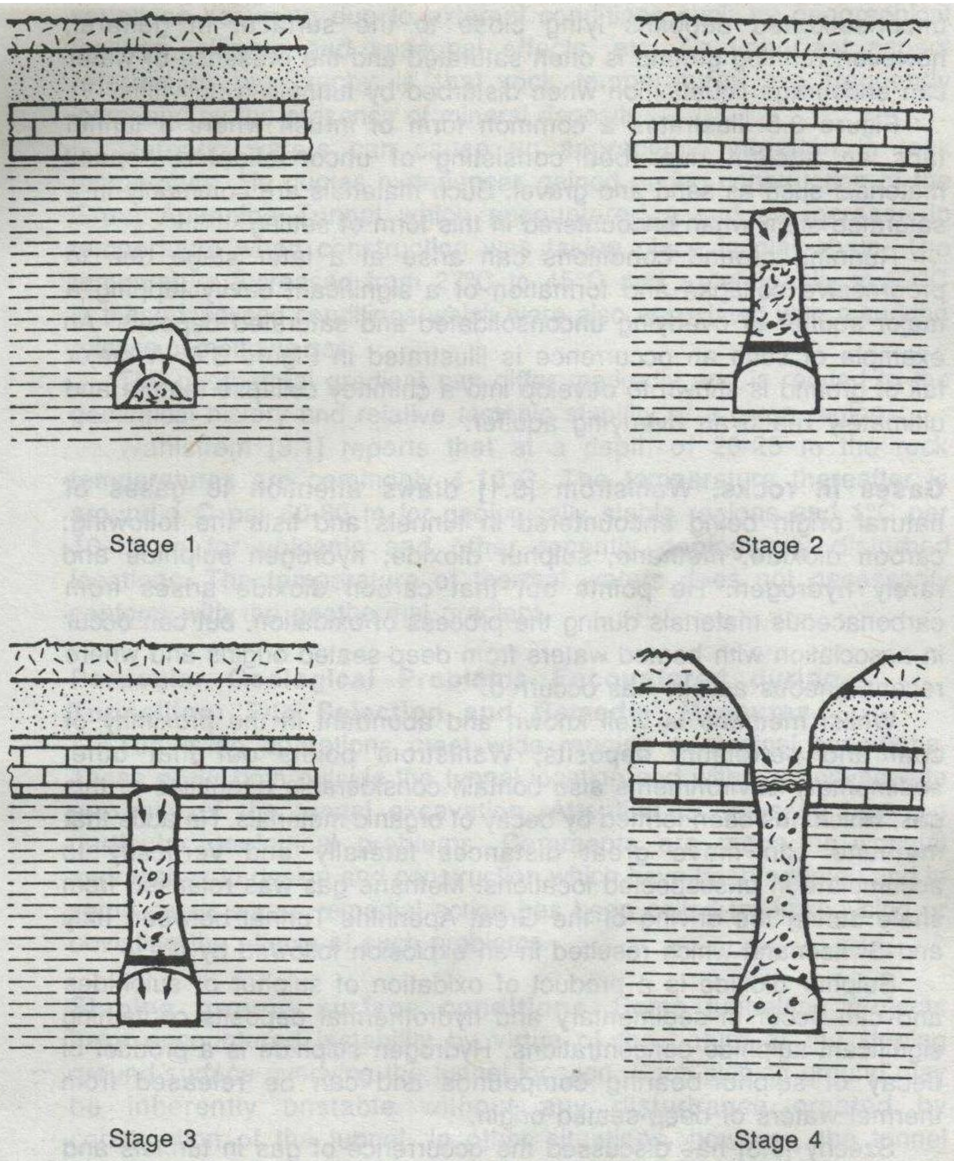


Figure 3.6 Effect of a progressive collapse tapping a significant aquifer and giving rise to a potential inrush and running ground conditions

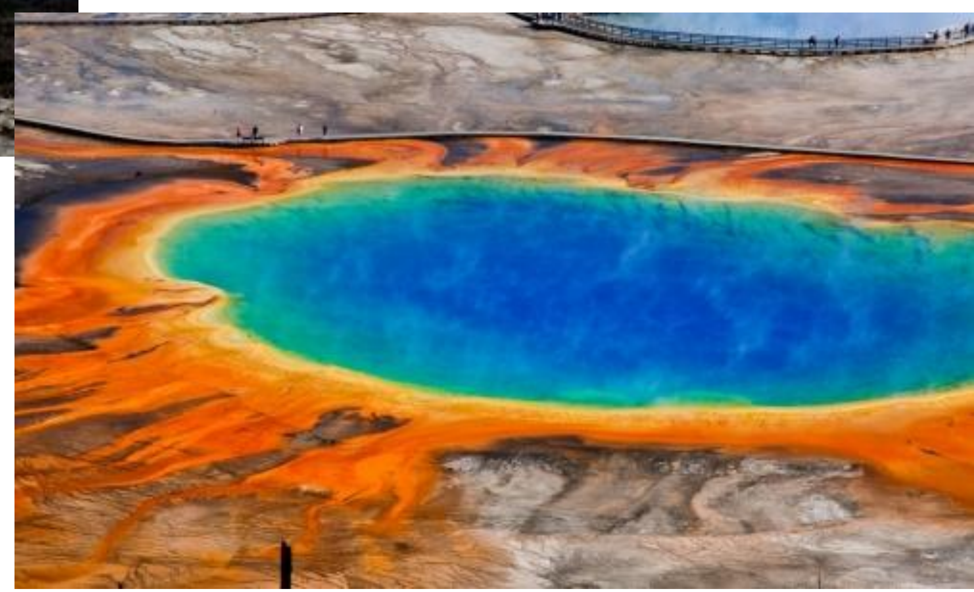
Gases in Rocks

- Gases such as CO_2, CH_4, SO_2, H_2S and H_2 can be encountered in tunnels.
- CO_2 arises from carbonaceous materials during the process of oxidation, but can occur in association with heated waters from deep-seated origins and close to recent igneous activity.
- CH_4 is found in the proximity of coal and petroleum deposits. Other sedimentary environments also contain considerable quantities of this gas formed by the decay of organic matter. Shale as a source of methane has reported in the case of Apennine Tunnel b/w Italy and Switzerland.
- SO_2 and H_2S can occur in sedimentary and hydrothermal deposits.
- Methane can be encountered in dolomite and limestone rocks where an impervious clay layer may result in migration laterally of this gas through fissures in adjacent rocks.

Rock Temperatures

- Could be very high in certain tunnels
- Simplon tunnel experienced water whose temperature was 56°C at 2134 m below the surface.
- Rocks and groundwaters gain heat from several sources such as: Earth's crustal heat and cooling igneous bodies, deep-seated transmission of heat to groundwaters, volcanic and radioactive emanations.
- Active thermal springs are useful indicators of any abnormally high temperatures.
- Meteoric waters (from precipitation) can cause an appreciable variation in rock temperatures.
- In Great Apennine Tunnel (clay-shale) temperature increased from 27°Cto 25°Cand exceptionally to 63°C.
- **At a depth of 20-25 m the rock temperatures are commonly 4-10°C. The temperature thereafter is around 1°C per 60-80 m for geologically stable regions and 1°C per 10-15 m for volcanic and other recently geologically disturbed locations.**

Some Geysers of Yellowstone National Park, Wyoming, USA.



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