From the research to ADECO-RS

There are no tunnels which are easy or difficult because of the overburden or the ground to be tunnelled, but only stress-strain situations in the ground in which it is, or is not possible to control the stability of the excavation, which will depend on our knowledge of the pre-existing natural equilibriums, on a correct approach to the design and on the availability of adequate means for excavation and stabilisation.

The dynamics of tunnel advance

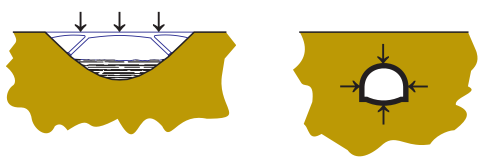
1.1 The basic concepts

Anyone who sets out to construct underground works, finds themselves having to tackle and solve a particularly complex civil engineering problem, because it is far more difficult to determine the basic design specifications for underground works in advance than it is for surface constructions (Fig. 1.1).

It is not, as with surface constructions, a question of gradually assembling materials (steel, reinforced concrete, etc.) with well known strength and deformation properties to build a structure which, when subject to predictable loads, finds its future equilibrium in the desired final configuration. On the contrary, one has to intervene in a pre-existing equilibrium and proceed in some way to a "planned disturbance" of it in conditions that are only known approximately.

Another peculiarity of underground works, well known to design and construction engineers, but not always given sufficient weight, is that very often, the stage at which the structure is subject to most stress is not the final stage, when the tunnel is finished and subject to external loads predicted at the design stage, but the intermediate construction stage. This is a very much more delicate moment because

DIFFERENCES BETWEEN THE DESIGN OF SURFACE AND UNDERGROUND WORKS



	SURFACE WORKS	UNDERGROUND WORKS
MEDIUM (construction material)	●	○
ACTION (loads on structures)	●	○
REACTION (response in term of stress and strain)	●	○

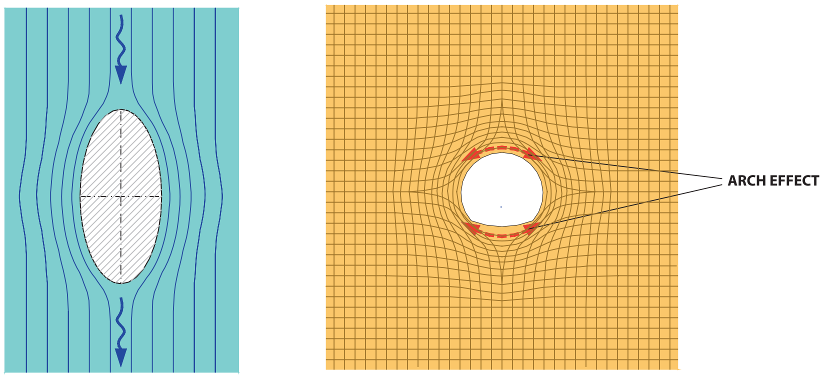
● Determined a priore ○ Not predetermined

Fig. 1.1

The arch effect

THE LINES OF FLOW IN THE CURRENT OF A RIVER AROUND THE PIER OF A BRIDGE

THE LINES OF FLOW IN THE STRESS FIELD OF THE GROUND AROUND A CAVITY



In a similar fashion to the lines of flow in the current of a river, which are deviated by the pier of a bridge and increase in speed as they run around it, the flow lines of the stress field in a rock mass are deviated by the opening of a cavity and are channelled around it to create a zone of increased stress around the walls of the excavation. The channelling of the flow of stresses around the cavity is termed an **arch effect**.
The arch effect ensures that the cavity is stable and will last over time.

THE FORMATION OF AN ARCH EFFECT IS SIGNALLED BY THE DEFORMATION RESPONSE OF THE ROCK MASS TO EXCAVATION

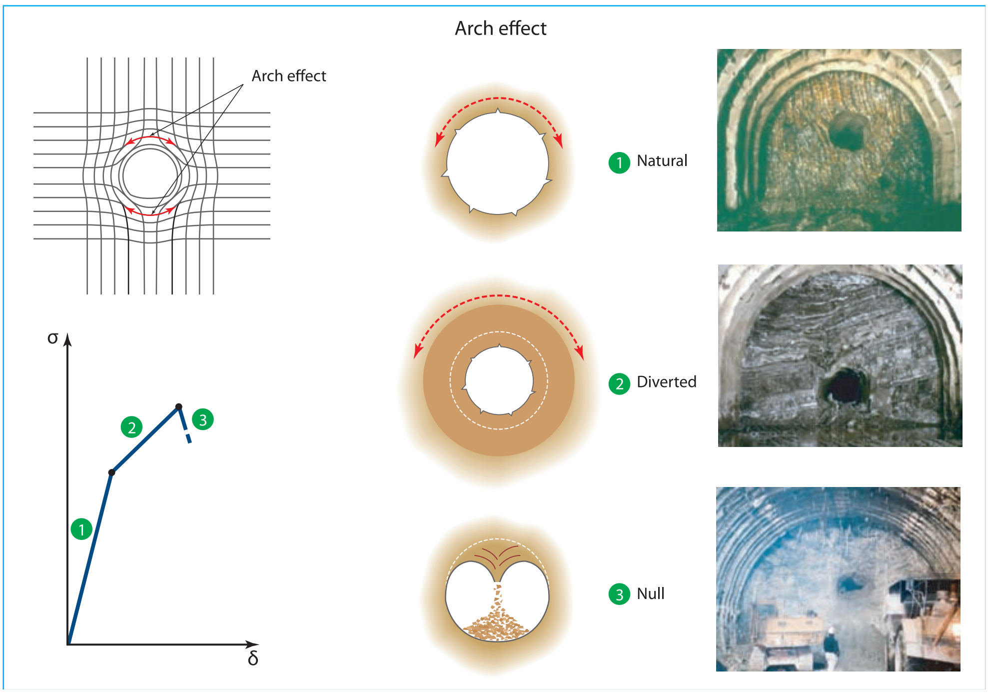


Fig. 1.2

the effects of the disturbance caused by excavation have not yet been completely confined by the final lining at this stage, when the pre-existing stresses in the rock mass are being deviated by the opening of the cavity and channelled around it (**arch effect**) to create zones of increased stress on the walls of the excavation.

The particular delicacy of this intermediate stage becomes clear if one considers that it is precisely on the correct channelling of stresses around the cavity that the integrity and life of a tunnel depends. Channelling can be produced, depending on the size of the stresses in play and the strength and deformation properties of the ground, as follows (Fig. 1.2):

1. close to the profile of the excavation;
2. far from the profile of the excavation;
3. not at all.

The first case occurs when the ground around the cavity withstands the deviated stress flow around the cavity well, responding elastically in terms of strength and deformation.

The second case occurs when the ground around the cavity is unable to withstand the deviated stress flow and responds anelastically, plasticising and deforming in proportion to the volume of ground involved in the plasticisation phenomenon. The latter, which often causes an increase in the volume of the ground affected, propagates radially and deviates the channelling of the stresses outwards into the rock mass until the triaxial stress state is compatible with the strength properties of the ground. In this situation, the arch effect is formed far from walls of the excavation and the ground around it, which has been disturbed, is only able to contribute to the final statics with its own residual strength and will give rise to deformation, which is often sufficient to compromise the safety of the excavation.

The third case occurs when the ground around the cavity is completely unable to withstand the deviated stress flow and responds in the failure range producing the collapse of the cavity.

It follows from this analysis of these three situations that:

- an arch effect only occurs *by natural means* in the first case;
- an arch effect by natural means is only produced effectively in the second case if the ground is “helped” with appropriate intervention to stabilise it;
- in the third case, since an arch effect cannot be produced naturally, it must be produced *by artificial means,* by acting appropriately on the ground before it is excavated.

The first and most important task of a tunnel design engineer is to determine if and how an arch effect can be triggered when a tunnel is excavated and then to ensure that it is formed by calibrating

The medium

If we simplify to the maximum, we can say that there are three main mediums in nature: sand, clay and rock, which have three different natural **consistencies**:

- the consistency of sand, which has its effect above all in terms of friction, giving rise to **loose** type behaviour;
- the consistency of clay, which has its effect above all in terms of cohesion, giving rise to **cohesive** type behaviour;
- the consistency of rock, which has its effect in terms of cohesion and friction, with markedly higher values than in the case of sand and clay giving rise to **rock** type behaviour.

It is the **natural consistency** of the medium which determines local differences in the earth's crust.

Morphology characteristic of the consistency of sand

Morphology characteristic of the consistency of clay

Morphology characteristic of the consistency of rock

In its natural state, the medium appears with the characteristics of its own type of consistency, however, when tackled underground, where it is subject to stresses which increase with depth, it has a consistency which varies as a function of the entity and anisotropy of the stress tensor (**acquired consistency**).
The manner in which the consistency of the medium varies as a function of its stress state is studied by means of triaxial tests on samples and is described by the intrinsic curve and stress-strain diagrams.

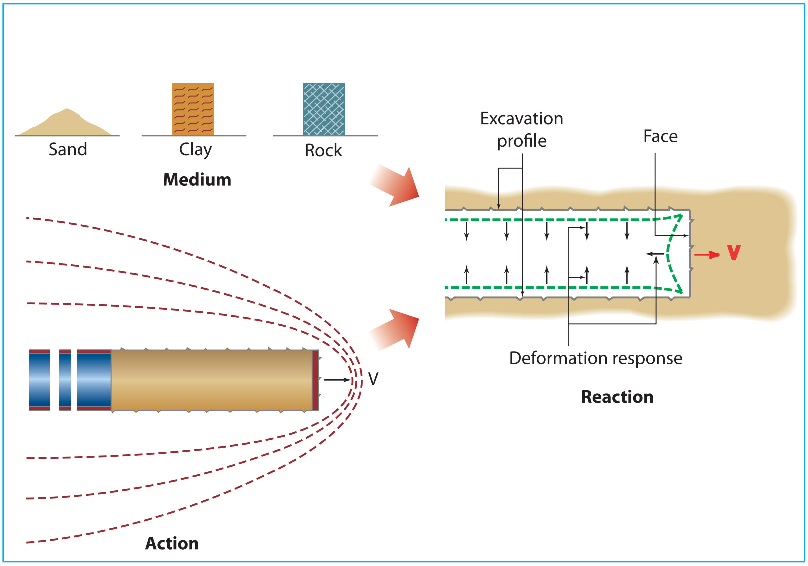


Fig. 1.3

excavation and stabilisation operations appropriately as a function of different stress-strain conditions.

To achieve this, a design engineer must have a knowledge of the following (Fig. 1.3):

- the *medium* in which operations take place;
- the *action* taken to excavate;
- the expected *reaction* to excavation.

1.2 The medium

The **medium**, and that is the ground, which is in practice the actual "construction material" of a tunnel, is extremely anomalous when compared to traditional materials used in civil engineering: it is discontinuous, unhomogeneous and anisotropic. *On the surface*, its characteris-

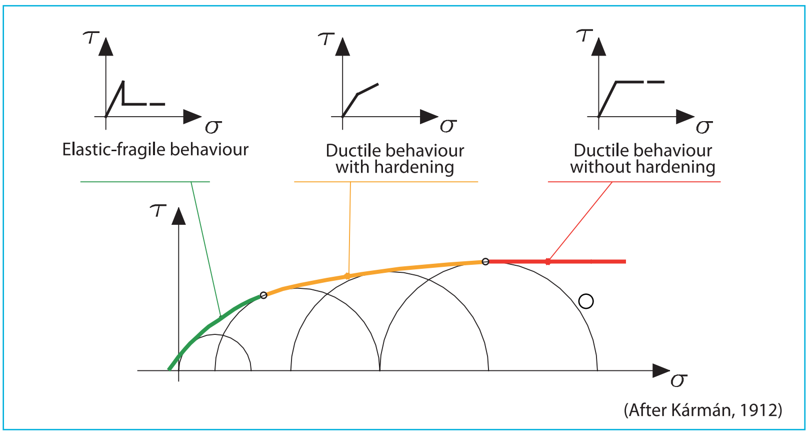
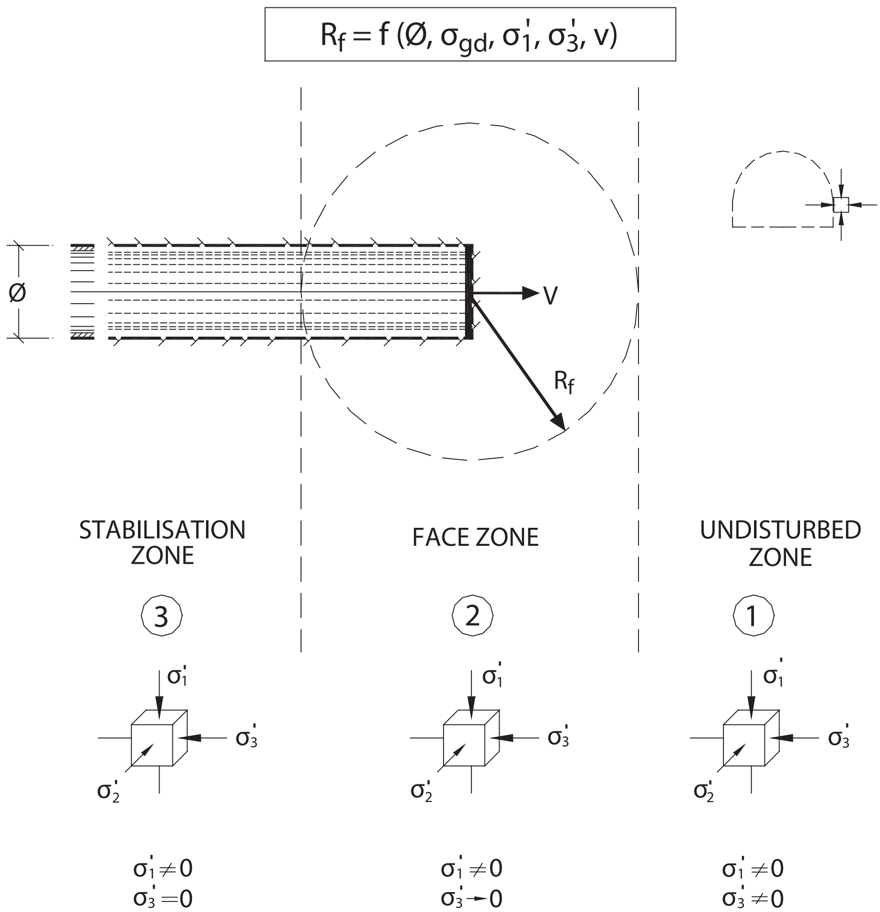


Fig. 1.4 *The same material can reach failure with different types of behaviour according to the stress range*

The characteristic zones



Three characteristic zones can be identified during tunnel advance in an unlined tunnel.

1. an undisturbed zone, where the rock mass is not yet affected by the passage of the face;
2. a tunnel face or transition zone, corresponding to the radius of influence of the face, in which its presence has a considerable effect;
3. a stabilisation zone, where the face no longer has any influence and the situation tends to stabilise (if possible).

It is important to observe that in passing from the undisturbed zone to the stabilisation zone, the medium passes from a triaxial to a plane stress state and that the face zone is where this transition takes place. Consequently, this is the most important zone for the design engineer. It is here that the action of excavation disturbs the medium and it is on this zone that all the attention of the design engineer must be focused for proper study of a tunnel. It is not possible to achieve this without employing three dimensional analysis approaches.

tics vary but this depends solely on its own intrinsic nature (natural consistency), which conditions the morphology of the earth's crust, *while at depth* its characteristics also change as a function of the stress states it is subject to (acquired consistency) and this conditions its response to excavation [1] (Fig. 1.4).

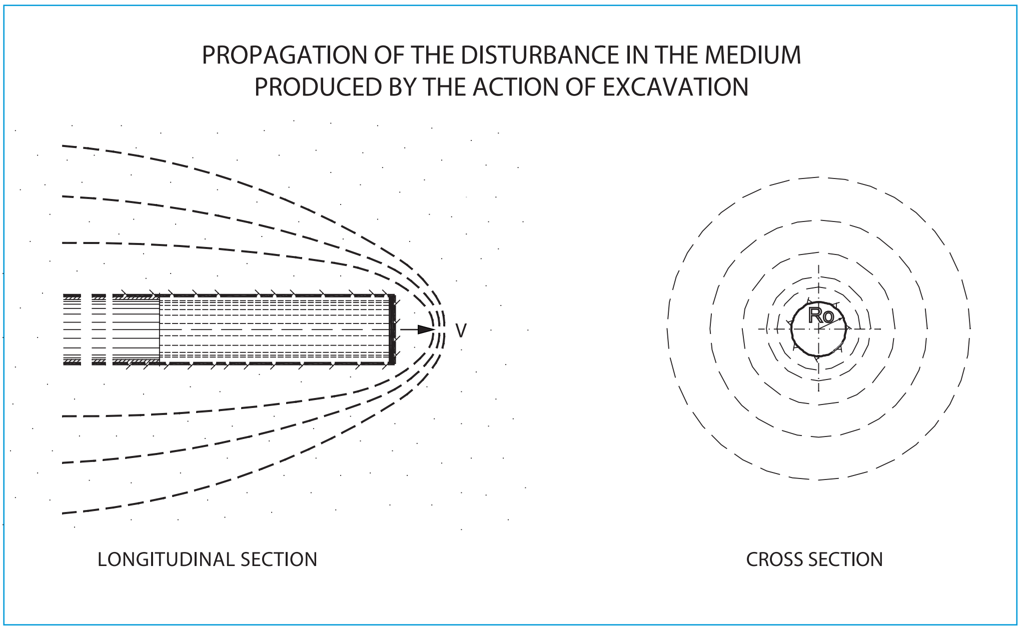
1.3 The action

The **action** is that whole set of operations performed to excavate the ground. It is seen in the advance of the face through the medium. It is therefore a *distinctly dynamic phenomenon*: the advance of a tunnel may be imagined as a disk (the face) that proceeds through the rock mass with a *velocity* **V**, leaving an empty space behind it. It produces a *disturbance in the medium*, both in a longitudinal and transverse direction, which upsets the original stress states (Fig. 1.5).

Within this disturbed zone, the *original field of stresses*, which can be described by a network of flow lines, *is deviated* by the presence of the excavation (Fig. 1.2) and concentrates in proximity to it, producing increased stress, or, to be more precise, an increase in the stress deviator. The size of this increase determines the amplitude of the disturbed zone for each medium (within which the ground suffers a loss of geomechanical properties with a possible consequent increase in volume) and, as a result, the behaviour of the cavity in relation to the strength of the rock mass σ_{gd}.

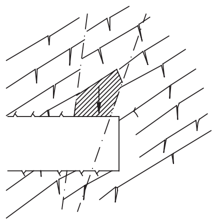
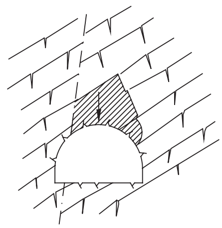
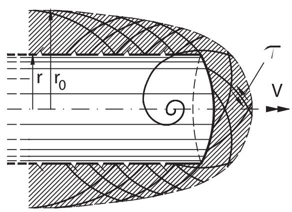
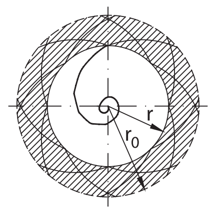
The size of the disturbed zone in proximity to the face is defined by the *radius of influence of the face* R_f, which identifies the area on which

Fig. 1.5



The type and the development of the deformation response (reaction)

The deformation response of the medium to excavation manifests in different forms depending on the range in which it occurs and these can be described with simple diagrams. For example:

a ***solid load*** response, primarily when the failure occurs in a medium generally subject to stress in the elastic range, which is localised and produced mainly as a result of gravity, when the strength of the medium is exceeded along pre-existing discontinuity surfaces;		
a ***plasticised ring or band response***, primarily when the failure is generated in the elasto-plastic range, which spreads around the excavation and is produced along helicoid surfaces that are generated inside the medium after it has plasticised.		

Let us now consider the three characteristic zones illustrated on page 8 and examine how the stress and deformation situation evolves in each of them.

1. **Undisturbed** zone characterised by:
   - natural stress field;
   - triaxial stress state at all points;
   - nil deformation.

2. **Face or transition zone** (corresponding to the radius of influence of the face Rf), characterised by:
   - disturbed stress field (variation in the stress state);
   - the stress state evolves from triaxial to biaxial (increase in the stress deviator);
   - increasing, immediate and negligible deformation if in the elastic range, deferred and large deformation if in the elasto-plastic range.

3. **Stabilisation zone** for deformation phenomena (if the design specifications implemented in the face zone were correct) characterised by:
   - equilibrium of the stress field restored;
   - biaxial stress state;
   - plane deformation state;
   - deformation phenomena at an end or ending.

Experimental measurements indicate that no less than 30% of the total convergence deformation produced in a given section of tunnel develops before the face arrives. It follows that the ground ahead of the face is the first to deform and that it is only after it has deformed that convergence of the cavity is produced. It also follows that the convergence measurements taken inside the tunnel only represent a part of the total deformation phenomenon that affects the medium.

the design engineer must focus his attention and within which the passage from a triaxial to a plane stress state occurs (the face or transition zone); proper study of a tunnel therefore requires three dimensional methods of calculation and not just plane methods.

1.4 The reaction

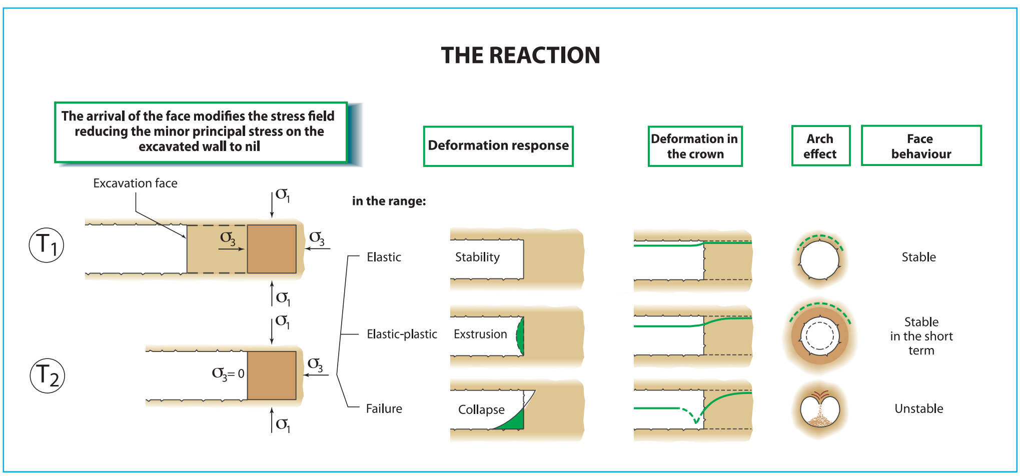
The **reaction** is the **deformation response** of the medium to the action of excavation. It is generated ahead of the face within the area that is disturbed, following the generation of greater stress in the medium around the cavity. It depends on the medium and its stress state (consistency) and on the way in which face advance is effected (action). It may determine the intrusion of material into the tunnel across the theoretical profile of the excavation. Intrusion is frequently synonymous with instability of the tunnel walls.

Three basic situations may arise (Fig. 1.6).

If on passing from a triaxial to a plane stress state during tunnel advance, the progressive decrease in the confinement pressure at the face ($\sigma_3 = 0$) produces stress in the elastic range ahead of the face, then the wall that is freed by excavation (the face) remains *stable* with *limited and absolutely negligible deformation*. In this case the channelling of stresses around the cavity (an "arch effect") is produced by natural means close to the profile of the excavation.

If, on the other hand, the progressive decrease in the stress state at the face ($\sigma_3 = 0$) produces stress in the elasto-plastic range in the ground ahead of the face, then *the reaction is also important* and the wall that is freed by excavation, the face, will deform in an elasto-plastic manner towards the interior of the cavity and give rise to a condition of *short term stability*. This means that in the absence of intervention, plasticisation is triggered, which by propagating radially and

Fig. 1.6



The three fundamental situations of stability

The behaviour of the medium at the face as a result of being ‘deconfined’ depends above all on its acquired consistency.

If the ***consistency*** is that ***of rock*** then rock type behaviour and therefore a stable face situation results.

If the ***consistency*** is that ***of clay*** (cohesive type behaviour), the face and the perimeter of the cavity deforms plastically intruding into the tunnel giving rise to a stable face in the short term situation.

If the ***consistency*** is that ***of sand*** (loose type behaviour) an unstable face situation results.

As we will see, the stability of the face plays a very decisive role in regulating and controlling deformation phenomena and therefore also for the short and long term stability of an underground construction.
It is in the face (or transition) zone that the design engineer must intervene to regulate and control the deformation response.

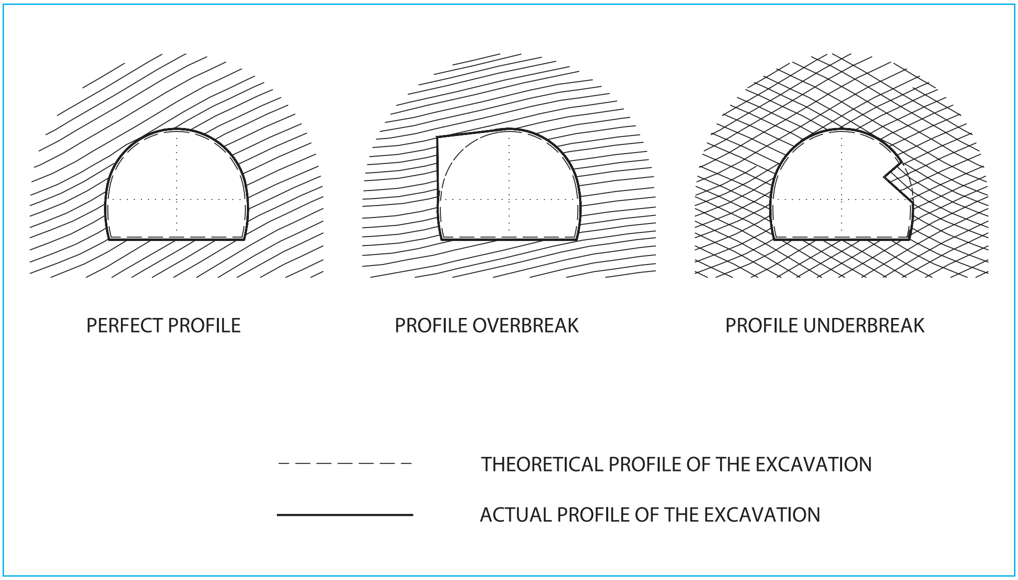


Fig. 1.7

longitudinally from the walls of the excavation, produces a shift of the "arch effect" away from the tunnel further into the rock mass. This movement away from the theoretical profile of the tunnel can only be controlled by intervention to stabilise the ground.

If, finally, the progressive decrease in the confinement pressure at the face ($\sigma_3 = 0$) produces stress in the failure range in the ground ahead of the face, then the *deformation response is unacceptable* and a condition of *instability* exists in the ground ahead of the face, which makes the formation of an "arch effect" impossible: this occurs in non cohesive or loose ground and an "arch effect" must be produced in it artificially since it cannot occur by natural means.

It therefore follows that it is important from a statics viewpoint to avoid over-break and to keep to the theoretical profile of the tunnel, especially in fractured and stratified rock masses. Accidental over-break, caused mostly by the geological structure of the ground, helps to shift the arch effect away from the walls of the cavity and this decreases the stability of a tunnel (Fig. 1.7).

However, the most important conclusion to be drawn is that the formation of an arch effect and its position with respect to the cavity (on which we know that the long and short term stability of a tunnel depend) are signalled by the quality and the size of the "deformation response" of the medium to the action of excavation.

The next chapter illustrates the evidence accumulated over the last twenty five years from research study on the relationships between changes in the stress state in the medium induced by tunnel advance and the consequent deformation response of the tunnel.

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