

The Control of Ground Response - Milestones up to the 1960s

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ABSTRACT

The first major step in controlling ground response by means other than timbering was the invention of the shield technique at the beginning of the 19th century. The full development of the conventional method of tunnelling today, namely the "SCL method", did not appear until the mid-1950s. Its scientific roots go back to the 19th century, but rock bolts and shotcrete were first applied in the 1910s. The paper traces the fascinating story of the developments in rock bolting and shotcreting and sheds light on their relation to the so-called NATM.

1. INTRODUCTION

By the term "ground response" we understand the way in which the rock responds to the creation of an opening, i.e. the excavation and the ground support. It was always the central problem of tunnelling: how to influence the "ground response", so that during execution the safety of the opening is guaranteed as well as its long-term functionality. The realisation of this task we call "control of ground response". It includes both planning and technical aspects in the execution, and it must always take economic considerations into account.

Since its beginning tunnel engineering has endeavoured to understand the processes taking place in the ground during the excavation of an opening and to predict the expected ground behaviour, clarification of which is closely related to the influence of a number of factors. The most important are the nature of the ground, the method of excavation (sequence of excavation in the cross-section and in the direction of the tunnel axis), as well as the method, the place and the extent of the support measures employed.

The beginning of tunnel engineering can be seen in the 1.1 km long Tronquoy Tunnel of the channel of St. Quentin in France, built in 1803. The tunnel with, for that time, an unusually large width of 8 m passed through "sandy, i.e. squeezing rock" (Willmann 1920; Sandström 1963). From Fig. 1 it is clear how, with the aid of a number of individual small adits, the arch was constructed from the bottom to the top, allowing the core to be removed subsequently under its protection. Thus this tunnel is regarded as the first to be built on engineering principles, since here, for the first time, a large area of excavation in difficult ground conditions was realised. It is at the same time a good example of the practical side of the "control of ground response". One tube of the Straight Creek (Eisenhower) Tunnel in Colorado (USA)

was constructed on the same principle 170 years later (Hopper et al 1972). The historical development of the “control of ground response” can be traced separately from the technological and scientific standpoints; the interaction and the mutual fertilisation of technological and scientific ideas has, at the same time, always to be kept in view. Engineers, who have worked on new technological developments or who in their practical application have performed pioneering work, were also always interested in scientific questions. As a rule, therefore, it was engineering practice that gave the impetus to achieving new theoretical insights.

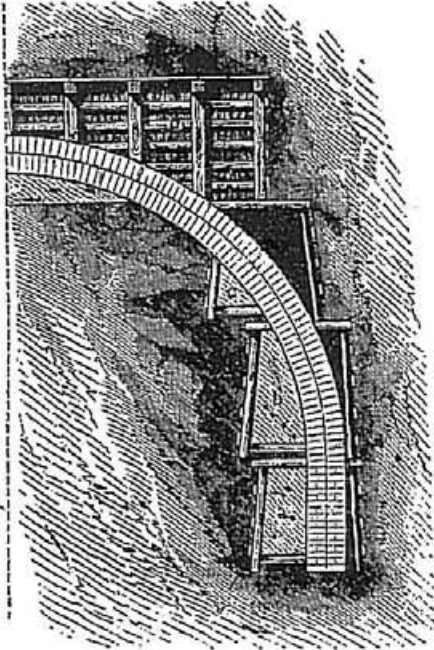


Figure 1: Tronquoy Tunnel of the channel of St. Quentin in France, 1803 (Sandström 1963)

At the beginning of the 19th century only timbering was available as a means of temporary support. Tunnels were usually driven using multiple heading methods, and the excavation often could only be stabilised at great expenditure in terms of labour – in soils even requiring the breasting of the face. If 150 years later we cast a look at tunnelling methods, we find instead of timbering either the shield method with the installation of lining segments, a steel lining or the “sprayed concrete lining” (SCL) method. Thus, the technology of tunnelling between 1800 and 1960 has basically changed. How did this development come about? Whereas the history of the development of the shield technique is well described in the literature, the milestones in the evolution of the individual support techniques, i.e. steel support, shotcrete and rock bolting; generally speaking, the history of the SCL method, has not yet been given proper attention.

As to the shield technique, we confine ourselves here to the basic facts. It was invented by M.I. Brunel, who applied it in 1825 with a rectangular form for the under tunnelling of the Thames River in London. The shield of cylindrical form with the placement of

cast iron segments, originates from a patent of P. W. Barlow, who applied it first in 1869 for the second Thames Tunnel (Tower Hill Tunnel), the method being notably improved by the supervising engineer J.H. Greathed. Therefore, the underlying problems of the open shield were solved by a few eminent engineers within a few decades in England. In contrast, the conventional tunnelling approach only progressed slowly and not steadily: Progress was made in stages and sometimes isolated, confined to a few countries. Only since the end of the 1940s can an acceleration in the development and a more intensive international exchange of scientific knowledge and experience be observed. Over a period of about 15 years this has finally led to the method of tunnelling which today is called the “SCL method”.

In the course of its history the biggest impulses in tunnelling were first given by the construction of the railways, whose beginnings go back to the 1830s and 1850s. The word “tunnel” itself was coined in England, the pioneer in railway construction: It originates from the old French “tonnel” for “tonne arch”, “barrel” (designated “tonnelle” in modern French). In the Alps, with the bordering countries Austria, France, Germany, Italy and Switzerland, already in the middle of the 19th century the need arose for longer, deeper railway tunnels. One thinks for example of the great alpine tunnels Mt. Cenis in Italy, St. Gotthard and Simplon in Switzerland and Arlberg in Austria.

In the first decades of the 20th century the era of water power began, with new hydroelectric power stations, which beside pressure tunnels also demanded new types of underground

structures like power houses and inclined shafts. Except for disruptions due to the wars, this activity stretched up to the 1990s, but from the end of the 1940s it experienced a big upturn not only in the alpine regions, but world-wide, especially in the Scandinavian countries, the USA and Australia. The construction of hydraulic structures flourished in the 1950s and 1960s, a period in which intensive activities in the construction of the motorways began. Finally, since the 19th century there was also constant growth in production mining so that this triggered new developments, which were also decisive for tunnel engineering. The two most important points of contact between mining and tunnelling concern research on the rock pressure phenomenon and the development of economic methods of rock support. Different needs were already common at the start of tunnel engineering, namely the necessity of having bigger excavation profiles first for canal tunnels and a little later for railway tunnels, as well as for the special design of the permanent tunnel lining. In the following historical considerations, as far as possible we want to delve down to the deepest roots of the development and to highlight pioneer achievements both in scientific and practical terms. By extensive quotation we let the persons of the time speak to better realize the road along which science and technology proceeded.

2. THE SCIENTIFIC DEVELOPMENT

An accurate assessment of ground behaviour during excavation and the construction of the lining as well as during the service life of tunnels was already of practical importance in the construction of the first railway tunnels. Those involved took into consideration ground failure, collapse of the timber work or over-break because of poor estimates of ground behaviour or geological "surprises". The site engineers were therefore the first to consider the question of the stability of the underground opening and with the need for timber supports and the loading they were to carry. When studying handbooks of that period and articles in the engineering journals, one notices that to answer this question, they turned from the very beginning to the methods of the natural sciences. It was clear that one had to research the causes of observed effects. At first, however, one had to be content with qualitative explanations. Already M.J. Brunel, in the development of his rectangular-shaped shield, was prompted by certain theoretical considerations: The essential point of his discovery he sees in his

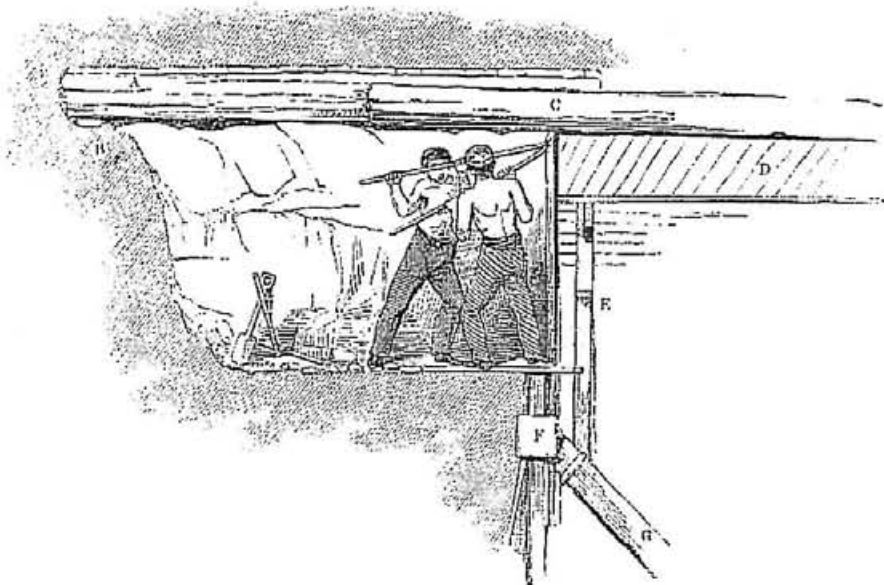


Figure 2: Drawing the crown bars in the top heading of the Blechninglay Tunnel (Simms 1844)

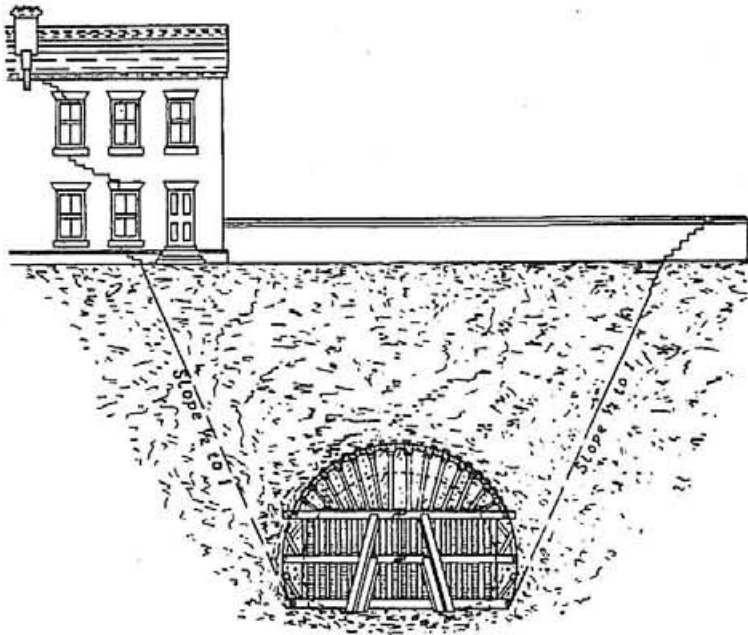


Figure 3: Explanation of the damage caused by tunnelling near surface in the Widening Tunnel, Metropolitan Railway, London 1865-1867 (West 1988)

patent (1818), “never to remove more earth than can be immediately replaced by the tunnel, so that the surrounding earth is always kept in the state of its natural strength and density” (Schlick 1827).

The period between about 1830 – 1860 was decisive for the development of differentiated concepts and technical terms. For this purpose they also used the then current expressions from the fields of engineering science (including geotechnical engineering) and mining.

One major step to be noted is that up to the middle of the 19th century the most important forms of “ground response” were clearly defined. Thus they differentiated clearly between “loosening” rock pressure in the roof, “swelling” and “squeezing”. In the construction of near-surface tunnels one was familiar very early with the phenomenon of surface settlements (Fig. 3). Accurate hypotheses regarding the mechanisms underlying these phenomena were also postulated. It was only the problem of genuine rock pressure which had to wait until 1910 for a solution.

Possibly the first publication on observations of rock behaviour in tunnelling and on considerations of its possible causes stems from the Englishman, F. W. Simms. In his book from the year 1844 (the very first textbook on tunnelling) he reports, among other things, on his experiences in excavating the 1.2 km long Blechinglay railway tunnel, the construction of which was begun in August 1840. The ground conditions encountered he describes very precisely as follows:

“The Blue Clay of the Weald in which I was working was at first greasy to the touch; and when dry, and in situ, formed a hard shale, requiring an extensive use of gunpowder in its excavation, but upon exposure to damp and atmospheric action, it swelled considerably and then slaked; this obliged me to close-pole the face of the work in all directions as far down as the lower sill, and frequently to the bottom. The expansion, or swelling, was occasionally so great as to threaten the hurling in of the lengths after they were completely timbered, and would probably have done so but for constant watchfulness, and strong timbers properly applied. The pressure upon the work was sometimes so great that sound oak bars, fourteen or fifteen

inches in diameter, were cracked and broken as if they had been mere sticks. The pressure we had to contend with was variable, and uncertain in the highest degree. (...) The greatest pressure (which mostly acted upon the crown) took place towards the ends of the Tunnel, where the surface was so much nearer to the arch."

Simms is confronted with the influence of water on claystone rock: slaking, swelling and the development of rock pressure. A measure for the pressure (which he recognised to be variable and uncertain) is the failure of the timbering. The importance of a constant watchfulness as to the behaviour of the tunnel is emphasized. His explanation of the higher pressure at smaller overburden depths is remarkable:

"The greater pressure upon the work in shallow ground over that where the tunnel is very deep below the surface, I can explain only upon the supposition that, in the former case, the whole superincumbent mass is acting perpendicularly downwards; whilst, in the latter case, a small portion only gets into motion, the upper part acting as a key, (if I may so express myself) by which the mass supports itself. This action was clearly shown in pit No. 11, where the working below could be distinctly traced upon the surface of the ground, by its sinking in the form of a basin as our work proceeded, and at the same time cracking into large fissures."

Here, for the first time, the hypothesis is expressed, that the rock pressure is triggered by a movement of the rock above the roof. Where the masses remain at rest, *"the mass supports itself"*. This latter formulation, reveals his insight, that ground has the character of a structure. In this respect Simms clearly states that:

"It is the general movement of the mass in adjusting itself to equilibrium, after the disturbance occasioned by the excavation, that causes the weight, and whose searching influence finds out the weak points in the work."

Thus, very early, today's mechanics-based idea was given expression, according to which the excavation results in a disturbance of the equilibrium. As site engineer he devised an appropriate practical rule, which points to the tight connection between the lining and the rock:

"It must here be again impressed upon the practical man, the necessity of always keeping the work tight against the earth, to prevent the possibility of its moving; and it should be an invariable rule, never to leave a vacuity behind the work."

In another place he says:

"The only thing necessary to guard against is the first displacement of the strata; which can generally be prevented with very slight timbering, judiciously placed; if this is not watched, and done in time, a slip of the rock will frequently bring in so much as to leave a great cavern, which must be filled solid behind the work to make it secure from future danger:" (...) *"the danger of leaving an empty space above the arch is too obvious to need any remarks."*

Finally, we would like to point out a fundamental aspect of tunnelling, which was already mentioned in this pioneering work:

"The extensive use of timber is to be avoided as much as possible ..."

Furthermore, we see that in the call for tenders for the Islington Tunnels in 1812 (addressed to Architects and Engineers) there is the following statement: the owner *"was anxious to have the best information which science and practice can afford on the subject."* Thus, tunnel engineering from its very beginnings lays claim to being a scientific discipline.

We have quoted from Simms so extensively because, with his explanations, the beginning of our scientific knowledge in tunnelling is marked. The conscientiousness in his observations and his attempts at explaining the phenomena will always remain exemplary.

Computational models

As early as in the second half of the 19th century the first attempts were undertaken to calculate the loading on the timber work and the permanent lining. All computational models had one thing in common, namely that they only consider the processes in the immediate vicinity of the opening and were either based on assumed failure mechanisms or on the effectiveness of simple structural support mechanisms in the ground (Fig. 4). Simplifying assump-

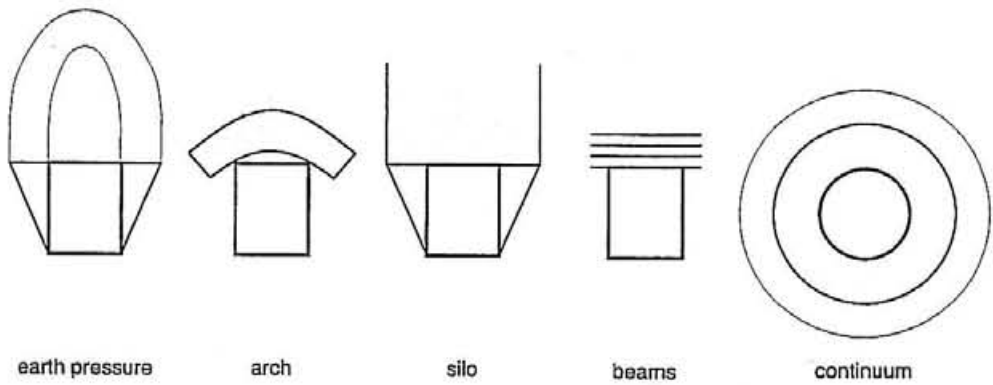
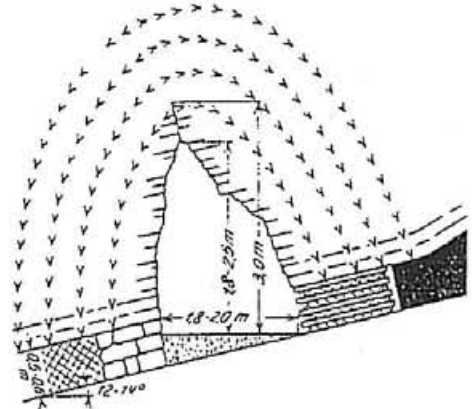
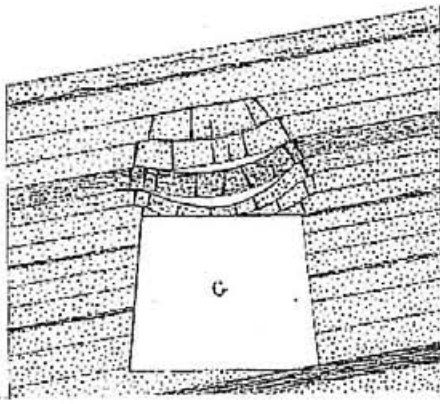


Figure 4: Computational models up to the 1920s

tions were also made with regard to the material. For cohesionless ground Culmann (1866) proposed a method based on the well-known earth pressure theory. Ritter (1879) modified this model, by postulating the formation of a stable, natural dome over the tunnel and considered the weight of the mass of material underneath as a vertical loading. He determined the horizontal pressure in a similar way to Culmann, using earth pressure theory. Ritter's theory found its way into standard books on tunnelling. For example Drinker (1888) says: "When we make an opening in an undefined and homogeneous mass, the particles of which are kept from sliding over each other by the resistance offered by cohesion attrition, in the abstract it is always possible to find for the top of such an opening a curve of equilibrium which would be the curve of a natural cavern". Engesser (1882) was the first who tried to explain the support effect in cohesionless ground by the formation of a "ground arch" above the opening. For him the loading was given by the weight of the mass enclosed between the ground arch and the lining. Janssen (1895) proposed a silo effect of the cohesionless materials above the roof. Fayol (1885) investigated a layered rock and tried to explain the processes in the rock by the structural action of a stack of beams. Early illustrations for mechanisms in the ground are shown in Fig. 5. All these models contain key ideas, which were applicable under certain conditions and therefore were also useful. These models also assume, in common, that rock deformation occurs (displacements in the direction of the opening). With the exception of the silo theory, the models lead to the conclusion that with increasing roof settlement the rock pressure increases. Thus they provided a theoretical justification of the earlier statements and suppositions of Simms. Building upon these basic ideas, numerous variants were developed later (Komerell 1912, Bierbaumer 1913), which will not be dealt with further here.

It was already clear at that time that those computational methods were in contradiction with each other and also with observations. In other words: they contained severe shortcomings. Questions concerning the influence of the depth of the tunnel on the rock pressure, the development of pressure on the invert arch and the phenomena of squeezing remained unanswered. One of the reasons for the bottom heave in tunnels and the pressure on the invert could at least qualitatively be explained at an early stage by the swelling in clay and anhydrite due to water. However, no explanation could be found for the squeezing phenomena. In the following, we would like to discuss the development of the understanding of one of the theoretically most complex problems in tunnelling.

The first theoretical works to explain the phenomenon of squeezing rock are closely related to the construction of the approximately 20 km long Simplon Tunnel, which has a maximum depth of overburden of 2100 m. The Simplon Tunnel I was constructed in the period from 1898 until 1906, and Simplon Tunnel II between 1912 and 1921. The long construction time for the second tunnel was due to the events of war. The alpine geologist Heim warned in an article (1878) that was much acclaimed by professional colleagues at the time, that in his opinion insuperable difficulties would be encountered when tunnelling at great depth. He maintained that "for each rock one needed to envisage a column so high that its weight



a. Failure mechanism in the roof of layered rock (Fayol 1885)
 b. Visualization of a natural ground arch above an overbreak (Lüthgen 1929)

would exceed the strength of the rock, and therefore the foot of the column would be crushed. Depending on the strength of the rock this column would be higher or lower, but the envisaged conditions would always occur." Under "strength" Heim understood the uniaxial strength of the rock. He believed that upon reaching this strength, "hydrostatic conditions" would dominate, and he coined the term "latent plasticity". Further, he assumed that "the internal friction would be so reduced under the all round pressure that a stress redistribution would occur without cleavage and the rock begin to flow, just like ice flows in a glacier. The material would try to flow into the tunnel opening". From this he concluded that beyond a certain critical depth, depending on the type of rock, the tunnel construction work would become impossible to control technically. It was Wiesmann (1912), one of the chief supervising engineers on the construction of the Simplon Tunnel, who discovered the error in Heim's reasoning. Firstly, for the behaviour of the rock surrounding the tunnel, it is not the uniaxial but the triaxial compressive strength that applies: "The bearing capacity of enclosed bodies, this is the governing rock strength". He could already consult the results of the von Kármán's (1911) triaxial tests on marble from the year 1905. Secondly, the behaviour of a rock in a plastic state cannot be compared to that of a fluid. In a viscous (Newtonian) fluid it is only a question of time until a hydrostatic stress state develops. Due to internal (Coulomb) friction, however, rocks behave quite differently: After the creep and relaxation processes fade away, there remains, due to the cohesion and internal friction, a deviatoric component of stress state, which allows a difference in principal stresses – for axisymmetrical conditions between the radial and tangential stresses – in the rock surrounding a tunnel. As one of the first, Wiesmann recognised the significance of the stress redistribution in the vicinity of an underground opening (Fig. 6a) as well as the influence of the failure state on the stress redistribution, in that he called the zone of rock affected by stress redistribution a "protective zone". Wiesmann argued in a qualitative way basing his considerations on experience known to him of tunnelling in squeezing rock, on the findings from triaxial tests and on the stress conditions in an elastic plate containing a hole under in-plane loading. He recognised and also gave clear reasons for the relationship between rock pressure and deformation: "With each fraction of a millimetre with which the rock mass moves, the amount of pressure acting (on a lining) decreases".

The first computational model for describing the stress redistribution in a plate with a hole in it, taking into account a failure criterion, comes from the bridge engineer Maillart (1923), who in 1923 considered the idea of a "protective zone" to be outdated. In fact, this represents a considerable scientific advance, to speak of separate plastic and elastic regions, whereby the rock mass is stressed to the limit of its triaxial strength or where this is no longer the case. From Maillart we also get the pregnant formulation "If we construct a tunnel lining so as to withstand the external rock pressure acting on it, the strength of the rock mass is

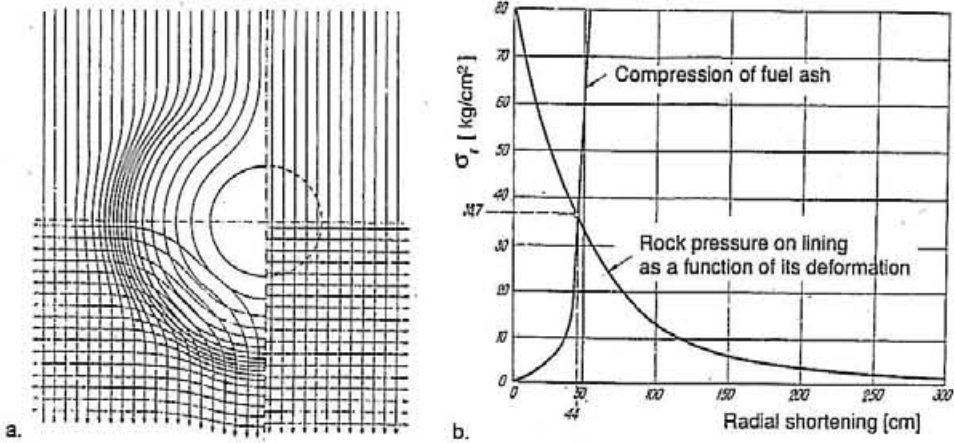


Figure 6: a. Visualisation of the state of stress prior and after the excavation of a deep tunnel (Wiesmann 1912)
 b. The first representation of the ground response curve and lining characteristics (Mohr 1957)

increased, thus enabling it to support itself." Mohr (1957) has shown later how the interaction between squeezing ground and the lining can be determined using the characteristic line (ground response curve) and the lining characteristics (Fig. 6b). The subsequent, internationally well established theoretical developments led to the so-called "characteristic line method", which permits quantitative assessment of the rock pressure. Under characteristic line one understands the functional relationship between the radial displacement at the edge of a hole and the resisting force acting there. Thus, the characteristic line is limited purely theoretically to the axisymmetric conditions: this applies both to the cross-sectional shape (circle) and to the material properties (homogeneity, isotropy), the primary state of stress (hydrostatic condition) and the lining resistance. In a lecture held in 1956 Mohr stated that "the forces acting on a lining will be smaller if the rock mass is allowed to deform a little. The practical use of this knowledge requires that the rock mass should only be supported to the extent that it becomes able to support itself."

Observations and measurements

Since in the solution of their problems tunnelling engineers feel obliged, as far as possible, to adopt the methods of the natural sciences, it is not surprising that they laid much emphasis on observations and measurements. Very early on, systematic deformation measurements were carried out in tunnels. From the behaviour of the timbering they became aware of the development of rock pressure. As an example, we refer to a publication of Wiesmann in 1920 (Fig. 7a). Since the 1920s in situ measurements had become important in the construction of pressure tunnels. Measurements in test tunnels had also often been performed. The first report on an "experimental tunnel" that we have found in the literature is one that concerns the New Croton Aqueduct under the Harlem river in New York (Proctor & White, Terzaghi 1946). By the 1950s the engineer had at his disposal a number of measuring techniques for the observation of rock deformations and rock pressure. Mining also supplied important contributions. We refer here to the corresponding chapters in the standard works on tunnelling, as well as hundreds of articles in technical journals (Fig. 7b). Our listing of scientific developments would be incomplete, if the numerous laboratory model tests to clarify the mechanisms of ground deformations around underground openings were not mentioned. Here we mention, among others, the early work of Fayol (1885) on the behaviour of layered rocks and the tests of Engesser (1882).

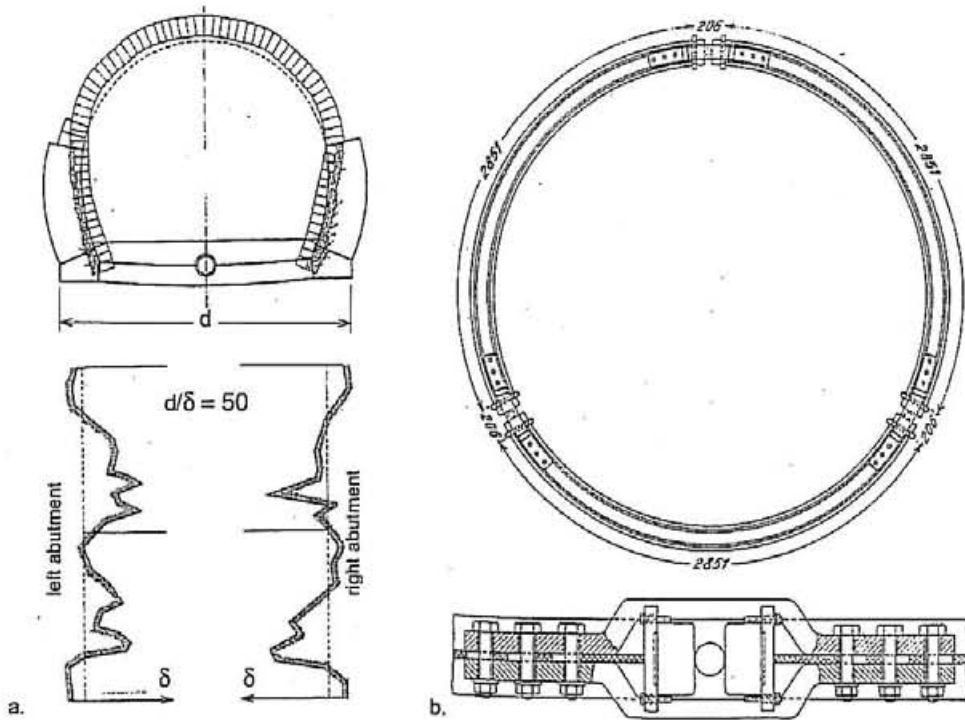


Figure 7: a. Convergence measurements to check the necessity for placing an invert arch (Wiesmann 1920)
 b. Pressure cell between steel sets to determine rock pressure (Gremmler 1933)

3. ADVANCEMENTS IN SUPPORT TECHNOLOGY

As just mentioned, conventional tunnelling world-wide was virtually dominated by timbering until the 1950s. Only gradually were steel supports, then shotcrete, followed by anchors and, finally, the systematic combination of these support measures on a broad scale, introduced. A proper understanding of this development necessitates, first of all, the enumeration of the many disadvantages of timbering (Fig. 8):

- the enormous amount of time and labour necessary to install timbering,
- the obstruction of excavation and mucking activities, as the timber structure would often involve up to 60% of the excavation face, thus impeding the mechanisation of excavation using large machines,
- over-excavation made necessary because of the timbering,
- the difficulty of constructing a sufficiently stable and stiff system, both transversally and longitudinally, out of wood,
- the complexity of the working phases during the construction of the arch for the permanent lining, using simultaneous support of the rock mass with the timber structure,
- the limited possibilities for adjustments to the timbering in the case of geologically caused over profiles (cave-in, karst),
- the decrease in bearing capacity of the timbering following rotting of the timber,
- the excessive air resistance for the ventilation during construction,
- the risk of fire, especially in coal mines,
- the enormous consumption of wood, which led to wood shortages in many regions.

Therefore, it is not surprising that Simms, as early as 1844, had already strongly advised the use of timber "as little as possible". It is also not surprising that timbering was eventually replaced by other support methods. The first of such measures proposed were curved steel rails. Further, Rziha (1867) was able to reduce the need for timber construction substantially

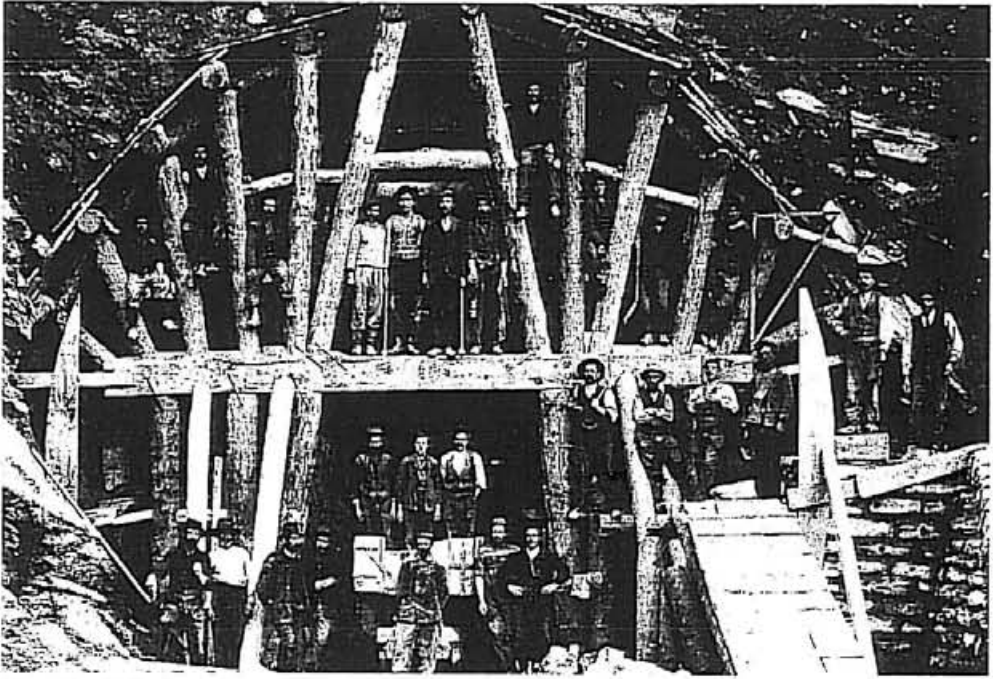


Figure 8: Timbering at the south ramp of the Lötschberg tunnel (1908-1913)

and to increase the clearance in the tunnel by using a modular steel structure which could be dismantled. However, since his structure was tied to a predefined profile geometry, this method could not be applied generally. A true remedy would only be offered by the new support measures – steel ribs, shotcrete and bolts. Their development will now be briefly presented.

In this regard, tunnel construction owes very much to mining, as the conditions for new developments in that field were especially favourable for three reasons. New ideas and technologies could be tried out more easily in small diameter adits than in railway tunnels. In addition, section lengths are generally much longer in mining than in tunnelling. Thus, mining offers continuity in operation over a period of years or decades, providing good conditions for the testing of new methods. On the other hand, tunnelling had to fulfil the task of developing, based on scientific considerations, the use of the new support measures towards the "SCL method".

When we ask ourselves today why timbering was not abandoned much earlier in favour of other support measures, it should not be forgotten that, in addition to a prevailing conservative attitude where innovations were concerned, economic points of view were also decisive. The labour needed for timbering was cheap, while steel and cement prices remained proportionally high for a long period of time. Only when mining productivity could be greatly increased through the use of larger machines, such as loading and transport machines, was the time ripe for abandoning timbering.

Steel supports

The first use of steel profiles in combination with or in place of timbering is obscure. It is to be supposed that, first of all, old railway rails were used. The first real impetus for steel supports came with the arrival of the first rolling mills in the middle of the 19th century (Fig.9). From a publication dating from 1869 (Glückauf 28), it may be seen that *"the application of iron for the replacement of timber and arching has been used with great success over the last few years in many excavations in Prussia, for tunnel support as well as for the*

then in 1906 report: "The measurements carried out at regular intervals until the end of 1905 revealed not the slightest deformation".

In 1932, with the development of the Toussaint-Heintzmann ribs with sliding connections, significant progress was seen for both the design and the construction of steel supports. "For its design profile, it was crucial to consider the cross-sectional values in the axis of the smaller of the moments of resistance in order to increase buckling safety. On the other hand, this tended to reduce resistance to bending." (Würker 1934). The design of the walls with "friction connecting loops" permitted this type of support to withstand larger convergence with constant lining resistance. This was the dawn of the first industrially-produced supports in squeezing rock, by means of which ground pressure could be reduced with the increased convergence.

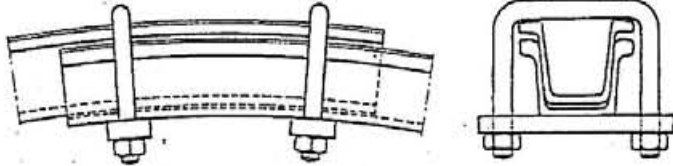


Figure 11: Sliding connection of Toussaint-Heintzmann (Fröhlich 1948)

The high technical and scientific level of tunnelling with steel support in the 1940s is best demonstrated by the famous book of Proctor and White (1946) with a major contribution of Terzaghi.

Shotcrete lining

The development of shotcrete technology started with the invention of the "cement-gun" by the American C.E. Akeley. He obtained a patent in 1911 for an "Apparatus for mixing and applying plastic or adhesive materials". Among the numerous engineers who advanced this technological development through further inventions, the German-American, C. Weber, the Swiss, G. Senn and the Dutch, M.J. Stam may be mentioned (Teichert 1979). This sprayed mortar was called "gunite" and later "torkret" and since 1937 also "shotcrete", thus the operations are referred to as "guniting", "torkreting" and "shotcreting".

In 1914, the United States Bureau of Mines began to replace timbering with shotcrete in the Bruceton experimental mine (Rice 1918). "The cement-gun method was tried and found to be such an advantage that now mine guns have been purchased by the Anaconda company. (...) The finished work shows that the mixture of sand and cement has been shot into every crack and fold of the rock until it can hardly be distinguished from the rock itself." And "it may be found necessary to use a reinforcing wire mesh in the gunite...". Furthermore, it is stressed "how much safer is a smooth, concrete lining as compared with timbering. By a thin coating of cement it is possible that the heavy expense of timbering in many cases may be avoided."

From a report (Knox and Potter 1920) we learn, that in the Calumnet & Hecla Conglomerate mine a transportation route at a depth of over 1500 m gunited along a stretch of 2.7 km, stating that "there's not a single stick of timber being used in any part of the completed portion for the purpose of supporting loose ground. The most sceptical of us have become enthusiasts in the use of gunite under these conditions...". The authors in their enthusiasm conclude that there are probably "hundreds of thousands of feet of mine openings that should be 'gunned' instead of timbered. It's relatively inexpensive, fireproof, easily repaired, and astonishingly effective in certain instances."

The term "shotcrete method" appeared for the first time in the 1920s. The possibilities for the application of shotcrete were recognised and utilised very rapidly by the technical world. The first application in tunnel and shaft construction was carried out even before 1920. Using this method, an unlined railway tunnel in Illinois was lined with a net reinforced gunite shell,

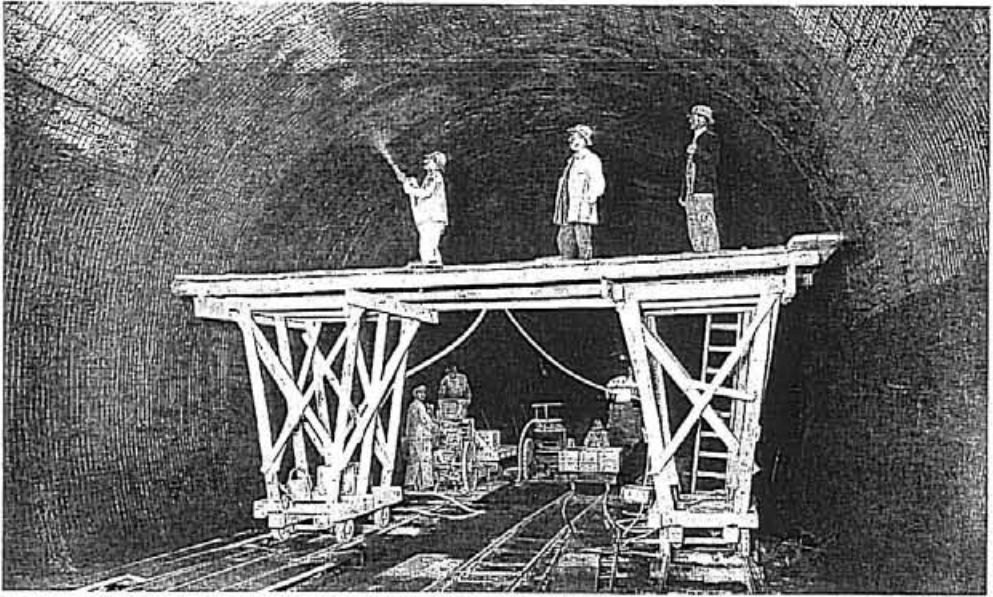


Figure 12: Shotcreting at the Ulmberg-Tunnel in Zurich, Switzerland (1927): Transformation of a railway tunnel into a road tunnel (Photo courtesy D. Prader)

without suspending the rail service. H. Schlüter (1920) in the magazine "Zement" and K.E. Hilgard (1921) in the "Schweiz. Bauzeitung" were the first in Europe to report on this new technology. From Hilgard, it is learned that in this period two waterway tunnels (Klosters-Küblis and Amsteg) were lined with reinforced shotcrete in Switzerland. Also, repair work in older railway tunnels was carried out with shotcrete (Coldrerio and Massagno Tunnels near Lugano). In Germany, a 6 km long waterway tunnel for the Heimbach power station was lined with shotcrete for the first time in 1922: *"It is a distinct advantage to be able to carry out excavation and torkreting simultaneously. How fast the sprayed concrete stuck to the rock after torkreting was to be seen, once blasting operations were resumed shortly after torkreting procedure. However, only when the torkreted layer was 4 days old did rupture occur entirely in the rock during blasting. In small zones the concrete layer disengaged itself from the rock face."* The article closes with the sentence *"It is to be hoped that this new construction method will enable the construction of hydroelectric power plants to be carried out more rapidly and more economically."* This is the first time that the term "construction method" related to sprayed concrete lining was used.

Various hypotheses explaining how shotcrete works in tunnel construction appeared relatively early on (Tübben 1923): *"The described success of the procedure seems bewildering at first glance, however the explanation is extraordinarily simple in my opinion. While reinforced concrete is composed of a firm, stiff mass within, shotcrete forms only a very thin skin which to some extent is elastic like rubber. That an elastic body can withstand proportionally higher loading than a rigid one is obvious"*.

In 1925 two different and exhaustive monographs were published concerning the application of shotcrete in construction and especially in mining and tunnelling (Szilard 1925, Meyer 1925). Meyer reports that with torkreting, it is possible to *"take up ground pressure or at least hinder rockfall using this support measure"*. In this work, a concrete lining closed to a full ring in squeezing rock was reported on for the first time, i.e. the formation of an invert arch with shotcrete. Thus, Meyer furnished proof that timbering or steel supports could be replaced by a reinforced, closed shotcrete shell.

In order to illustrate the widespread use of shotcrete in the 1920s, we refer to an article in the "Neue Zürcher Zeitung". Under the headline *"Shotcrete or torkret procedure"* (1926), among other things, it was stated that *"especially for the construction of pressure tunnels,*

the method has already proven itself. The tunnel lining is generally made up of two rings: an outer tamped concrete ring and an inner, reinforced ring. Because of the very close-meshed reinforcing net of the latter, the concrete placement using pneumatic methods represents a substantial operational and economic improvement."

The Swiss contractor Prader AG, Zurich carried out guniting work in several countries, for example in the pressure tunnels Saltos del Cala at Sevilla (1926) and Saltos del Alberche (1928), the waterway tunnel Pinet, France (1928) and the pressure tunnel Joginder Naggur (1931-32) near Lahore in India (Conversation D. Prader). If one casts a quick look at the developments on the North American continent, then first of all the McIntyre Mine in Ontario, Canada, has to be mentioned, in which "guniting of rock surface has been standard practice for several years" (Keeley 1934). "By adaptation of this process mining problems connected with scaling and loose ground have been completely solved. (...) The arch-supporting effect and the shearing strength of the concrete are considerable." It has been pointed out that replacement of timbering by guniting leads to 50 per cent savings in the cross-section of a mine drift. One of the outstanding features of this case is the early application of the combination of rock bolts, wire mesh and gunite as temporary support under difficult ground conditions (depth over 1500 m). In a later publication (Anonymous 1957), it is confirmed: "Guniting has been a standard practice at the McIntyre mine since 1930 for the support of all large excavations of a permanent nature."

Our next example is the 45.8 km long Hetch Hetchy water supply tunnel in California. "Difficulties with moving ground resulted in excessive maintenance and in replacing the timbering twice and sometimes three times. To effect some relief from this condition, a circular sub-lining of pneumatically sprayed concrete (gunite) was tried where conditions were most severe. Success in the use of this technique was great. (...) Savings effected in eliminating retimbering, re-excavation and in reducing track maintenance suggested the possibility of using this lining to eliminate timbering altogether. The method has now been worked out in detail and has been used with marked success for thousands of feet at several of the headings" (Anonymous 1933). Convergence measurements were taken in studies of rock pressure to be resisted (Anonymous 1931).

The extent to which the technology of shotcrete had reached a sophisticated level already in the 1920s in Europe is demonstrated by the example of the Mersey Tunnel between Liverpool and Birkenhead. The four-lane tunnel with a diameter of 13.4 m was the largest road tunnel at the time and today is still the largest sub-aqueous tunnel in the world. The cast-iron segments of which the tunnel is constructed had to be covered over the roadway by a 3 cm thick reinforced shotcrete layer. The total length of the shotcreted section was 4.2 km, involving approx. 70'000 m² of surface area. It is, therefore, not surprising that a "Handbook on Cement Gun Work" was published in 1934 in London. We will come back to address the further developments of shotcrete after the Second World War later.

Rock bolting Technology

The history of bolting began with a patent specification (No. 302909) obtained by Stephan, Fröhlich and Klüpfel in 1913 (Fig. 13): "Method for the support of roof and walls in mining without support from below". The invention aimed at "creating a support, the fix point of which is being placed in the ground. This replaces traditional support by timbering, the fix point of which is at the bottom of the drift!" In order to achieve this goal, "bore-holes of sufficient depth will be drilled into the rock in which rods, tubes or cables made of a load-bearing material, for example steel, will be inserted and fixed at the end in a proper manner or cemented along the whole length."

The outbreak of the First World War delayed the issuing of the patent until 1918. The names of the holders of the patent and the patent with this number were long unknown in the technical literature. However, in the German-speaking literature, a publication from 1919, without information concerning the author, was found in which a short paragraph in the middle of a larger treatment of mining is dedicated to the topic of the maintenance of transportation routes. The subtitle was "Tunnel support with iron anchors". It may be learned that in the coalfield Königshütte in Ober-Schlesien (at that time Germany) "for the last several years iron test anchors have been used to replace timbering for resisting ground pressure". We

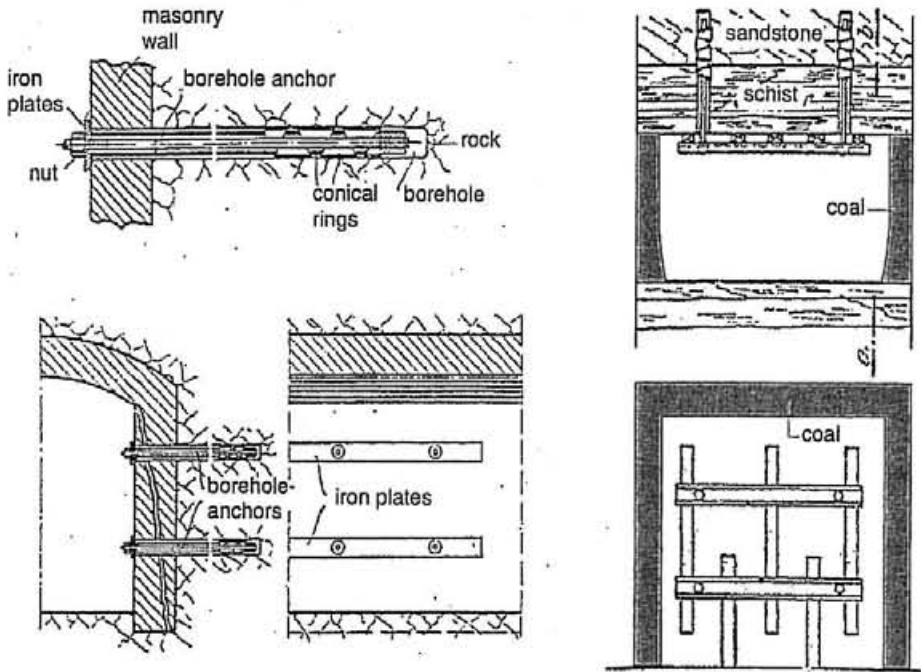


Figure 13: The first known rock bolt and its application in a failed lining in the wall and in the roof (1913)

assume that this publication relates to the above-mentioned patent, even though the name of the patent holder was not mentioned. The authors, already in 1913, were fully aware of the significance of their invention, i.e. the replacement of timbering with anchors: *"The cross-section of the profile is in no way obstructed or restricted, an unintentional knocking out of the supports is not possible, legs and struts are eliminated and replacement of timber supports due to rotting is abolished."* Facts substantiated the far-sightedness of the authors; bolts were placed in the roof as well as in the walls for protection against cave-ins or cross-section narrowing. The anchor heads were linked together with cables and U-profiles. A four-year test period with mechanical anchors showed that *"the section supported with bored anchors remained entirely intact while the section with timbering collapsed due to the rotting of the timber."*

This revolutionary invention unfortunately sank into oblivion and did not find its way into general practice. The first publication on anchors, appearing some 25 years later than the above-mentioned article, was by Weigel (1943), from the United States. He reported on tests which were carried out in the years 1936 and 1937 in the Leadwood mine in Southeast Missouri (St. Joseph Lead Co.). The new system *"consists of supporting the ground below the natural arch line and anchoring it to the solid rock above and especially to the rock above the pillars. This is done before the rock actually comes loose. As the self-stopping condition of the back is usually progressive action, if the lower layers are caught and held tight, the upper ones do not cause trouble. The succession of thin layers thus becomes one thick, heavy beam of sufficient strength to carry from pillar to pillar"* (Fig. 14).

In a comprehensive publication from 1945, the Dutch engineer Beyl reported on successful anchor tests which he had carried out in England in the years 1942 and 1943. With the help of convergence measurements, he endeavoured to study the influence of the anchors on ground deformation. He observed a prestressing action and remarked: *"It is necessary to insert the anchors as soon as possible after the exposure"*. Beyl was not immediately successful in Europe with his ideas and field tests. His publications did however help to promote the use of anchors later in the 1950s.

In the period 1943-1950, the use of rock bolts in the American mining industry, especially in

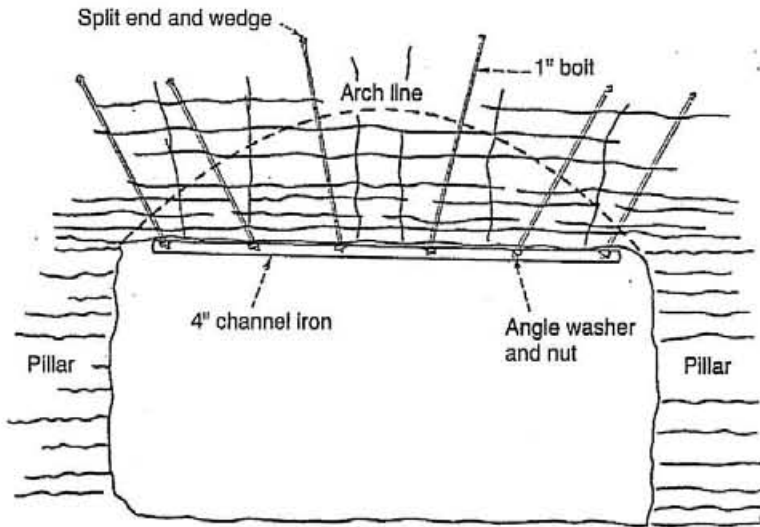


Figure 14: "Channel iron and long bolts are employed to support loose back below the natural arch line in a heading" (Weigel 1943)

coal mines, and from 1952 onwards in Europe, experienced an unusually rapid growth. This development began after the publications of C.C. Conway (Consolidated Coal Company, Illinois) and E. Thomas (US Bureau of Mines) in 1948. Conway dedicated a special chapter to "The theory of rock bolting" in his work. Of course there was also resistance to bolting (Thomas et al 1949): "The method appears at first glance to approximate holding oneself up by one's bootstraps. Many persons suggested the term 'sky hooks'". We learn here about a remarkable view on the effect of rock bolting: "the roof apparently supports itself instead of being supported by conventional timbering".

The success of anchors in the USA in a very short space of time can be measured by some statistics. In the years 1948-1950, a total of 1400 km of tunnel in 350 mines were supported with anchors (Forbes 1950). The production of "tons per man-shift doubled". "In 1949 the coal and ore mines achieved their best all time safety record attributed to roof bolting. Bolt-ing greatly decreased injuries due to rock fall" (Bucky, June 1950).

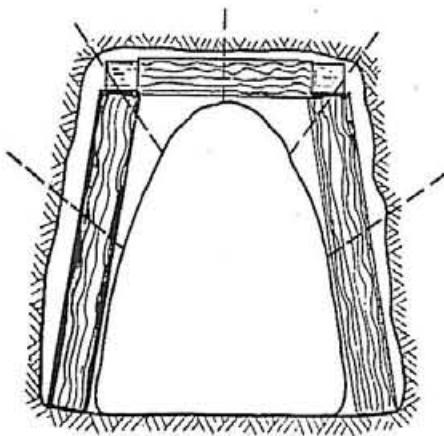


Figure 15: Comparison of a rock bolted cross-section (3 x 2 m) with a 3.5 x 3 m timbered cross-section (Pollish & Breckenridge 1954)

To explain the rapidly spreading use of the anchor in the USA during the 50s, a glance at two figures is sufficient: In the USA, at the beginning of 1953, 0.5 million anchors were installed per month, whereas during 1957, the total rose to 3.0 million (Schmuck 1957). It is certainly correct to state that "timbering, since the days of the cavemen, has been the means of maintaining underground openings". This author considers "the general principle behind rock bolting, except in the case of simple suspension, is that the bolt must be able to make the ground itself an integral part of the support structure". The increasing use of anchors in mining, namely in England, France and Germany, began in 1950 - 1952, and led there to similar success. In only a few years the use of wooden supports vanished from European mines. Anchoring will be a subject for further investigation. From the 50s

we also come across a substantial number of publications pertaining to laboratory and field research, as well as textbooks and the first technical standardizations on anchors. Anchors, in contrast to steel linings and sprayed concrete, were for a long time only used in mining.

Tunnel construction continued to be affected by this rapid development. One of the first applications of systematic rock bolting in a waterway tunnel was in the approx. 250 m long diversion tunnel of the Keyhole Dam, Wyo. in the USA in 1950. "After blasting, the contractor resorted to roof-bolting - commonly used to prevent overbreak in coal mining - to hold cracked formations that otherwise might slip or fall out" (Anonymous, Engineering News Record 1951). The horseshoe profile of the 3.5 x 4.0 m tunnel was supported by radially arranged rock bolts. "Roof-bolt locations were mostly a matter of judgement exercised by the tunnel foremen". We learn that in this tunnel "an expensive system of steel ribs and lagging or timber bracing to protect workmen from falling rock" could be completely dispensed with. In order to demonstrate the developments on a broad international scale, we also mention here the construction of the 16 km long Notable Water Tunnel near Manchester also 1950 (Anonymous, Water Power 1951). The approx. 3.5 x 3.5 m sized horseshoe section was secured "where shale and gritstone beds were encountered lying more or less horizontally (...) the steel arches being replaced by a suspended form of support: (...) This method is very economical in the use of steel, the quantity being about one-sixth of that required with steel arches and bank bars".

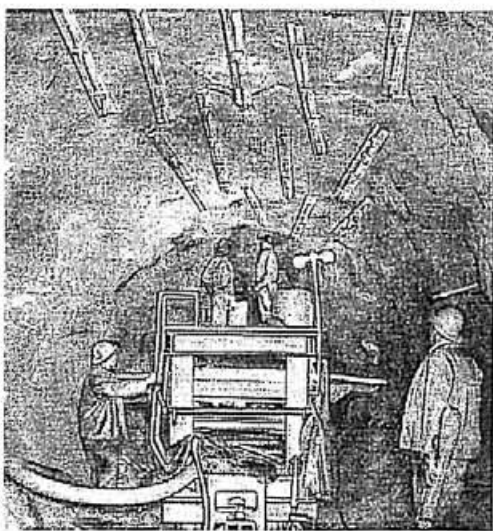


Figure 16: Rock bolts installed for roof support in the East-Delaware Tunnel (Weiss 1952)

A true breakthrough of systematic rock bolting in tunnelling is the case of the 42 km long Delaware Water Supply Aqueduct in New York. "Due to the shortage of steel the Walsh-Perini Company asked the Board of Water Supply for permission to use roof bolting method" instead of the usual steel ribs. On November 8, 1950 permission was given to the contractors under several conditions. Among them were the application of steel roof ties (channels bolted to the rock) and "guniting the rock as soon as possible after bolts and plates are put in place" (Nolan 1952). It was concluded that "no timber is needed with this method, and the advantage over the conventional steel rib support involves a reduction of 85 % in the amount of steel used to support the roof". In a further report (Pierce 1953) it is mentioned that in this scheme more than 19.5 km of roof were rock-bolted "but not one fatality or one lost-time accident occurred due to roof falls. (...) One reason for the good

record is that bolts can be applied much closer to the face than steel sets, thus giving the workers protection most of the time they are underground" (Fig. 16). As to the support mechanism, it is mentioned that "whereas ordinary timber sets come into play after failure has occurred, roof bolts cause the rock to contribute to its own support" (Miller 1952).

The high advance rates, the excellent safety record and the economic success achieved on this large project had an enormous influence on tunnelling industry world-wide. This was facilitated by the high technical level of the publications on the works. So this New York Water Tunnel, together with the experience gained in the mining industry, encouraged the profession world-wide to employ rock bolting, with or without shotcreting, in pending projects of similar or even greater size. We mention here in an approximately chronological sequence: The Kemano Powerhouse in British Columbia 50 m high, 36 m wide and 210 m long, constructed 1952-53. "The rock is granodiorite, and bolts up to 4.5 m long were used to pin slabs and otherwise stabilize the walls until the concrete could be poured for permanent support"

(Woodruff 1954).

The Harsprånget Powerhouse in Sweden (1952-53) with radially arranged roof bolting and guniting in the roof: The first time fully grouted anchors were applied - sometimes referred to as the "Swedish method" (Heggstad 1953). The width of the chamber was 18 m. Here we must mention the invention by the Swedish engineers F. Lidingö and A. Lundqvist in 1952. This is the fully-grouted Perfo-bolt, which signalled a major breakthrough in rock bolting technology (Patent No. 1462256). Rabcewicz wrote 1957: "By far the greatest advances of this technology were achieved without doubt in Sweden. Due to the circumstance that there, large water power plants, among others, had been carried out... There is a long-term continuity; besides there generous resources for research and testing are always available. As an example, take the roof of the underground power house of Harsprånget, which was only supported by grouted anchors and torkret".

A number of large span, underground power houses constructed in the early 1950s in Norway: Heggstad (1956) mentioned that "the introduction of the 'roofbolt' method has led to considerable simplifying of the excavating operations for power stations". Cement grouted bolts and also arches of reinforced gunite with thickness of 10 to 12 cm were used.

The 11.7 km long water-way tunnel, Isère-Arc, of the Hydroelectric Scheme Randen in France (Martin 1954): The maximal overburden was 2000 m, and the excavation began in 1949 after great difficulties because of the heavy rock burst phenomenon. Systematic rock bolting (from September 1951 until December 1952) brought the solution. Thanks to the rock bolting method, full face excavation could be applied, which permitted the rate of advance to be doubled or even tripled when compared with timbering (Kobilinsky 1955). The width of the cross-section is 7.6 m. The introduction of this technique surprised all engineers of the construction site. The French engineer, J.T. Talobre (1957) proposed a model (Fig. 17) to explain the effect of a radially arranged bolting pattern in weak rock by assuming a ground arch surrounding the opening. Talobre introduced in the 1940s the term "rock mechanics" and he is considered as one of the founders of this discipline.

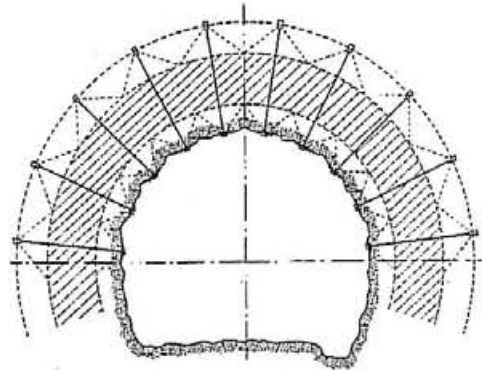


Figure 17: Ground support arch, created by rock bolts (Talobre 1957)

The 11.6 km long two-lane Mt. Blanc road tunnel, with a maximal overburden of over 2200 m, between France and Italy was constructed between 1958 and 1962. The area of the cross-section is variable (75-90 m), depending on the size of the ventilation duct under the roadway. The phenomena of squeezing rock and heavy rock bursting could be controlled by systematic rock bolting. Thanks to this technique, full face excavation could be applied even under difficult geological conditions, the face also being supported with up to 50 bolts. It is reported that, over a period of two years, in total 72'000 rock bolts were used. Based on the excellent experience in the Isère-Arc pressure tunnel, systematic rock bolting as a means of rock support was decided on already in 1954 in the early design phase of the project.

The Snowy Mountain Hydroelectric Scheme is one of the greatest civil engineering projects of the last century (Endersbee 1999). Its construction involved a total length of 145 km of tunnel with a width of approx. 6 m and machine hall caverns. At the proposal of L.A. Endersbee, already in 1949, rock bolts of the slot and wedge type were included in the contract drawings. Tunnel construction started in June 1955. "Following the successful use of rock bolts in large excavations of the Authority's underground power stations, the specifications required that supports for the works should be bolts, unless the use of steel rib supports was directed or approved of by the Engineer" (Andrews et al 1964). From the point of view of high speed tunnelling, the fact was emphasized that rock bolting can be carried out simultaneously with face drilling, whereas installation of steel rib supports disrupts routine activi-

ties. Only in squeezing ground was a steel arch support required. A special feature of this project was the systematic rock bolting for the large Tumut I machine hall cavern, 23 m in width and 33 m in height. Rock bolting was used both as temporary and as permanent support (Fig. 18). "There was an evident need for a better scientific understanding of the mechanics of rock bolting and a need to explain the principles and practices to workmen whose lives depended on sound rock support in underground excavation. T.A. Lang initiated a series of studies directed to those purposes" (Endersbee 1999). A great number of outstanding scientific papers resulted from his studies, the best known entitled "Theory and Practice of Rock Bolting" (Lang 1961). Lang concludes his paper saying that "A special tribute must be paid to the mining industry of the U.S. for their work in initiation and developing the use of rock bolts". At the 1999 Symposium to commemorate the 50th anniversary of the Snowy Mountains Scheme, Endersbee (1999) claimed that "The Snowy Mountains Scheme had led to a major change in world tunnelling practice in hard rock". We completely agree with him.

The first tests with rock bolting in the Austrian mining industry were carried out in the Salzach Coal Mines (SAKOG) near Salzburg in 1955 (Anonymous 1960).

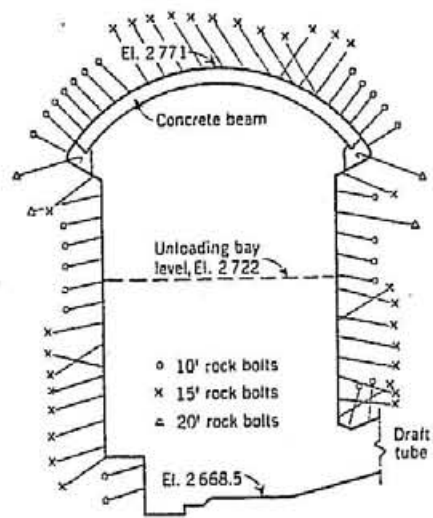


Figure 18: Rock bolting in the large Tumut I machine hall cavern of the Snowy Mountain Hydroelectric scheme (Lang 1958)

4. COMBINED APPLICATION OF SUPPORT ELEMENTS

We have seen that systematic rock bolting and guniting were already applied in combination in several countries since the 1930s, the emphasis lying mainly on the rock bolts. With the introduction of the first "true" shotcrete machine by the Swiss engineer G. Senn in 1950 (Teichert 1979) for a max. aggregate size of 25 mm, with an efficiency of 3 m/h and other major operational improvements, a new era started for the "shotcrete method". It was soon realised that a shotcrete lining may assume a more important role in controlling ground response than was the case earlier. The urgent need for waterway tunnels for a great number of new hydroelectric schemes and, somewhat later, also for traffic tunnels in Central Europe,

accelerated the spread of this view. Shotcrete assumed the same or in the first enthusiastic stage even a higher importance than rock bolt and steel sets did earlier. Very soon, however, it was realised that in many cases a combination of these support elements provides the most efficient method for controlling ground response and therefore the most economical solution.

The new type of shotcrete machine was first applied 1952 on a large scale in the 26.7 km long Verbano waterway tunnel of the Maggia Hydroelectric Scheme in Southern Switzerland having an excavated section of 21.4 m. According to the resident engineer (Sonderegger 1955), "Shotcrete was applied with great success in place of

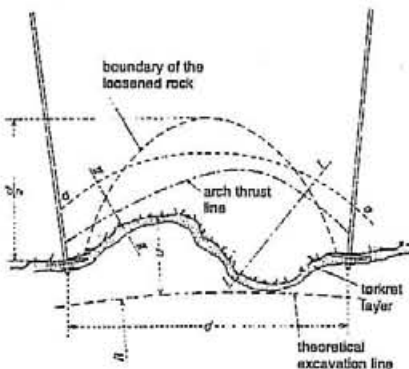


Figure 19: Statical effect of the torkret layer between anchor heads (Sonderegger 1955)

a temporary support (timbering) as an immediate support in weak rock. (...) The effect of gunite and shotcrete is seen in the filling out of open joints on the rock surface. In this way, from the beginning, a movement of rock blocks is impeded." He also noticed that shotcrete had the task "to fill the gap between steel sets, forming a secondary arch between them. The shotcrete lining proved itself excellently also as a final lining, instead of cast-in-place concrete as well." (Fig. 19). A remarkable publication of Frey-Bär (1956) reveals the consciousness of engineers of the importance of these developments when he speaks of "new types of support methods", asserting the following: "Shotcrete in combination with rock bolting is an excellent means of support where earlier time-consuming heavy timbering was required. With shotcrete the engineers have a means at their disposal with several advantages: great adaptability in the application as to the thickness and the extension of the area on the rock surface and the increased rates of advance because the work at the face is not disturbed." Furthermore, "shotcrete lining sprayed immediately after an attack is capable of withstanding rock pressure." Frey-Bär concludes his paper with a detailed comparison of the costs per tunnel metre of the individual support measures and says: "It is to be remembered that the three so different elements (rock bolts, shotcrete and steel sets) can be combined with each other."

The Austrian engineer Rabcewicz wrote in 1964: "The first successful application of surface stabilisation by shotcrete for tunnels in unstable ground as an integral part of the driving process, instead of using timber or steel as temporary support, was carried out in the Lodano-Mosogno tunnel for the Maggia Hydroelectric Scheme, Switzerland 1951-1955" (Fig. 20). In view of the continuous world-wide application of guniting since the 1920s, this statement is of course not true. It shows that Rabcewicz only discovered the importance of shotcreting after this application.

In Austria Senn's shotcrete apparatus (supplied at that time by ALIVA, Baden, Switzerland) was first applied in the Prutz-Imst Hydroelectric Scheme 1953-1954 and at the Schwarzach Scheme 1954-55 (Rotter 1958). As to the applications in mining in Austria, "The lead mine was the first in Austria's mining industry having the courage to break new ground with the application of shotcrete (ALIVA machine) in 1957 - apart from a first test in the Salt Mine Bad Ischl in 1953." (Rainer 1961). In Italy 1958 the 15.2 km long waterway tunnel ($\varnothing=7$ m) of the Monastero Hydroelectric Scheme at Como was lined with shotcrete in combination

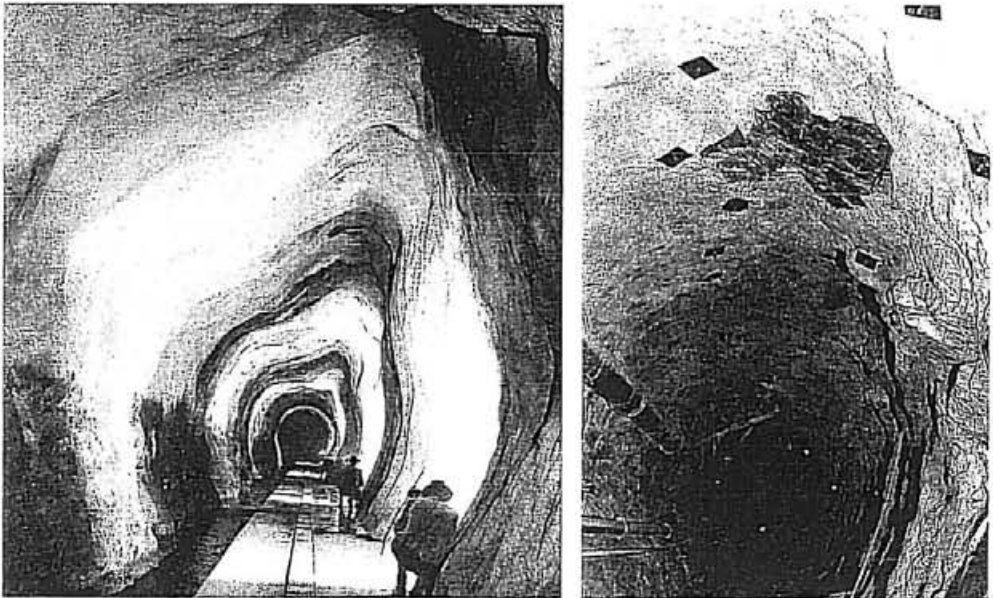


Figure 20: Use of shotcrete and bolts in the waterway tunnels of the Maggia Hydroelectric Scheme (section Pecchia - Caveragno), Switzerland 1952-1955 (Photos courtesy D. Prader)

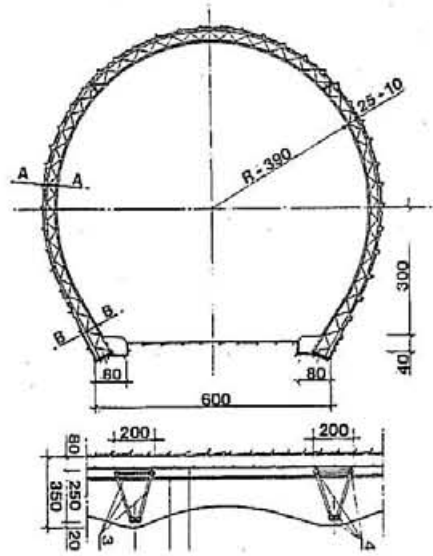


Figure 21: Use of lattice girders with shotcrete in the Monastero pressure tunnel, Italy 1958 (Curzio 1963)

with steel lattice girders, using Senn's machine (Fig. 21). A remarkable publication of the contractor (Curzio 1963) on these works, as well as on large diameter road tunnels in Italy, carries the typical title: "New Systems of Tunnel Construction". It is seen from his report that systematic deformation measurements were carried out at these sites under the supervision of G. Oberti (ISMES, Bergamo). Between 1958 and 1960, shotcreting was also applied in the Serra Ripoli Tunnel of the "Autostrada del Sole" (Zanon 1960).

In retrospect one can say that by the 1960s the technological means as well as the scientific background of the "shotcrete method" were well established. Quickly it completely ousted timbering world-wide. The term "shotcrete method" was used commonly throughout the German speaking countries, i.e. in Austria, Germany and Switzerland. Similar expressions can be found in other languages, for example "sprutbetongmetode" in Swedish.

In 1963 Rabcewicz, who in a paper renamed the "shotcrete method" to "New Austrian Tunnelling Method", speaks of a "shotcreting-rock-bolting-method having been developed and tested in Austria.". Rabcewicz is even more explicit saying that "due to its country of origin", the method is called "New Austrian Tunnelling Method". Later the acronym NATM became widely used. Still today NATM is defined by the Austrian code as "a tunnel constructed using open face excavation techniques and with a lining constructed within the tunnel from sprayed concrete to provide ground support, often with the additional use of ground anchors, bolts and dowels as appropriate". (HSE report 1996).

In most publications two even more important claims are made in favour Rabcewicz and other NATM protagonists: At first the replacement of timbering as a whole and secondly, the possibility of applying thin tunnel linings: "This was truly a pioneer work and it required enormous courage to employ a thin-sprayed concrete skin instead of heavy timbering or steel supports and a thick concrete lining. Therefore this concept was justifiably called NATM." (Poisel and Engelke 1994). Here we only mention that in all the history of tunnelling engineers world-wide were in the process of abandoning timbering. An example is a paper of O'Rourke from 1913 having the typical title "Elimination of Timbering in Rock Tunnelling: A Proposal". He says: "Anything that can be done to reduce or avoid the necessity of timbering is of greatest importance in the art of tunnelling." Another constant claim is that thanks to NATM, the tunnel lining can be kept thin and closed to a ring by an invert. We consider here only one example illustrating the 10th NATM principle (Fig. 22a): "Temporary and final lining slim" suggesting that earlier, irrespective of the ground conditions, constantly heavy support was made. "Today" indicates the NATM-tunnel and "earlier" stands for tunnels of

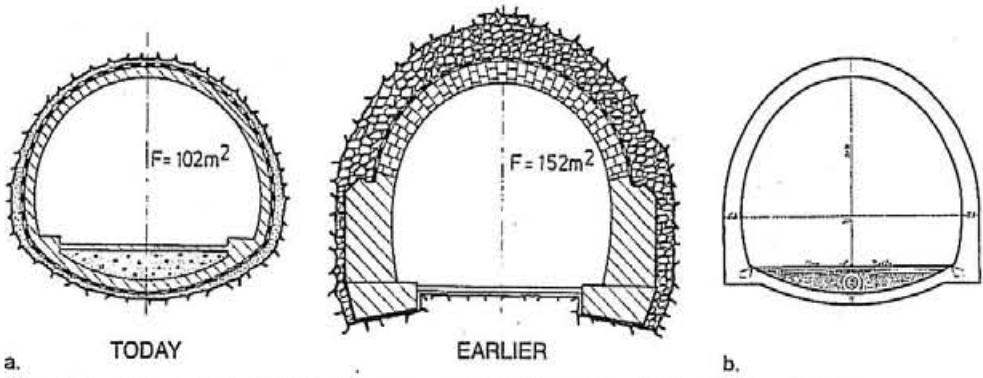


Figure 22: a. 10th principle of NATM: "Temporary and final lining slim" (Müller & Fecker 1978)
 b. Brunel's Box Tunnel, Great Western Railway, London 1836 (Sandström 1963)

the "pre-NATM" period in tunnelling. With nine such figures the history of tunnelling is stigmatised by Müller (1978). However, as an example for a tunnel profile featuring a thin lining and an invert, reference can be made to the famous Box Tunnel on the Great Western Railway (Fig. 22b) designed by Brunel in 1836 (Sandström 1963).

Such distortions of the history of tunnelling can be found in the official document on NATM (Definition and Principles, in 10 languages) issued 1978 by the Austrian National Group of the ITA.

Among the most frequently used arguments to justify the renaming of the "shotcrete method" to NATM are the following:

- Rabcewicz invented and patented NATM as early as 1948.
- Rabcewicz introduced rock bolting and shotcreting into tunnelling.
- Brunner invented and patented NATM in 1955.
- Müller and Pacher were also to be considered "fathers of NATM".
- With NATM the ground supports itself.

These arguments are unfounded:

The patent of Rabcewicz (*"Procedure for lining of underground openings, specifically tunnels"*) issued in 1949 only deals with a tamped concrete lining, closed immediately at the face to a ring. He proposed deformation measurements to check the development of rock pressure, which obviously had no practical meaning due to the extreme stiffness of the lining (Fig. 23). The assertion that NATM represents also an "observational method" has one of its origin in this erroneous idea. The patent was withdrawn by Rabcewicz already in 1952 (Spang 1996). There is no mention in this patent of rock bolts and shotcrete. Notwithstanding, he always claimed that NATM was his patented invention. Also NATM historians confirmed later: "From his exile in South America, he patented NATM in 1948." (a3 BAU 1994). Even in his doctoral thesis (Rabcewicz 1950), which he completed in December 1950, he demonstrated that he had no idea at that time about the new developments in support technology. He is still dealing only with tamped or pumped concrete linings having a thickness of 30 cm as primary support. Only during his connection with the Swedish company Svenska Entreprenad A.B. (SENTAB) in the early 1950s did he become acquainted with

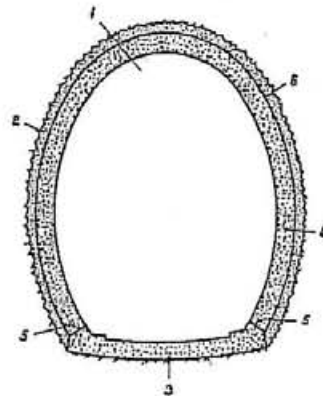


Figure 23: Rabcewicz's NATM patent (1948) for full face excavation with two concrete linings both erected behind a formwork

rock bolts. In the manner of the Delaware Aqueduct in New York he applied some rock bolts ("six days after the excavation had taken place") and guniting in the rock chamber of a hydroelectric scheme in Brazil with modest results. His first paper on rock bolting appeared 1953 followed by two other publications without any personal contribution. In 1957 Rabcewicz reports on laboratory tests with rock-bolting in a cohesionless model material with no reproducible results. His first paper on the application of shotcrete and rock-bolting appeared in 1961. After this publication, as mentioned above, in 1963 he renamed the "shotcreting method" to NATM.

We have collected the papers, as far as available, from all over the world on the development and application of shotcrete and rock bolts since the time of their invention. The number of pages published per year is depicted in Figure 24. One can recognise continuity for shotcrete, obviously interrupted by the Second World War. In the case of rock bolts, however, the invention around 1910 went unnoticed until the 1940s. But then there was an explosive interest in their application and further development. When the term NATM was introduced in 1963 very few of the publications were from the protagonists of NATM, which date only from the mid-1950s.

Brunner, in 1955, applied for a patent ("A method for the construction of adits, tunnels and shafts in squeezing rock") in Austria and also in Germany. The patent was issued 1956. Brunner was involved, for example, in the construction of the above mentioned Serra Ripoli Tunnel in Italy (Zanon 1960). Later the importance of Brunner's invention was emphasized by NATM protagonists saying for example: "NATM was patented by Brunner in 1958 and launched on a waiting world..." (Darling 1990). He proposed an archaic multiple adit method of tunnelling and he thought that it was enough to simply replace timbering in squeezing ground by a thin shotcrete lining without using any rock bolts or steel sets (Fig. 25). Brunner worked as foreman in several tunnels, using Senn's machine. He claimed for himself the sole right for the application of shotcrete in tunnelling. Therefore, his patent was soon attacked and owing to decisions of the responsible courts his patent ceased to exist as early as 1966 in Germany and 1967 in Austria (Spang 1996). According to the two "NATM-patents",

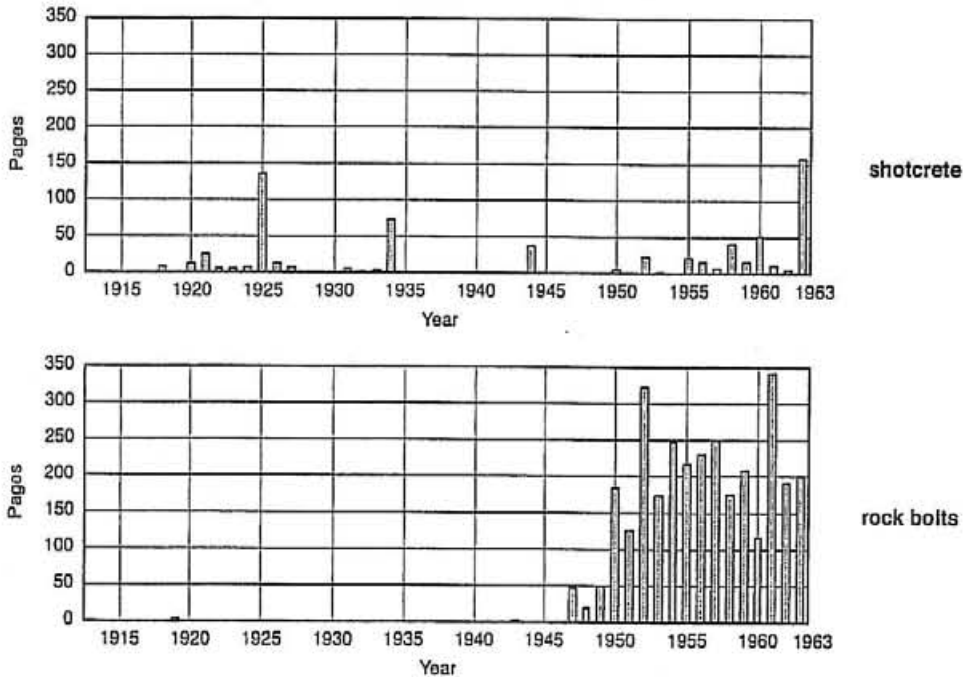


Figure 24: Evolution of the number of published pages on "shotcreting" and "rock bolting" up to 1963

NATM is defined as both a "full face" and a "sequential" method of excavation. Pacher, until 1968, did not publish anything on tunnelling applying rock bolting or shotcrete. His proposal of a special trough-shaped ground response curve in 1964 gained over the years such importance that he got the reputation of being one of the "fathers of NATM". Many reports in the NATM literature deal with the allegedly successful application of this curve permitting minimising rock pressure. It can be shown that his concept violates the fundamental principles of the conservation of energy in the same way the idea of perpetuum mobile (perpetual motion) does. However, NATM protagonists today still defend the erroneous postulate of Pacher saying that: "it is reasonable, although it could not up till now be verified by measurements or numerical simulations" (Kolymbas 1998).

Also Müller eventually aligned himself with NATM (Müller and Spaun 1977). It was his idea to trivialize the science and technology of conventional tunnelling with his 22 aphoristic NATM principles. The formulations, as far as they are correct, were borrowed from the scientific patrimony of international tunnelling. Others are typical of the NATM ideology. Consider the 6th NATM principle: "Construct the lining not too early or too late, and not too rigid or too flexible" (Müller and Fecker 1978). Müller, on the other hand, warns us: "the slightest deviation from the principles may be detrimental to the safety of the workmen and to the structure." (Müller 1979).

As to the key argument "with NATM the ground supports itself" we refer to Simms (1844).

5. CONCLUDING REMARKS

Shotcrete and anchors are well-established. Today all conventional construction methods in soil and rock, in tunnels, caverns and shafts, generally use as a temporary support measure, shotcrete with or without anchors and steel arches. The term "shotcrete method" has been employed in the technical literature since the 1920s. Nobody would oppose the UK Institution of Civil Engineer's recently published guidelines (1996) concluding: "The use of sprayed concrete support for a tunnel is often erroneously referred to as NATM. In view of this, and to avoid any confusion, this guide will generally use the description 'sprayed concrete linings (SCL)'." This choice derives from the pseudoscientific character of NATM's "edifice of thoughts". This was shown elsewhere (Kovári 1994). In this paper, we could prove that NATM also involves plagiarism. Pseudoscience and plagiarism are the two sides of the same coin and both arise from a lack of intellectual integrity. Considering the enormous and continuous effort of the international tunnelling community since the 1800s to understand ground response and to develop suitable means of support, i.e. shotcrete, rock bolts and steel arches as providing alternatives to timbering, the renaming of the "shotcrete method" to "New Austrian Tunnelling Method" definitively is not justified.

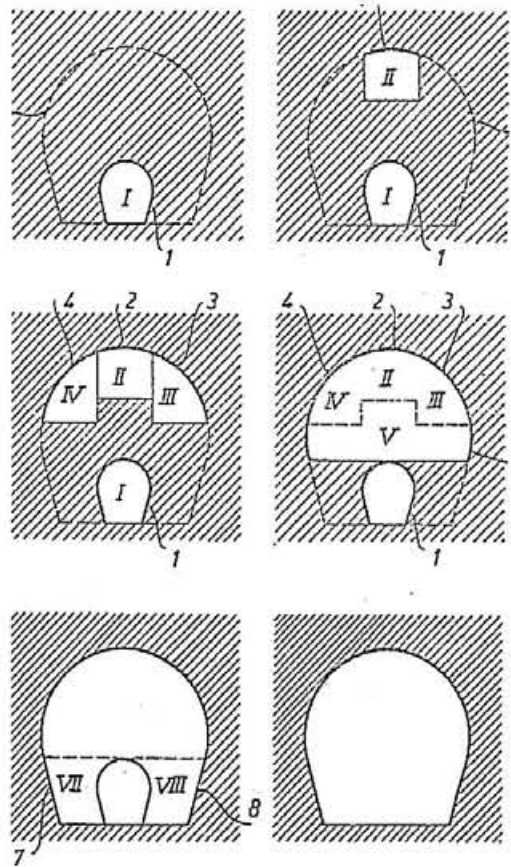


Figure 25: Brunner's NATM patent (1955), sequential excavation with shotcrete support and without rock bolting

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