THE FUNCTION OF SHOTCRETE IN SUPPORT AND LINING

OF THE

VANCOUVER R.R. TUNNEL

by

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The tunnel was driven three shifts five days weekly, no blasting being allowed by city ordinance between midnight and 7.00 a.m. A 6-drill jumbo was used to drill a 10-foot round, 110 holes blasted three times daily. A 2" layer of shotcrete was applied to the newly blasted arch commencing within 45 minutes of blasting. This was done from a flying deck that extended over the muckpile from the jumbo. (Figure 2.) Also during the mucking cycle the preceding incomplete arch support was brought up to 6" specification. The walls were sprayed 4" thick during the drilling cycle. (Figure 3.) The shotcrete machines and aggregate bins were mounted on the jumbo.

Basic Facts

Shotcrete is defined (ACI 506-66) to include indiscriminately pneumatically applied mortar and concrete. European practise separates these two products, emphasizing the functional difference between mortar and concrete. It is spray concrete (Spritzbeton) not spray mortar (Spritzmortel) that was developed to such effect to serve as ground support in so many major tunnels and underground powerhouses in the Alpine countries and Sweden. The technique since has spread in Europe, to some South American countries, Hong Kong, Japan and now to this continent.

Pneumatically applied mortar (gunite) has been in use as an overlay material for at least 50 years on this continent. It has not been found capable of providing a dependable support in underground excavations, however. It has a tendency to loosen as rock surfaces relax, and spall with the greater degree of relaxation of more incompetent rock areas and members. This could be due to thinness of individual applications $\pm$ 1"), aggravated by shrinkage induced by a high cement content.

Spray concrete, on the other hand, bonds effectively with any form of rock surface; and applied with skill can support even a cohesionless soil. Its adhesion to cohesive surfaces is attributed to the peening effect of the coarse aggregate particles driving their predecessors into the subject surface, and to the high early strengths reached with the aid of a suitable accelerator. It can be applied in layers of 4" - 6" thick in one pass, thus achieving its supporting function in addition to a seal.

Shrinkage is less than in mortar mixes, the possibility decreasing further with the lesser cement requirement of each increase in aggregate sizing.

Figure 4 shows photograph of cores drilled from the arch of the Vancouver tunnel, typical of adhesion in these rocks. The bond between shotcrete and rock is hardly discernible. Tests conducted on a hard granite did not show equal shotcrete penetration. Adhesion would seem to have been relatively effective, however, corings after 5 days breaking in the granite rather than at the bond. Thickness of the shotcrete application would seem to have been a factor in preserving the bond.

Use of accelerating admixes enables the shotcrete to reach quick enough set to adhere to wet and running water surfaces. Compressive strengths up to 650 psi were reached in the Vancouver tunnel in 2 hours with 300 psi flexural-tensile. From 75% - 80% of the 28-day strengths were reached in 48 hours. These averaged 5200 psi compressive and 1150 psi flexural-tensile. Blasting of an 110-hole round with 450 lbs of semi-gelatin explosive was done within 1 - 2 hours of spraying the arch to the drilled face.

Development of coarse aggregate shotcrete-concrete underground support is said to have begun at the Kaprun hydroelectric scheme 1953-1954, and followed through at the Salzach-Schwarzach development 1955-1958 in the Austrian Tyrol. Shotcrete machines until then were incapable of handling in excess of 1/2" aggregate. It was found that at least 15 mm - 20 mm aggregate was required to build up a thick enough layer of shotcrete to provide a support function. Firstly, the Aliva BS-12 shotcrete machine was developed for the Kaprun project, then the BSM and Torkret machines for the second project. These machines had capability of 1" - 1 1/4" material.

Coarse aggregate shotcrete since has proved itself as a support medium over a broad spectrum of difficult situations underground. Used alone, with rock bolts, with steel arch supports or light steel reinforcement as circumstances required, the technique has been found capable of stabilizing virtually all conditions encountered in tunneling. These have included intensive fractured and mylonitized rocks, very wet; plastic, water-bearing and swelling marls; and cohesionless gravel.

Principles

Support in a tunnel has been defined as the structure erected after blasting to protect against rock-falls; and to prevent invasion of the excavated opening by the surrounding rock until a permanent lining has been placed. Conventional steel supports yield first at the blocking, such yield often being sufficient for the rock to assume the remaining load. If the rock is incapable of carrying the remaining load, it will relax further and continue to redistribute load from the arch section to the less highly stressed walls. Ground relaxation and expansion into the opening hence is implicit in this system.

Shotcrete on the other hand, applied immediately after blasting will supply both a seal and support stabilizing a new rock surface. The intimacy of the rock-shotcrete bond is such that a new tough skin is formed upon the opening that restrains loosening, decompression and bending that accompanies normal relaxation. Tensile stresses due to bending are diminished and compressive stresses absorbed in the surrounding ground. Thus, a rock of minor strength is transformed into a stable one. Such would explain why excavation in weak to plastic rocks remain stable against a few inches of shotcrete support.

Shotcrete is a cohesive material, tougher than conventional concrete of similar mix proportions. It is waterproof, and is characterized by high early strengths, due to the degree of compaction received from impact velocities of 250-500 ft/sec, to its low water-cement ratio (about 0.35), and the use of accelerators developed for the function. These accelerators have no corrosive effect on steel. Minimum compressive strengths of 200-250 psi are required in 2 hours, 800 psi in 12 hours, and 1500 psi in 24 hours from a 4000 # 28-day concrete. Flexural-tensile strengths will amount to 50% and 30% of compressives in 1/2 and 2 days respectively, and 20% in 28 days. Due to its creep properties it can sustain significant deformation over months or years without failure by cracking. (see Figure 5)

As a support system it can be utilized either as a structural or non-structural support. Thus, weak to plastic rocks and soils, and cohesionless soils, require application of a rigid, competent structure to restrain the ground from loosening or flowing into the opening. This can be supplied by design thicknesses of shotcrete of 4 inches or more. In more competent rocks it may be applied only to joints and fractures, to prevent the lesser rock movements that trigger rock pressures and failure. The shotcrete is applied in 2" - 4" thicknesses on the saw-tooth surfaces, filling cracks and hollows and eliminating notch effects, with only minor application on smooth rock surfaces. Much of Swedish practise is of this type. Some lessening of aggregate size is possible in this second instance.

Vancouver Tunnel

The rock heading was started with conventional steel arch supports in soft, weathered shales dipping gently towards the face. Included was a 12" coal seam overlying 18" of gouge and overlain by 3' of weathered plastic shale. The ground became saturated quickly as the face advanced, and required forepoling. Thus, an early trial of shotcrete was in order. The voids above the spiling first were filled and the face consolidated with shotcrete. Short wall-plate drifts were driven and shotcreted, the arch perimeter excavated as a ring and shotcreted, the arch erected, and finally the bulk of the excavation completed with shotcrete. With every advance the necessity of sectional excavation lessened. Within 25 feet use of the steel supports was abandoned.

Thus, the technique had an early and satisfactory baptism. No question remained as to continuing with it. The first 200 foot length of work was treated as a test section extra to the contract. Lessons had to be learned in treating wet areas and water flows. These were more numerous in the first 1200-1500 feet of the tunnel than subsequently, several flows of initial consequence being encountered in this section. A disconcerting experience was the first encounter with the conglomerate underlying a shale contact. It had a water saturated sandy-clay matrix which disintegrated in minutes, providing a hail of falling pebbles accompanied by the disruptive dripping of water. It was in excess of 30 minutes of spraying before a thin base coat of shotcrete began to adhere.

Dry-mix was mixed in a batch plant above the tunnel portal and dropped 70 feet through a 26'' diameter standpipe to shotcrete cars for delivery to bins on the jumbo. A maximum standing time of 60 minutes for the dry-mix was observed. After a number of trial mixes having reference to some difficulties with accelerators, the following was standardized:

Cement	650 lbs
3/4'' stone	900 lbs
1/4'' stone	850 lbs
Sand	1520 lbs

Periodical sieve tests were made to maintain a specified gradient. Any significant departures from same often due to variables in supply resulted in segregation through the standpipe, and hose blockages in spraying. To combat dusting a limit of 2%-10% was placed on minus 100 mesh material and of 2% on minus 200 mesh.

Vancouver cement is low in C_3A(7%) resulting in some difficulty with accelerators. An initial set of 1.5 - 2 mins is required of the shotcrete. Excessive cement content and excessive calcium chloride resulted in numerous shrinkage cracks. Application of excessive thickness on the walls without benefit of accelerator resulted in horizontal sag and cracking at separation. Rabcewicz states the object is a crack-free lining. With the above mix this was obtained finally. Cracks are of less consequence in the so-called non-structural lining, however.

The rocks consisted of a late Tertiary series of conglomerates, sandstones and shales. The conglomerate consisted of up to 4-inch pebbles cemented with sand and clay. The cement composition varied, the more sandy matrix forming an almost unconsolidated material. Occasional sections were calcified forming reasonably competent rock. Blast shatter was negligible in these rocks. The sandstones were coarse to fine grained, usually soft and water saturated. These rocks broke cleanly with little evidence of blast shatter. Their porosity, however, combined with the imperviousness of the shales caused water to collect on the contacts, producing a dangerous condition when present in the tunnel arch.

Physically two kinds of shale were present, a massive brittle fine grained shale, and a coarse-grained bedded shale, both commonly interspersed with coaly streaks and seams. The former broke in a very jagged or conchoidal manner, with fractures propagating to depth. The latter broke more or less on bedding planes or joints and did not suffer as intensive shatter.

It was evident much of the tunneling in these rocks would require support. Having regard to their proneness to rapid atmospheric deterioration, sealing of the rock surfaces appeared to offer advantage in the final measure of support and lining. The European shotcrete technique offered both seal and support functions against the single function of the steel support system. It also offered possibilities of a major saving. With instrumentation its behaviour under load could be observed and precautions against failure taken if necessary. Finally, instrumentation could determine the necessities of final lining (in the present instance found unnecessary). It was on this basis that the coarse aggregate shotcrete system was chosen.

The instrument programme consisted of two components. Firstly, it was the intention to make numerous spot checks along the tunnel on the outer shotcrete surfaces where tensile stresses occur. The biaxial photoelastic strain gauge was chosen as simple and inexpensive An attempt was made to adapt three 1" length (SR4) electrical strain gauges in a plastic sandwich. The results were meaningless, however. Indiscriminate application of photoelastic gauges also proved meaningless attachment not being completed until 48 hours after blast. The initial strain preceding 48 hours hence remained unregistered.

The over-coring technique also was used. A set of three cores was extracted from the tunnel arch at 300' intervals with photoelastic gauges attached, measuring the instantaneous rebound. Of 91 samples taken 60 were too low to read (-200 psi). Of the remainder, 3 were in compression reading from 270-530 psi in the major stress direction and 28 were in tension, indicating these cores were in flexural stress condition. These readings with one exception did not exceed 500 psi. This exception read 1250 psi adjacent to Gloetzl cell readings of similar nature. (sta. 48 + 05). The latter was in compression, however. As already noted beam tests have yielded an average flexural strength of 1150 psi, ranging from 800-1800 psi. There is no indication of failure at this point.

The intention of the second stage of instrumentation was accuracy of continuous monitoring of in situ shotcrete pressure and rock-shotcrete contact pressures. Terrametric's Gloetzl pressure cells were chosen and three installations made. Each installation consisted of 11 cells, of which 5 reported rock pressures and 6 reported pressures in the concrete. They were installed within 8 hours after a blast, hence monitored very early pressure build-up. The Gloetzl cell is essentially a thin sensing pad containing hydraulic fluid. Static pressures are measured with a simple hydraulic pump with gauge.

The following describes the stations (see Figure 6)

67 + 87	Conglomerate, calcified matrix, 280' cover. Soundest section of rock encountered. No blast shatter.
60 + 21	Sandstone, coarse grained, loosely cemented overlain by flat bedded and jointed shales. Continuous trickle of water from sandstone and contact. Sandstone broke cleanly, shales blast shattered. Cover 240'. Bolted 5' x 5' pattern, grouted bolts.
48 + 05	Shale, dense, fine grained, brittle, overlain by soft sandstone and thinly bedded shale, almost dry. Intensely blast shattered. Cover 140'. 5' x 5' bolt pattern, grouted bolts.

The Gloetzl cells measure pressures which can be said to represent average stress measurements. (Figure 6) The contact cells report radial stresses and the concrete cells tangential stresses. Very high radial pressures were reported, the highest being 110 psi (15,840 psf) at 60 + 21 and 48 + 05. Highest radial pressure at 67 + 87 was 40 psi.

These maximum stresses were all located on the east side of the arch. Tangential stresses were generally low, 290 psi and 380 psi at 67 + 87 and 60 + 21 respectively, but reached 1320 psi at 48 + 05. A plateau of equilibrium appears to have been reached in 60 days for both stresses in all cases, with subsequent deviation commencing about 100 days. A feature of interest is the lack of radial stresses at the springline in every instance.

Figure 7 is obtained from von Rabcewicz's paper "Development, Completed Projects and Experiences" in "Der Bauingenieur, 1965." It shows similar stress diagrams from pressure cell measurements from the Schwaikheim railway tunnel near Stüttgart, Germany. This tunnel was driven with shotcrete support through plastic marls chiefly. The pattern of irregular loading is similar, though the magnitudes are relatively less. Again is found the decrease of radial pressures to zero at the abutment. It is evident a shotcrete lining does not support loads by transferring them to the tunnel floor as do steel sets, rather are they redistributed in the arch by arching of local irregularities of rock and shotcrete contour. Rabcewicz remarks "The customary form of increased abutment with a sidewall support area (haunches) is therefore redundant and wasteful."

Magnitudes of loadings in the Vancouver Tunnel are high measured against conventional assumptions of steel support design. The steel support system would not expect to encounter such loads, however. Radial stresses would tend to be cushioned or dissipated in the zone of relaxation and loosening, and loadings would result chiefly from weight of the latter. For instance, 8 WF28 steel sets at 5' spacing will support 15 psi vertical pressure, and would have proved adequate for much of the Vancouver Tunnel. With shotcrete, relaxation and loosening is sharply restricted, hence rock pressures must build up and similarly shotcrete pressures in restraint of the former, without the relief provided by relaxation.

Radial stresses in the shotcrete supported Schwaikheim tunnel also were low relative the Vancouver readings, maximum being 37 psi. Questionability of the Vancouver readings would seem to be met by the general agreement found by independent systems such as the Gloetzl and the photoelastic gauges. One common denominator can be found for the steel support system and the shotcreted Schwaikheim tunnel, their yield capabilities. Yield is implicit in the steel support function and in the flow tendencies of the Schwaikheim ground. Both provide relief from direct radial stresses by redistribution tangentially. The relatively rigid Vancouver rocks would not have equal yield.

However, the most important fact obtained from the instrumentation programme is that general equilibrium has been reached, and no significant changes can be anticipated. The high of 1200 psi read in one shotcrete gauge is relative a 2250 psi allowable stress. Also, since concrete creeps considerably, its ultimate failure in compression depends markedly on rate of loading; it may fail at normal rate at 5000 psi and yet not fail at 8000 psi if the loading is applied increasingly over several days. The instance of Figure 5 should be considered. Hence the use of 2250 psi allowable stress is conservative. The shotcrete support of 6" on arch and 4" on walls thus has been found adequate both as an initial support and a final lining.

LIST OF ILLUSTRATIONS

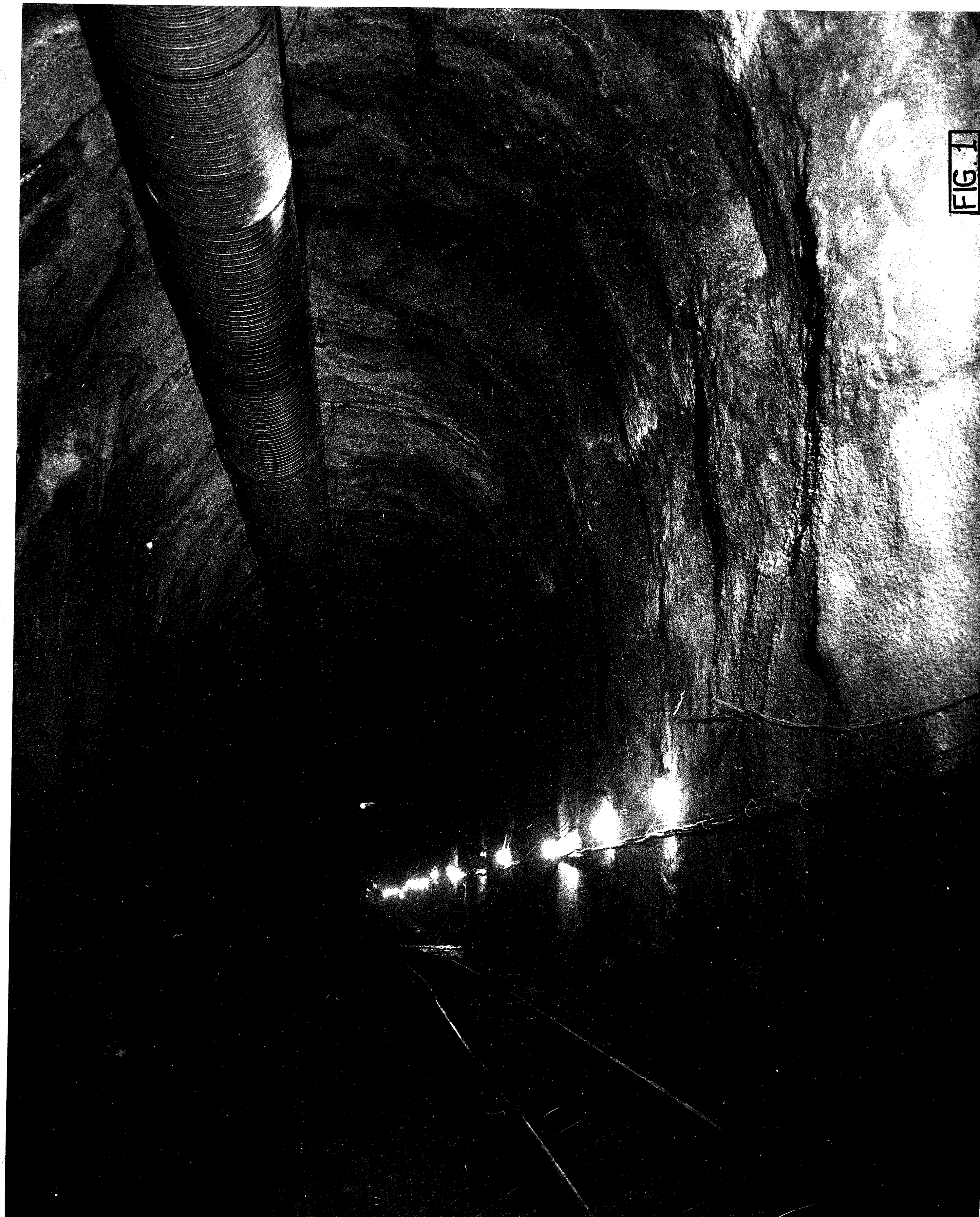

FIG. 1
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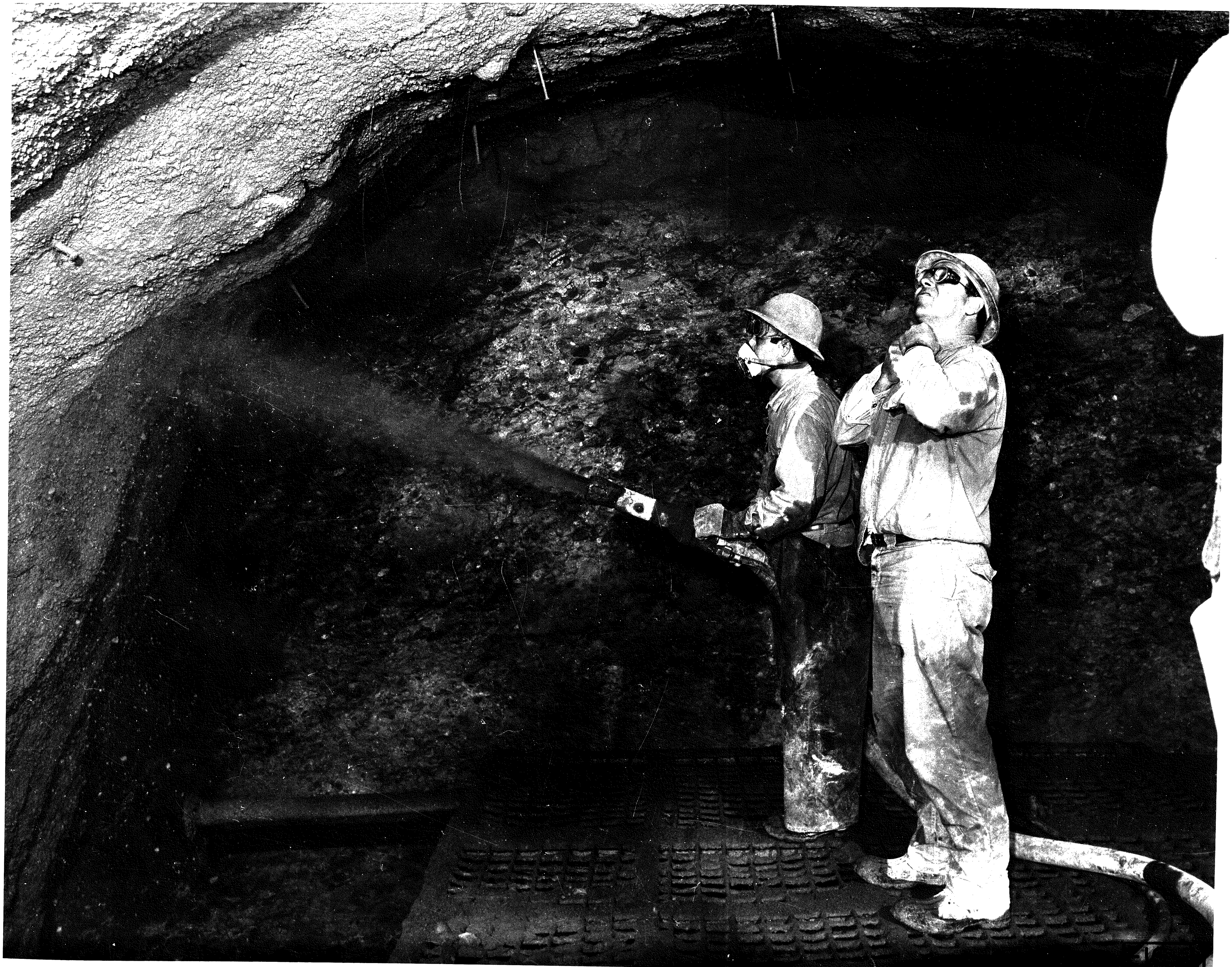

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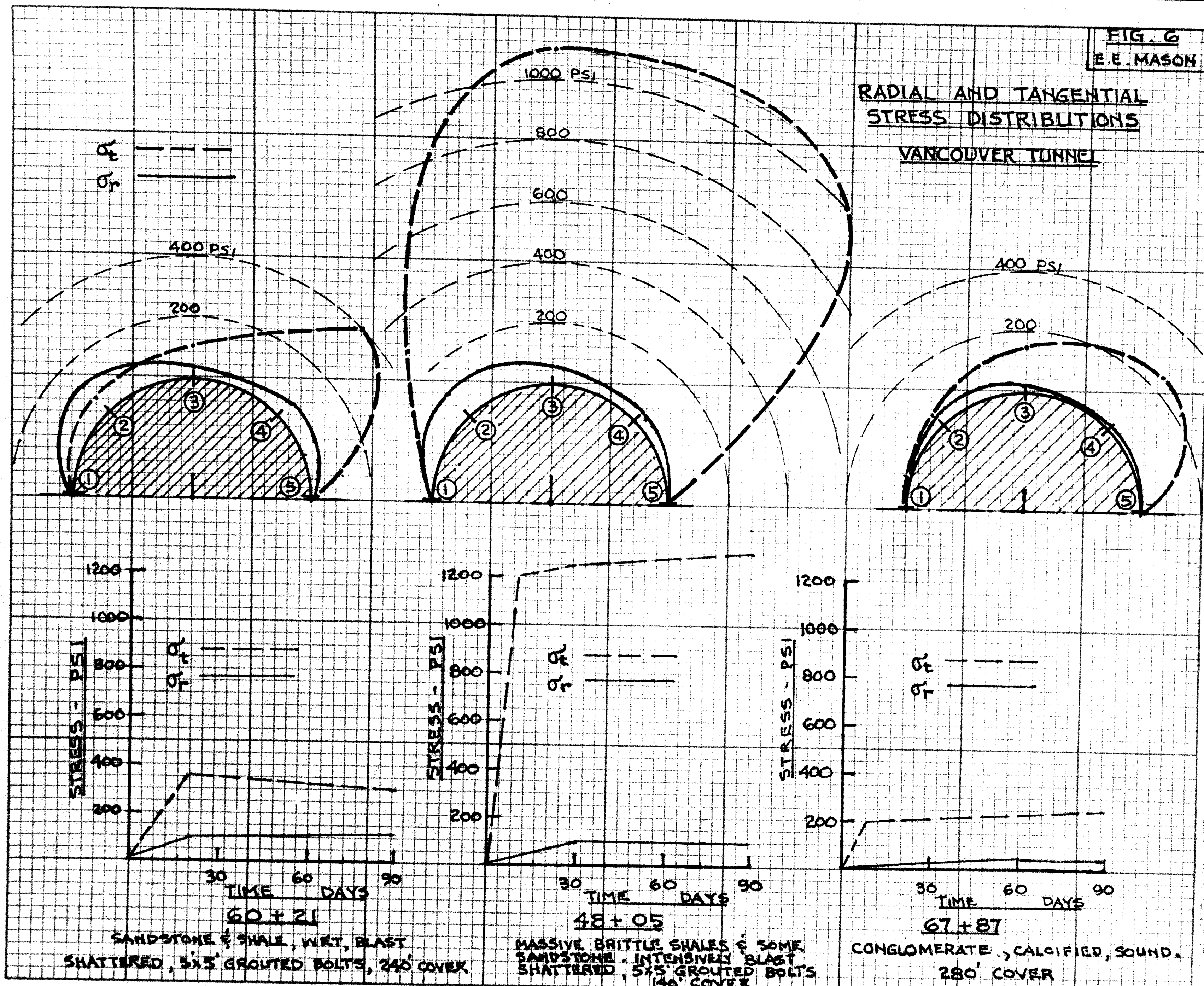

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