SHOTCRETE AS UNDERGROUND SUPPORT ON THE ARENAL HYDROELECTRIC PROJECT IN COSTA RICA - CENTRAL AMERICA

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INTRODUCTION

Costa Rica is one of the five Central American countries and, because of its temperate climate and mountainous topography, it is often referred to as the Switzerland of the Americas. For the past twenty years, the Government of Costa Rica has been aggressively developing its considerable hydroelectrical resources through an autonomous power authority called "Instituto Costarricense de Electricidad" (ICE). The use of shotcrete as temporary and permanent underground support has greatly contributed towards the successful completion of a number of hydroelectric projects constructed by ICE during the last decade.

Of principal interest to the subject at hand are the tunnels and other underground construction features of the Arenal Hydroelectric Project. This project is now under construction and is well advanced for scheduled completion towards the end of 1978. The purpose of this paper is to attempt to describe in detail the use of shotcrete as underground support on this interesting project.

The project is situated in the province of Guanacasta, approximately 200 kilometres north-east of the capital city of San Jose. It is managed and staffed by ICE's own forces consisting mostly of the same personnel which was involved in the successful completion of the very difficult Tapanti Tunnels. To assist with construction problems, Jacobs Associates of San Francisco were engaged as consulting construction engineers.

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Principally, the Arenal Hydroelectric project involves the construction of a 587-metre long river diversion tunnel, a medium sized earth filled dam, a 6,700-metre long power tunnel, surge shaft, penstocks and other associated power generating facilities.

The construction of the Arenal River Diversion Tunnel was completed in December, 1975, and the excavation of the power tunnel has progressed to a point where approximately 1,000 lineal metres remain to be excavated. For the purpose of this paper the principal features of interest are the excavation and shotcrete support methods employed during the construction of the Arenal River Diversion Tunnel and the Arenal Power Tunnel and are in continuation elaborated in somewhat more detail.

Shotcrete as Underground Support

Due to the lack of readily available advanced geological information, and because of past experience with shotcrete, and its proven good performance and flexibility, ICE decided to use shotcrete as temporary underground support wherever prevailing ground conditions permitted. The decision to use a dry-mix coarse-aggregate shotcrete support system was principally based on the fact that ICE's tunneling crews were trained and well experienced with the Swiss made Aliva machine, which is capable of placing high quality dry-mix shotcrete at an acceptable production rate.

Generally, prevailing rock conditions dictated excavation methods to be used, length of advance per excavation cycle, as well as the type of quality of the underground support. Basically, three conventional tunnel-
ing methods were used. They were the Standard Full Face Method, the Top Heading and Bench Method and the Crown Pilot Tunnel Method.

The selection of the required temporary support was based upon geological conditions encountered at the time of the tunnel excavation. In all cases, dry-mix coarse-aggregate shotcrete formed an integral part of the overall support requirements. It was used either alone, with or without steel reinforcement, or in combination with structural steel rib support and steel reinforcement.

In sound dry rock a full face method was used, advancing the tunnel face by 1.5 or 2.0 metre rounds, requiring none, or very little shotcrete support to prevent air slacking. Normally, a 5-centimetre thick shotcrete application was quite sufficient to prevent air slacking and provide efficient support for the tunnel. In blocky, fractured and highly jointed rocks, 5 cm to 15 cm of dry-mix shotcrete was applied to the crown and walls. In this case shotcreting of the arch and part of the walls was done right after, or even during, mucking operations following each successive tunnel excavation cycle advance. The first application was later reinforced to the required shotcrete thickness by a second and possibly a third application. If steel reinforcement of the lining was required, the reinforcing steel bars were placed between the first and second application. The steel reinforcement consisted mainly of variously spaced deformed reinforcing steel bars (19 mm and 25 mm diameter). In wet areas, where the performance and quality of a temporary shotcrete lining was doubtful, full-face, four segmented WF 6 x 25 lbs
structural steel ribs were installed at a spacing ranging from one metre to a maximum of 2.0 metres center to center, to act as temporary support and become part of the permanent tunnel lining, when at a later date, they were fully embedded by a 50 centimetre thick conventionally cast-in-place concrete tunnel lining. At that time water inflows had diminished a great deal and very little special drainage and water by-pass work was necessary to obtain a good, sound, permanent tunnel lining. Locally heavy and persistent water inflows were dealt with by the installation of drainage tubes preceded by drilling short strategically located drill holes.

Tunneling through highly fractured and loosely jointed weak and wet rock of low self-supporting quality, a standard Top Heading and Bench Method was used, and the tunnel advance was limited to one-metre long excavation rounds. Depending upon the quality of prevailing ground conditions, a 3-metre to 6-metre long bench was maintained at all times. Structural steel support for the top heading consisted of a single steel wall plate (WF 6 x 25 lbs), or WF 8 x 48 lbs), together with four segmented (WF 6 x 25 lbs) structural steel ribs, installed at 1.0 metre centers. To maintain lateral stability of the structural support system and to permit blasting in close proximity to the structural steel ribs, a total of seven double three-inch channel collar braces were welded between the steel sets. Generally, wood blocking and lagging were used. However, in some sections, the use of steel lagging was necessary. Once the steel rib installation was completed and the steel sets properly blocked and braced, a 5-cm to
15-cm dry-mix coarse-aggregate shotcrete lining was applied on to the steel ribs along the crown and down to the tunnel springline where the structural steel wall plate was completely embedded by multi-stage shotcrete application. In order to prevent tunnel face disintegration, while bench excavation was in progress, the shotcrete lining was extended up to and also on to the tunnel face proper. During benching operations, as soon as a set of WF 6 x 25 lbs wall posts had been installed under the wall plate, the required shotcrete lining was extended to the bench walls below the tunnel spring line. Invert struts (WF 6 x 25 lbs) were used wherever squeezing ground conditions were encountered. When necessary a conventionally poured concrete invert was installed at 5-metre intervals.

Tunnel excavation through very soft, unstable and wet fault gouge material was achieved by excavating first a 1.7 m x 1.7 m pilot tunnel, driven at the crown along the center line of the tunnel. This pilot tunnel usually extended some 6 m to 10 m ahead of the top heading face. It was then progressively enlarged to full tunnel size by Top Heading and Bench Excavation and support procedures. This same Crown Pilot Tunnel Method was also employed to advance the tunnel excavation through unconsolidated waterlogged fault zones. In this case, the Pilot Tunnel and the Top Heading were advanced by breastboarding and fore-poling methods.

Dry-mix coarse-aggregate shotcreting operations for the placing of the temporary shotcrete tunnel support were usually carried out as part of the excavation cycle directly behind the excavation face. However, when
required by adverse geo-structural conditions, the temporary lining thickness was increased and reinforced a short distance behind the excavation face as prevailing working conditions would permit, without adversely affecting the critical excavation cycle.

**Shotcrete Components and Methods**

The shotcrete dry-mix used on the Arena! Tunnel project is designed to produce 3,500 psi shotcrete in place and consists of the usual mixture of fine and coarse aggregates, cement and chemical additives. A typical shotcrete dry-mix design contains 340 kg of cement per cubic metre, 60% sand and 40% coarse aggregates (20 mm, passing), gradation of the fine and coarse aggregates conforming as closely as possible to the gradation lines suggested by the manufacturer of the delivery equipment (see Gradation Charts, Figure 1 and Figure 2). Bagged Type 1 Portland cement was used throughout.

In order to accelerate the initial setting process of the placed shotcrete lining, and possibly also to decrease somewhat the amount of rebound, chemical accelerators in powder form were incorporated into the dry-mix by dispensing them by hand into the mixture at the delivery equipment hopper. However, because of the great cost involved the inclusion of these accelerators into the dry-mix was restricted to locally wet zones and to first stage shotcrete applications carried out directly at the tunnel face, while excavating through unstable ground. Two percent of calcium chloride dispensed into the dry mix either in powder form at the delivery equipment,
Aggregate grading for shotcrete recommended by Rothfuchs. Grading lines B for shotcrete with fine aggregate up to 1 in.; Line E for shotcrete with coarse aggregate up to 1 in.

Figure 1

Aggregate grading for coarse-aggregate shotcrete suggested for use with Aliva BS-12, compared with Line E of Fig. 1.

Figure 2
or in liquid form into the discharge nozzle performed well and proved to be the most economical chemical accelerator for the purpose at hand. For special problem areas where for rapid installation an efficient shotcrete support is essential, liquid sodium silicate is added to the mixing water to accelerate the initial set of dry mix. In some instances where shotcreting had to be carried out through very wet zones and water bearing areas, the use of sodium silicate facilitated the reduction of the initial setting time to 15 seconds.

Because of the large distances involved in transporting the shotcrete material and the high humidity present in the tunnels, it was necessary to dry batch and mix the shotcrete ingredients without the inclusion of the cement. Dry batching and mixing were done by a small manually operated batch plant situated outside the tunnel near the Adit portal. The dry premixed shotcrete material is then loaded into specially designed 4-cubic metre covered bottom dump rail cars and hauled into the tunnel to the placing equipment, where it is discharged by a short belt conveyor into a small rail mounted mixer. The required amount of cement is then added to the dry batched aggregates and after a two-minute remixing period, fed directly into the receiving hopper of the rail-mounted shotcrete delivery equipment. In order not to cause any undue interference with other ongoing tunneling operations, the shotcreting equipment train is always situated on a side track some 300 metres back from the placing area. A steel pipeline (5 cm diameter) situated between the placing equipment and the shotcrete placing area facili-
tated the pneumatic transport of the dry-mix materials from the shotcrete machine to the placing hose. The use of discharge nozzles was eliminated. Nowadays, better results are obtained without the use of a nozzle; whenever frayed the discharge end of the delivery hose is simply cut back some 8 to 10 inches at a time. The required water usually is introduced at the nozzle. However, based upon past experience, it was found that by positioning a single or double watering "O" ring some 3 to 6 metres back from the discharge end of the delivery hose, the quality of the shotcrete in place is better and rebound is less. Also, the production rate of the machine is somewhat increased. A typical shotcrete placing operation carried out behind the tunnel face requires a seven-man crew. Shotcrete operations carried out at the tunnel face while excavation is in progress were considered to be part of the excavation and support cycle, and therefore handled by their respective excavation crews. Four complete shotcrete placing trains are used on the project.

Without doubt, dry-mix coarse-aggregate shotcrete employed on the Arenal Project either alone or in combination with other means of modern underground support components performed very well in providing a rapid, efficient and economical tunnel support system.

The Arenal River Diversion Tunnel

This tunnel is 587 metres long, circular, 6.0 metres in diameter, having a finished cross-section area of 28.3 square metres. It was excavated at a somewhat modified horseshoe cross-section of 45 square metres, roughly 7.5 metres high and 7.5 metres wide at the springline, tapered to a
ARENAL DIVERSION TUNNEL

Typical Tunnel Cross Section

Figure 3
5.5 metre width at the base of the section.

The materials through which the tunnel was excavated consisted mainly of loosely cemented agglomerates, soft decomposed tuffs, loose highly weathered lavas, all locally interbedded with lenses of loose gravels, poorly cemented conglomerates and pockets of fine sand. The materials were generally fairly dry and only a few local wet and ravelling conditions occurred. The location of the active Arenal Volcano is only approximately 3 kilometres from the site of the diversion tunnel.

Because of the anticipated unfavorable ground conditions, it was decided to excavate the whole length of the diversion tunnel by the classical Top Heading and Bench Method, i.e. the entire length of the Top Heading was excavated first, and later enlarged to its full size by a standard bench excavation method. A 25 square metre top heading cross section was selected as being the most suitable tunneling section to use, since it accommodated well the employment of all the rail mounted tunneling equipment, available from the Tapanti Project. The resulting top heading section being approximately 4.2 metres high and 7.0 metres wide at the base permitted tunnel drilling and support installation to be carried out from two side-by-side placed jumbos, and for mucking to use two Eimco 40W loaders working side by side loading into 4-cubic metre side dump muck cars at the face. Upon completion of the top heading excavation the bench was drilled vertically and mucked out by a single rail mounted overhead loader.
Excavation and Support Techniques - Arena! Diversion Tunnel

Having had the benefit of past experience with the excellent performance of shotcrete as underground support, it was only logical for ICE to make use of and improve upon this experience in the construction of the Arena! Diversion Tunnel. Taking into consideration all available geostuctural data of the site for the Diversion Tunnel, a specially designed composite, structural steel rib reinforced, shotcrete support system was selected to serve as an efficient and economical means of providing the required temporary underground support.

It was known well in advance of the actual excavation that the materials through which this tunnel was being driven are characteristically very low in self-supporting qualities. Therefore, in order that the selected support performs satisfactorily, it will be of the utmost importance that all elements comprising the temporary support system must be installed as soon after the excavation of a one-metre long tunnel advance was accomplished.

Past experience has shown that during structural support erection at the tunnel face a great deal of valuable time is being unduly lost because of the slow procedures associated with the installation of the required steel wall-plate. In the light of anticipated difficult tunneling conditions, this time loss is ill afforded, and therefore, a number of other possibilities of wall-plate requirements and their associated installation procedures were explored and studied in detail. This effort showed in its conclusion that the use of the troublesome structural steel wall plate could be completely
eliminated and substituted by an adequately designed shotcrete-placed beam, spanning along on both sides of the tunnel walls at the base of the previously installed steel rib. Detailed design calculation indicated that a conventional dry-mix, multi-stage shotcrete application 20 centimetres wide by 70 centimetres high, placed between and over the steel ribs at the foot blocks level would most adequately serve the purpose of completely eliminating the use of a multi-joint structural steel wall plate. Based upon the above outlined criteria, it was decided to substitute the structural steel wall plate by incorporating into the structural steel shotcrete reinforced lining a 20-centimetre x 70 centimetre shotcrete sprayed wall plate beam.

Basically, the temporary support for the diversion tunnel consisted of the installation of a three-segmented structural steel rib (WF 5 x 18.5 lbs) set on 30 cm x 30 cm x 12 cm concrete or wood foot blocks. The steel rib was installed at 1.0 metre spacing as close to the excavation face as prevailing ground conditions permitted, and a total of 6 collar braces (WF 5 x 18.5 lbs) were bolted between the ribs. Once the structure was blocked into place a 10-centimetre to 15-centimetre chemically accelerated dry-mix shotcrete lining was applied to the crown and walls of the Top Heading. Shotcreting the full cross-section of the 20-cm x 70 cm wall plate beam was achieved by a secondary application carried out some distance behind the excavation face while primary shotcrete support operations were in progress at the face.

While excavating through an approximately 70-metre long zone of particularly troublesome, wet and unconsolidated materials, it was neces-
SHOTCRETE FOR GROUND SUPPORT

SHOTCRETE TUNNEL SUPPORT

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Average hourly labor cost: U.S.$116.23/hour
Total shotcreting time: 765 hours
Total shotcrete labor cost: U.S.$88,918.00
Total shotcrete placed: 2,850 square meters
Total shotcrete labor cost: U.S.$31.20 per cubic meter
Total shotcrete equipment cost: U.S.$3.98 per cubic meter
Total shotcrete material cost: U.S.$29.29 per cubic meter
Total shotcrete cost: U.S.$64.47 per cubic meter
Total cost to support 1 lin.meter of tunnel: U.S.$185.67 per lin. meter
Total cost per lin.ft. of shotcrete supported tunnel: U.S.$56.61 per lin. ft.
Total cost per cubic yard of shotcrete: U.S.$43.28 cu yd

Figure 5
ARENAL PROJECT

ARENAL DIVERSION TUNNEL

TEMPORARY SUPPORT CRITERIA

REVIEW PROPOSED TUNNEL SUPPORT IN POOR GROUND

(BY RSR CONCEPT)

PROPOSED TEMPORARY SUPPORT: 6-inch shotcrete lining in combination with structural steel arches

PROPOSED STEEL RIBS: WF 5 x 18.5 lbs set at 4-ft centres plus 6-inch shotcrete

A. Datum Spacing: 
\[ S_d = \frac{PR}{331D} = \frac{4900}{331 \times 25} = 0.59 \]

B. Rib Ratio (RR) for a 4-ft spacing:

\[ RR = \frac{0.59 \times 100}{4.0} = 15 \]

C. Equiv. RR for 6-in shotcrete = 77

Total Equivalent RR = 92

D. Total equiv. rock structure rating for RR = 92

\[ RSR = \frac{8800}{(RR + 80) - 30} = 21 \]

RSR = 21 (Range of heavy support satisfactory)

E. Load carrying capacity of combined support:

\[ Wr = \frac{D \times RR}{302} = 25 \times 92 = 7.5 \text{ kips/sq ft} \]


Figure 4
sary to increase the capacity of the shotcrete embedded structural steel ribs. Accordingly, in this section, heavier (WF 8 x 48 lbs) structural steel ribs were used instead of the conventional WF 5 x 18.5 lbs structural steel ribs. Even under these severe ground conditions, the shotcrete composite underground support system performed very well indeed.

The above described temporary support system performed most satisfactorily and greatly contributed towards the successful and timely completion of the tunnel. In comparison with other similar tunneling projects in South and Central America, the excavation and support costs obtained on the Arenal Diversion Tunnel project were extremely low and are directly attributable to the good efforts and experience on the part of ICE's construction forces in the economical use of dry-mix coarse-aggregate shotcrete as underground support.

**Excavation and Support Techniques - Arenal Power Tunnel**

The excavation of the Arenal Power Tunnel is now well in progress. Access to the tunnel proper was gained through a 500-metre long construction adit located approximately 2,000 metres upstream from the downstream tunnel portal, and a 200-metre long inclined adit near the tunnel intake portal. (See Drawing No. D-111). The access adit (Ventana B) was constructed mainly through loose decomposed weathered tuffs by a standard full face excavation method. It was supported by structural steel ribs (WF 5 x 18.5 lbs) set at a maximum of 1.0 metre centers and was reinforced by a number of dry-mix shotcrete applications to a finished lining thickness of 35 centimetres. Access to Adit A was constructed by a top heading and bench
tunneling method through wet soft loose decomposed tuffs requiring heavy structural steel support reinforced by 20 cm of shotcrete.

The Arenal Power Tunnel is approximately 6,700 metres long, circular and will be lined by conventional concrete to a finished diameter of 5 metres. The tunnel is being excavated at a horseshoe type cross-section of approximately 30.0 square metres, dimensioned roughly 6.0 metres high and 6.0 metres wide at the springline tapered down to 4.2 metres at invert level. Presently available geological information indicates that the power tunnel will be excavated mainly through soft friable tuffs, loosely cemented agglomerates, decomposed and hard blocky lavas and a number of fault and contact zones. When dry this material does not present especially difficult support problems. However, when wet the development of heavy loads, accompanied by squeezing ground conditions, result in making excavation and tunnel support operation, to say the least, very difficult.

Depending upon prevailing ground conditions, the tunnel is being excavated either by a standard Full Face Tunneling Method or by Top Heading and Bench procedures similar to the ones described above. Contingent upon encountered ground conditions temporary support requirements are met by either a 5-cm to 10 cm thick unreinforced dry mix shotcrete lining for table ground conditions, or a multi-stage shotcrete lining reinforced by variously spaced structural steel ribs required for tunneling through ge-structurally weak formations.
SHOTCRETE FOR GROUND SUPPORT

ARENAL POWER TUNNEL

DRY-MIX COARSE-AGGREGATE SHOTCRETE

COST ANALYSES OF SHOTCRETE AS TUNNEL SUPPORT
FOR TUNNEL HEADING 2-2 (Tunnel Outlet)

Length of tunnel constructed: 990 lin. meters
Size of tunnel heading: 30.6 sq. meters
Total volume excavated: 30,254 cubic meters
Volume of shotcrete in place: 2,850 cubic meters
Volume of shotcrete per lin. meter of tunnel: 2.88 cubic meters

EXCAVATION AND SUPPORT COSTS

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