Innovative Rehabilitation Approach for Overstressed Existing Linings Using an Adaptable Yielding Support System

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ABSTRACT

Yielding support systems for application in underground construction have a long history, primarily in mining. Typical examples are tunnels subject to loading conditions that lead to overstressing of the newly installed support or existing tunnel structures in active fault zones. Recent applications for tunnel rehabilitation projects unveiled the capabilities and flexibility of combined yielding support systems presented in this paper.

Frequently, the main requirements for tunnel rehabilitation applications are a fast, safe, and simple installation along with the need for flexibility with regards to existing tunnel geometries. A combined support system consisting of steel sets with yielding connections and special groutable hoses has proven to be an efficient support measure providing a multitude of advantages compared to conventional rehabilitation approaches. The presented yielding support system provides an immediate and active support, while it allows for controlled yielding upon experiencing loads beyond its support capacity.

INTRODUCTION

The excavation of underground spaces leads to redistribution in the existing stress regime. This load redistribution goes along with deformations in the surrounding rock mass. Magnitude and duration of these deformations depend on the tunnel's depth and geological conditions, but also on the installed support system.

Modern civil tunneling infrastructure has generally an envisioned service life of about 120 years. Conventional tunneling provides typically a dual support system, split into the initial (or primary) and final (or secondary) lining. A typical design principle in civil tunneling is to let the vast majority of deformations acting on the initial lining cease, before the final lining is installed. Based on this approach, the loading on the final lining is significantly reduced and signs of overstressing, such as cracking of the lining, are typically limited to the initial lining. However, special cases in swelling and squeezing ground require different approaches, including yielding support systems.

Ground support design for mining applications takes a different approach. Here, the support is typically limited to the initial lining; final or secondary linings are rare exceptions. In general, the service life of typical mine development tunnels is much shorter compared to civil infrastructure. Therefore, the installed support appears typically much lighter, compared to initial lining in civil infrastructure. Different to civil tunneling, large deformation and ongoing convergence and rehabilitation or even re-mining of sections that show signs of overstressing or excessive deformations are generally accepted. The major driver for the support system and required rehabilitation cycle design is the cost for the infrastructure relative to its benefits for the operation of the mine.

Old civil, private, or mining infrastructure was bound to the means and methods of its time. While today's mechanization and the development of shotcrete and other sprayable support materials allow for a very quick installation of support measures after excavation, the installation of the support in the old days took much longer. Especially under difficult ground conditions, larger areas around the tunnel were loosened or were subject to excessive overbreak. This created considerably more loading on the lining than we are used to today, where relatively thin linings and light support became the standard. In some of these old tunnels, the load redistribution is continuing until today, creating ongoing creep and overstressing, and eventually the need for rehabilitation of the lining.

Another area of yielding support systems can be found were the surrounding rock mass itself is constantly moving. These constant movements can be induced for example by fault creep in active fault zones or in areas of active slides or slopes. If tunnels were built in these areas they may be subject to constant movements and load redistribution acting on the lining. Signs of movement and overstressing are typically observed right at the boundary between moving and stationary sections, which is not surprising.

Generally, two diametrical design approaches can be chosen to resist the active forces. On the one hand, the support can be designed stronger to resist the acting forces on the lining. However, strong linings typically also go along with more stiffness, attracting even more loading. If the acting forces are too large, the deformations cannot be stopped with the stiffer lining and eventually the lining will still fail. Another approach is to choose the opposite route: design of a relatively soft lining, yielding to excessive loading and deformation.

Yielding support systems in general comprise all ground control elements, which allow a considerable controlled stress release and deformation of the ground, while maintaining supporting forces. Main areas of application are squeezing and swelling ground conditions, weak ground in general combined with high overburden, and fault zones. Depending on ground conditions, magnitude of displacements, and lifetime of the excavation, different means and methods of yielding support are applied. Examples for support elements with a yielding ability are anchors and rock bolts with a free length or a deformable section, lining stress controllers (integrated in a shotcrete or concrete lining), or yielding steel support, just to mention a few [3], [4].

APPROACH AND DESIGN

The following introduces a yielding support system, which acts like a relatively stiff support system, until it is overstressed and yields automatically. It also allows for an active, controlled stress relief and was used for a recent rehabilitation project in a mining environment. However, it should be noted that it could also be used as an initial support system during excavation or for civil applications.

The rehabilitation concept was developed to achieve several major goals. Most importantly, the design had to consider the need for a relatively clean and simple installation process and limited available clearance, as well as the advantage of pre-assembly prior to construction.

Support measures initially evaluated included installation of shotcrete or a new cast-in-place lining, but had to be excluded from the beginning due to the lack of clearance during construction.

Options with rock bolts as the primary rehabilitation support did not appear to be feasible. It was to be expected that relatively long rock bolts would be necessary to pass the loosened area around the original tunnel to show a sufficient structural effect. Since no detailed information about the rock mass surrounding the tunnel was available, rock bolting was considered too risky for a long term solution. In addition, installation of long rock bolts would have been a challenge with regard to the given clearance and potential damages of a conveyor belt operated in the tunnel during construction by potential collisions and muddy drilling water. Due to similar concerns, shotcrete was excluded, but it appeared unattractive for another reason too: spalling of shotcrete from previous rehabilitation measures was one of the reasons to restrict access to the tunnel in the first place.

Considering the need for a relatively clean installation process and limited available clearance, as well as the advantage of pre-assembly prior to construction, steel sets appeared to be the only viable option. However, due to numerous passes of rehabilitation with rock bolts and mesh as well as shotcrete and combinations thereof, the steel sets had to provide sufficient geometrical flexibility during installation.

Regarding the ongoing slope movements, a stiff support appeared counterproductive. Therefore, a yielding support system had to be chosen, which allowed for movements while still providing sufficient structural support and a safe working environment. Yielding support also featured the greatest benefit to elongate the service life.

The design provided a yielding support system comprised of TH steel sets and prefabricated, grout filled fabric hoses, type BULLFLEX®. These grout filled fabric hoses allowed the TH steel sets to be designed with a 6-inch offset to the theoretical existing alignment, by providing continuous load transfer from the existing lining into the steel sets. The grout filled fabric hose system also allowed accommodation for geometrical imperfections of the damaged, existing lining or prior rehabilitation measures. In addition, joints of the TH steel sets were laid out to allow for vertical as well as horizontal adjustments providing additional geometrical flexibility during construction. Sections of the TH steel sets were laid out with an insertion piece, a so-called dutchman, to allow for adjustments for differing invert backfill levels (Figure 3).

TH steel sets were originally developed by H. Toussaint and E. Heintzmann (therefore TH) in the 1930's for mining operations in Germany, which are prone to highly squeezing ground conditions under high pressure. Due to its special shape, single interleaved TH sections are easily connected by different types of lock systems, which are defined by German standards [1], [2] (Figure 1). This allows both an easy and fast connection of single segments in underground operations. Different types of TH sections are available and classified according to their nominal weight in [kg/m], which equals 0.672 [lb/ft]). The TH steel sets are produced as straight pieces. The ground control supplier cuts and bends the TH profiles according to geometrical layout in the design drawings (Figure 3). Foot plates for the connection to spreader beams or nuts to allow for the use of spacer bars are factory welded.

The grout filled fabric hoses consist of textile encased columns made of high-strength fabric, which are subsequently filled with grout. For the current application as roof support backfilling system, grout filled fabric hoses were installed in the gap between existing lining and TH steel support to provide an immediate load transfer and form fit between the passive steel support and the lining surface (original concrete lining or rehabilitation measures, Figure 2). Due to the working mechanism of its fabric, grout filled fabric hoses allow even the introduction of an active pre-load into the excavation perimeter, while maintaining a controlled residual load. Excess water in the grout will be pressed out of the fabric by the grouting pressure, stiffening the grout. This process provides an immediate load transfer, even before the grout starts hardening. The grout filled fabric hose system has already been used previously for construction projects in the USA. Examples for applications are the Detroit River Outfall No. 2 [5] or the Northeast Interceptor Sewer in Los Angeles [6].

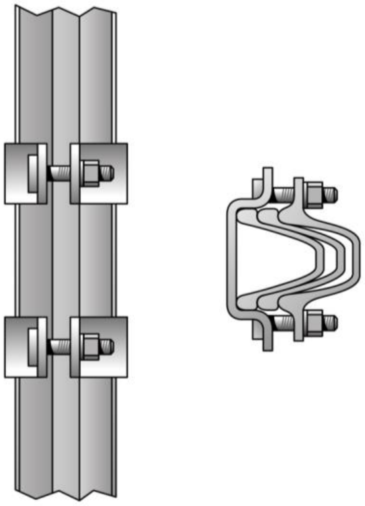

Figure 1: Principal assembly of the TH system

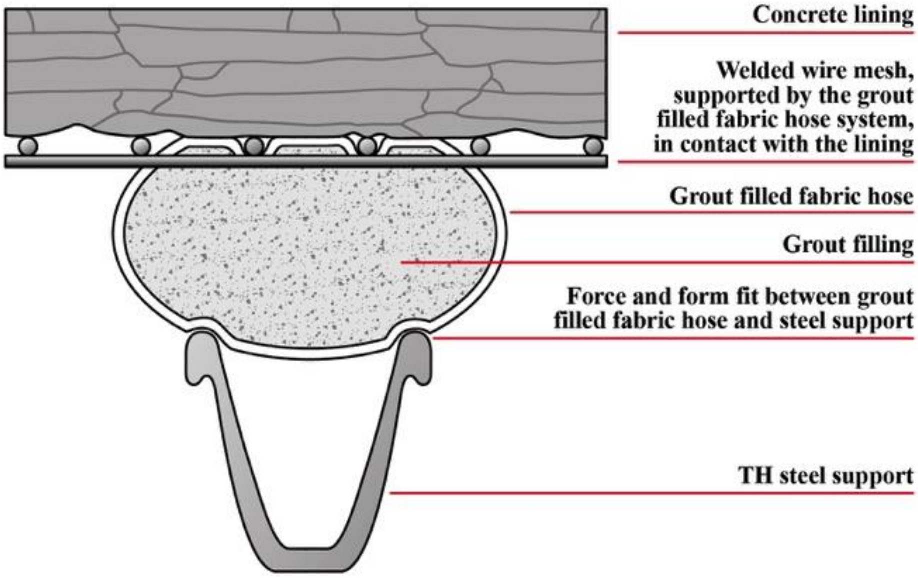

Figure 2: Schematic combined support system: TH steel set and grout filled fabric hose

The German standard DIN 21530-3 (2003-05) [3] also defines and standardizes the yielding load of TH joints connected by two or more locks, which is in the range of 150 to 200 [kN] (34 to 45 [kips]). Research regarding the load-deformation behavior of TH profiles with yielding locks in German coal mining dates back to the 1950's [7] and provides helpful insights into the yielding mechanism of installed

TH arch sections under progressive load and deformation or respective closure of underground openings. Simplified, the TH joints provide an ideal elasto-plastic like behavior. As soon as the slipping load in the joint is reached the joint slips by holding the load. However, by slippage in the joints the diameter of the entire cross section gets smaller and depressurizes the set – the support system, but not the steel itself, yields.

Based on the application at the case history project, ongoing ground movements are to be expected due to the surface and subsurface slope movements along a fault. Since the exact deformation mechanisms are unknown, the system was designed to allow for vertical as well as horizontal yielding. Yielding occurs as soon as the slippage load limit is reached. Due to the slippage the system distresses itself by yielding. Two vertical yielding joints are located at and below springline, and allow for sufficient yielding capacity in vertical direction. Two yielding joints in the back of the steel sets provide sufficient yielding capacity in the horizontal direction (Figure 3).

During the design, three different failure mechanisms were evaluated and quantified:

1. Yielding in the joints
2. Buckling of the vertical legs
3. Material failure of the steel

The system is designed in a fashion that buckling and steel failure can theoretically never occur, because the joints yield and de-stress the system before it can reach the buckling or steel failure load limits. In addition, the design for buckling conservatively disregarded the strutting effect provided by the grout filled fabric hose.

To avoid horizontal slippage of the steel set footings towards the center of the tunnel, the vertical legs are slightly sloped outwards to the concrete lining (Figure 3). A vertical load in the steel sets therefore always tends to push the footings outwards and hinders slippage of the footings towards the center, which could potentially destabilize the system. The geometrical layout locks the system in place to avoid this failure mechanism.

The open side of the TH steel sets is located towards the original lining. The grout filled fabric hose is pushed into this opening during grouting. Furthermore, the hose overlaps the sides of the steel sets as shown in Figure 2. After the grout in the grout filled fabric hose is hardened, it holds and supports the TH steel set in place and avoids a potential rolling out of the load plane of the set. A buckling of the system out of its load plane (cross-section) is naturally avoided by the system.

Therefore, the design provides a “self-protecting” system against numerous failure mechanisms. Buckling and overstressing of the cross section is avoided by yielding joints; buckling either in the cross section or out of plane is sidestepped by continuous support of the grout filled fabric hose. The potential for slippage of the footings is prevented by the geometrical layout.

It is also possible to conduct an active stress relief of the steel sets. During this procedure, the sections of the sets have to be de-stressed by temporary support measures. This allows to loosen and de-stress the joints. After distressing of the joints the load will be transferred back into the original set.

Another important design parameter is the spacing of the steel sets. The design of the case history project allows for a spacing of the steel sets between 3 to 6 feet. A 6 feet spacing allows to place additional steel sets in future rehabilitation campaigns on an as-needed basis.

Figure 3 provides the typical tunnel cross-section with the yielding support system.

Another element of the design is a so-called trigger action response plan (TARP), which is part of a ground control management plan. A TARP is a proactive management tool that defines pre-planned responses to escalating levels of risk. The scope and intent of the TARP is to ensure the health and safety of employees working in the tunnel by developing a mechanism for monitoring the tunnel against potential tunnel instability or failures and provide an action plan in case of any unwanted movement or instabilities, while the tunnel is still in service. The TARP serves as an integral component of risk management.

The TARP is a structured mode of addressing likely scenarios pertaining to the condition of the tunnel lining and provides suitable responses to mitigate and prevent health and safety as well as structural risks. Furthermore, the TARP defines the baseline level as a point of reference and two trigger levels, namely the warning level and the action level.

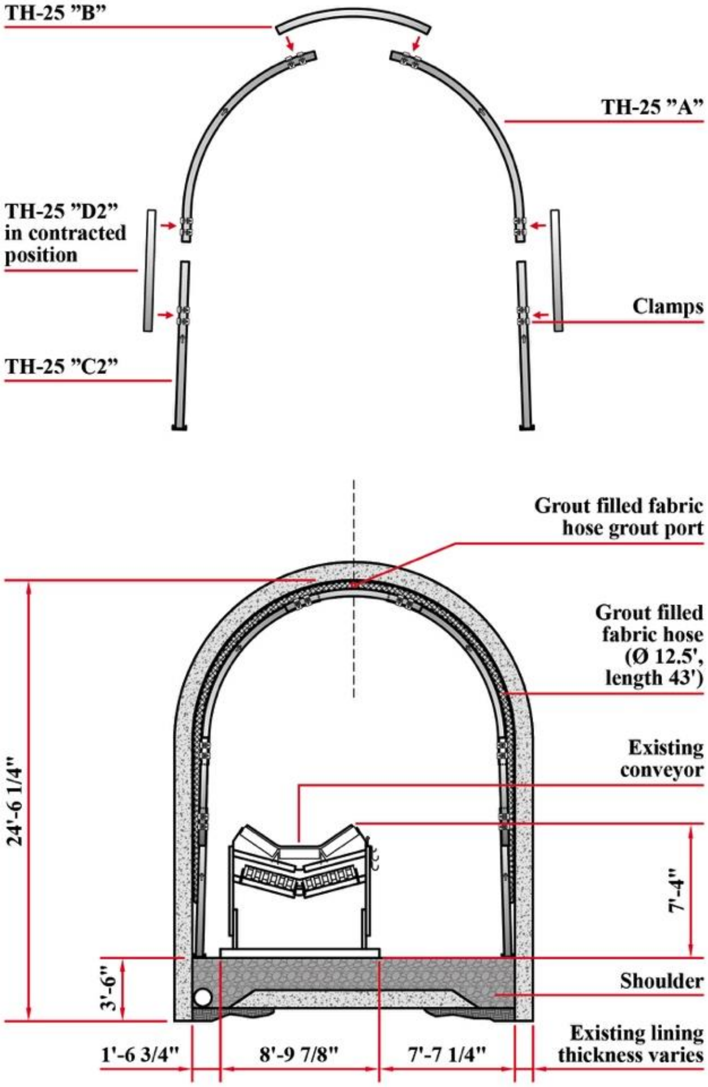

Figure 3: Typical tunnel section with TH steel sets

CASE HISTORY

The presented yielding support system was developed for the C6 Tunnel at Rio Tinto's Kennecott Copper (RTKC) operations at the Bingham Canyon Mine in Salt Lake City, Utah. The conveyor tunnel is considered a critical asset for the operation of the mine as it comprises the standard route for transporting crushed ore from the open pit to the processing facility on a continuous conveyor belt system.

The C6 tunnel was originally built as a railroad tunnel. Construction was completed in 1959. The original horse-shoe shaped cross section of the tunnel was 18 feet wide and 24-1/2 feet high [8]. The tunnel length was approximately 18,000 feet. However, the length of the tunnel towards the Bingham Canyon pit was shortened over the course of mining operations and the railroad tracks in the tunnel were removed. The invert was partially backfilled (3 feet typical) and a 72 inch belt conveyor was installed. Currently, the C6 Tunnel is nominally only approximately 21 feet high and 15,000 feet long.

The C6 tunnel was mined mainly with conventional mining methods, using drill & blast as the typical one. Weak geological sections, such as those encountered in the so-called Fortuna fault, were excavated by shaping and chipping with machine-held moils [8]. The tunnel was lined with steel sets embedded in concrete lining. A concrete lining with a minimum 4 inch coverage on the intrados of the steel support was specified. A large part of the tunnel was lined with 10, 12 or 14 inches of concrete to accommodate steel profiles of 6, 8 and 10 inches, respectively. The spacing of the steel sets varied from 2 to 6 feet according to the encountered rock conditions. The steel sets were backed with timber lagging (2 inches x 2 inches x 12 inches), which acted as a formwork at the extrados of the concrete lining. Voids between the lagging and rock were filled and tamped [8].

Figure 4 shows the typical geometry and support system of the C6 tunnel as completed in 1959. Figure 5 shows the C6 Tunnel in an area where it is partially unearthed by surface mining activity. Steel sets embedded in the concrete lining can be clearly seen, as well as timber lagging at the extrados of the lining. The deck shown in Figure 5 is not typical for the tunnel and was used close to the pit portal to protect the conveyor belt during demolition of the concrete liner, it has no structural support function.

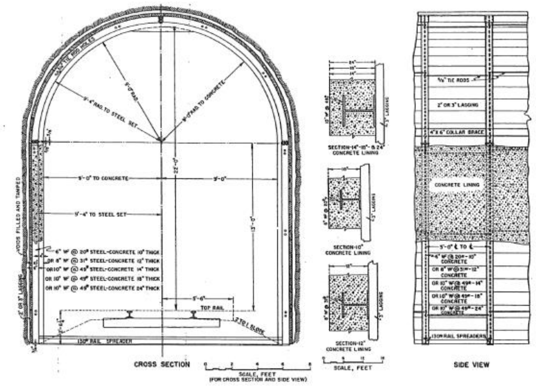

Figure 4: Typical geometry of the original C6 Tunnel [8]

Figure 5: C6 Tunnel, partially unearthed during open pit mining activity

A section of the C6 Tunnel between the pit portal and the Fortuna fault had already shown signs of deterioration in the past and was therefore subject to numerous rehabilitation campaigns prior to 2014. Shotcrete was used as a rehabilitation support measure. In other sections, the tunnel was previously rehabilitated with installation of 2-inch chain link mesh to control spalling and block failure.

Between January and June of 2014, excessive and progressing damage was observed (Figure 6). The existing structure showed signs of overstressing due to movements in the surrounding rock mass. Wide, open cracks covering the entire circumference of the tunnel and spalled concrete and shotcrete were detected. Significant damage was reported within the approximately 200-foot tunnel section along the Fortuna fault. The remaining portion of the tunnel between the Fortuna fault and the pit portal was also reported to have increasing rates of deterioration. As a safety precaution, access to the tunnel had to be restricted between the pit portal and the end of the Fortuna fault crossing.

Figure 6: Typical damages in the tunnel's back

The belt conveyor operated in the C6 Tunnel is a critical asset for the operation of the mine and needs continuous inspection and maintenance as a precautionary measure. Since a portion of the conveyor tunnel could no longer be inspected and maintained, the restricted access to the tunnel became a critical risk to the operation of the mine.

The primary purpose of the rehabilitation was therefore to restore the access to the C6 Tunnel to allow for inspection and maintenance works on the conveyor belt, to be able to avoid potential damage and a standstill of this lifeline of the mine. Time was of the essence and the authors developed the subject rehabilitation concept in a team effort under enormous time pressure.

Based on observations of the pit walls and the geological model of the mine, it was obvious that the documented damages in the underground tunnel are related to slope movements on top of the Fortuna fault system. The slope movements were concurrent with the damages in the first 1,200 feet of the C6 Tunnel until the Fortuna fault was crossed. However, an in-depth knowledge about the mechanisms behind the slope movements and a clear picture about subsurface movements of the slope was not available during the design phase.

The purpose of the subject design was therefore solely the restoration of access to the C6 Tunnel by providing a safe working environment. This goal was achieved by supporting the existing, deteriorating lining and providing a support system that could withstand the relatively large movements, and with this approach mitigate and slow down the ongoing deterioration of the lining. From an operational point of view, installed support measures had to ensure sufficient clearance, while the impact on operation during the rehabilitation installation had to be minimized.

As shown in Figure 3, the conveyor was located close to the left, with a nominal clearance of about 1 ½ foot between the conveyor and the sidewall. Providing more clearance by moving the conveyor towards the center of the tunnel was not an option, because the clearance on the right side of the conveyor was needed to provide a pathway for vehicles. In addition, a relocation of the conveyor would have required an additional shutdown and made access into the tunnel during the construction process much more difficult.

On the right side of the conveyor belt, a roadway with a minimum clearance of about 6 feet was to be maintained, which provided just 1 foot of available clearance for the width of the support system. All installation measures had to be installed from the roadway or above the conveyor, preferably while the conveyor was running.

To develop efficient installation means and methods a work stream was started immediately and in parallel with the structural design. The goal was the development of a construction method that minimizes the impact on operation of the conveyor and in addition allows working in close proximity to the running belt while minimizing personal exposure to meet the stringent safety requirements of RTKC. The team was comprised with a multidisciplinary team from RTKC, Gall Zeidler Consultants, acting as design lead, Beton- und Monierbau Herten, DSI, and Cementation USA. The design was based upon ground-structure-interaction modelling using the Finite Element Method (FEM) as well as the structural design of the steel elements.

The developed system evolved to an elevated work deck suspended from two monorails located in the arched profile of the tunnel (Figure 7). The work deck included a crane and jig for assembling the steel sets and placing the completed sets. In addition, it provided access for grouting of the grout filled fabric hoses and prevented contact with the operating belt.

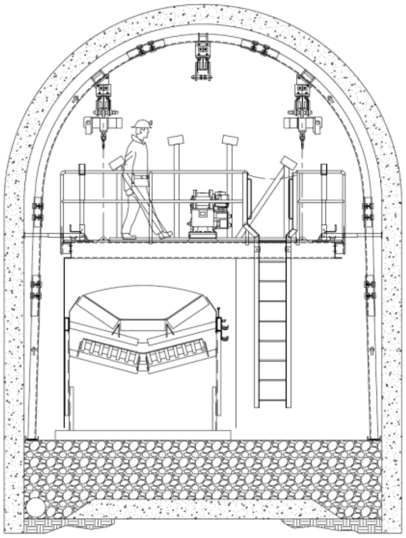

Figure 7: Cross section of an elevated work deck in the C6 Tunnel

For the present application, TH-25 and TH-29 type segments have been used. The nominal weight of these profiles is 25kg/m (17 lb/ft) and 29kg/m (19.5 lb/ft), respectively. TH steel sets were mounted in an assembly jig located on the deck. In the next step the legs were dropped into place and stood from ground level. After the legs were placed and the arch was assembled in the jig, a crane lifted the arch section into place and the legs were connected. Monorail brackets were installed on the profile before the groutable hoses were secured.

The groutable hoses were inflated using a grout mix supplied by a local ready mix supplier. Grout was pumped via a 2-inch slick line to the work deck to eliminate the need for bag handling and grout machine maintenance underground. 6 feet long monorail sections were suspended from the brackets and affixed to the stood and grouted steel sets, and attached to the end of each existing monorail section. After the extension was installed, the stops were moved forward onto the newly installed monorail section so that the deck could advance forward. This extension of the monorail occurred after two sets were stood and fully grouted, with each section aligned and plumbed to ensure the work deck could advance efficiently.

Due to load requirements on the monorail set spacing was fixed to 3 foot centers for all repair work using the work deck. The monorail system allowed set installation over the running belt with work continuing at a rate of 6 sets or 18 feet per day.

Figure 8 shows the finished rehabilitation with the installed TH steel sets and grout filled hoses with the conveyor belt underneath.

Figure 8: Completed tunnel section with TH steel sets

CONCLUSIONS

The authors have successfully developed an innovative rehabilitation concept. The flexible and stepwise ground support rehabilitation program utilized a combination of yielding steel arch sections with grout filled fabric hoses, a fast and safe backfilling support system.

The design allowed for sufficient geometrical tolerance to accommodate the variations of cross section geometry and supported a quick installation process. The installed yielding support system provides for long term mitigation of the expected movements and elongates the service life of the existing asset.

Hence, the best value demonstrated by this installation method is the fact that the installation of the TH profiles and groutable hoses could be undertaken while minimizing the impact on critical operations within the tunnel.

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