LINING INNOVATION AT MARCHE-UMBRIA

Italy's Quadrilatero Marche-Umbria project is benefitting from a new tunnel lining system reinforced by tubular arches. **Pietro Lunardi, Fabrizio Romozzi, Andrea Simonini, Dino Bonadies, Cesare Avignone** and **Carla Luigina Zenti** describe the application, installation and safety aspects of this new system

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GROUND-LINING interaction control is one of the most critical processes during a tunnelling project's implementation. Some of the design and construction decisions during a tunnel project are very critical to reduce the ground movements around the excavated tunnel.

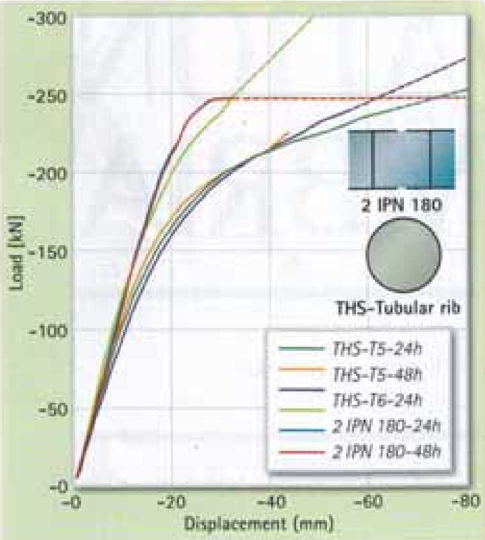
These movements have a direct effect on the tunnel stability and the design load of the lining system (Lunardi et al., 1994).

Tunnel linings are structural systems installed during and or after excavation to provide ground support, to maintain the tunnel opening, to limit the ground water inflow, to support appurtenances and to provide a base for the final finished exposed surface of the tunnel. Tunnel linings can be used for initial stabilization of the excavation, permanent ground support or a combination of both (Hoek E. et al, 1981).

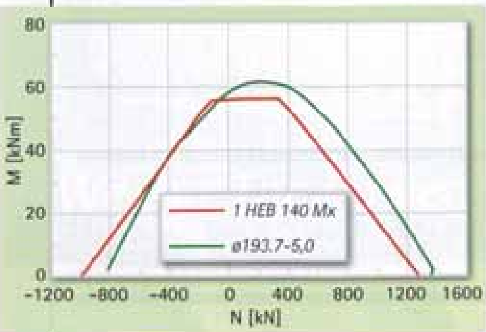
Tunnel linings are structural systems, but differ from other structural systems in their interaction with the surrounding ground, which is an integral aspect of their behaviour, stability and overall load carrying capacity. The loss or lack of support provided by the surrounding ground can lead to a failure of the lining. The ability of the lining to deform under load is a function of the lining relative stiffness and the surrounding ground (Beiniawski, 1984). Frequently, a tunnel lining is more flexible than the surrounding ground. This flexibility allows the lining to deform as the surrounding ground deforms during and after tunnel excavation. This deformation allows the surrounding ground to develop strength and stability. The tunnel lining deformation allows the moments in the tunnel lining to redistribute the main load inside the lining which are axial or eccentric load. The most efficient tunnel lining is one that has high flexibility and ductility.

The open steel profiles (IPE, HE, IPN) typically used as first lining support, show performance weakness in their static structural properties in directions other than the normal and central position. With reference to particular local conditions a closed circular profile will offer better performance conditions compared to an open profile. An example of a specific local condition is when there is a non-homogeneous contact between the profile and the

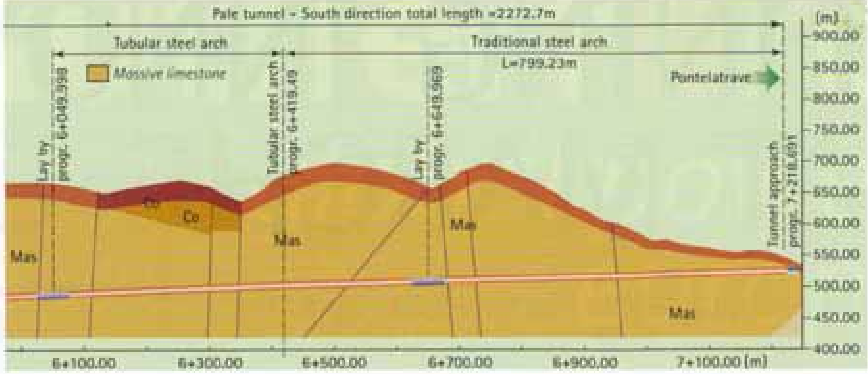
Above: The Quadrilatero Marche-Umbria project area



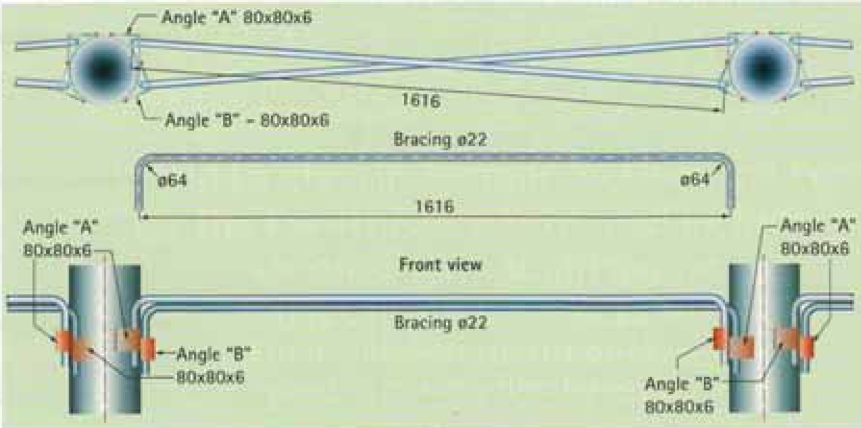
Top, left: Figure 1, average results



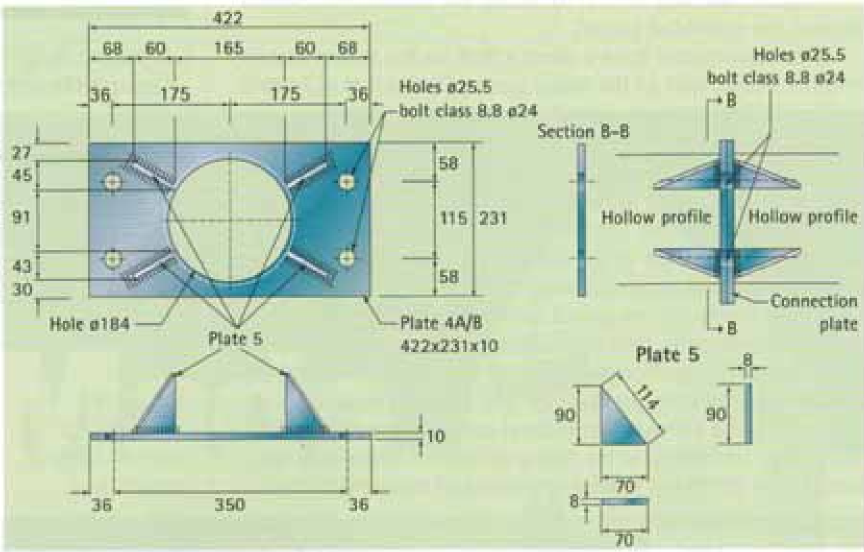
Above, left: Figure 2, Ultimate strength domains



Top, right: Figure 3, geological profile



Middle, right: Figure 4, double crossing chains



Bottom: Figure 5, junction plates

soil, which may occur during the tunnel excavation progress and not always found in a plane strain state. It is also acceptable to assume the worst performance conditions for a double "T" profile in the presence of a horizontal load component. These problems can be solved using a symmetrical axial cross, like a tubular rib. Substituting the open profile with a circular profile of the same area, provides a better stress redistribution. This enables the resistant cross section the capability to accommodate and control axial and eccentric loads, acting along any direction (Bringiotti, 2003).

In this paper the authors describe the application, installation and safety aspects of this New Tunnel Lining System reinforced by Tubular Arches utilized on the Quadrilatero Marche-Umbria Project, Italy. The system, consisting of the Tubular Steel Arch, shotcrete (with blended accelerants) reinforced with steel mesh and/or fibres, has been inserted into the project after the job site test validation described in a previous paper (Zenti, et al., 2012).

EXPERIMENTAL ACTIVITY

Extensive numerical analyses were performed prior to the experimental activity (see Figure 1). Those focussed on identifying the correct profiles to compare. The experimental work was carried out in two phases; (1) conducted in the laboratory, necessary for the validation of numerical analysis and (2) conducted on site in order to compare the structural response of the two types of ribs, standard and tubular.

The numerical and experimental investigation confirmed that the Tubular Hollow cross section shows better performance compared with an Open Steel profile Standard Rib. Laboratory test results confirmed the composite section performance of the tubular rib as usually modelled in the design phase. This assumption was not confirmed for the Standard open profile Rib. Field tests (see Figure 2) were carried out to evaluate the compatibility of the new type of ribs with underground work regarding installation and stress-strain response. From an operational perspective, the tubular rib is very stable and easy to handle during transportation and installation. This ensures

Table 1. Project outline

Contract	Lot	Project and intervention	Stage
Maxi Lotto 1	1.1	SS77 Collesentino - Pontelatrave (2,7 km)	Finish and open to traffic on 2009, December 3rd
	1.2	SS77 Foligno - Pontelatrave (34,7 km sub lotto 1+2)	Job Site start to work on 2009, November 9th
	1.3	Allaccio SS77 - SS16 Civitanova Marche (1,3 km)	Final Design Discussion
	1.4	Allaccio SS 77 - SS3 Foligno (8 km)	Final Design Approved
	2.1	SS77 Foligno - Pontelatrave	Job Site start to work on 2009, November 9th
	2.2	Intervalliva Macerata (3 km)	Final Design Internal Discussion
	2.3	Intervalliva Tolentino - San Severino (7,2 km)	Final Design Internal Discussion
	2.4	SS78 Sforzacosta - Sarnano (31 km)	PD in corso di istruttoria interna
	2.5	SS3 Pontecentesimo - Foligno (5 km)	Definite Project Plan - Next opening Job site
Maxi Lotto 2	1.1	SS76 Serra S. Quirico - Albacina, Fossato di Vico - Cancelli (22,3 km)	Job Site start to work on 2009, February 16th
	1.2	SS318 Pianello - Valfabbrica (8,1 km)	Job Site start to work on 2009,May 29th
	2.1	Pedemontana Fabriano - Matelica nord	PD approvato dal CIPE
	2.2	Pedemontana Matelica - Muccia/Sfercia	PD conclusa procedura Conferenza dei Servizi

Source: Authors

The high rigidity of the proposed profile **eliminates the potential risk of buckling** during the installation

60
Per cent of the 35km section is in tunnels

111
Steel arches are saved per kilometre by using the tubular arches

a higher level of safety to the site operatives. The high rigidity of the proposed profile eliminates the potential risk of buckling during the installation. In all sections tested, the deformation responses recorded were always maintained within the elastic range. The tensions measured at stress control stations in the tubular ribs showed significantly lower values compared with the corresponding standard open profile ribs.

The tubular hollow cross section offers a better stress redistribution and improved structural statics properties, providing the capability to accommodate axial and eccentric loads applied in any direction.

With reference to specific local load condition, hollow profile circular sections have better performance characteristics. A good example of this problem is the non-homogeneous contact conditions between the steel supporting profile and the soil, which can occur during the excavation of a tunnel. A plain strain condition is not always found.

It is acceptable to assume a double "T" worst working conditions in the presence of eccentric loads. These problems can be solved using a symmetrical cross section, such as in a tubular rib.

The design method and experimental activity detail have been described in a previous paper: "Zenti C.L., Lunardi G., Rossi B., Gallovich A. (2012) - A new approach in the design of first lining steel rib - Proc. World Tunnel Congress, WTC 2012, Bangkok, Thailand, 18-24 Maggio 2012."

THE PROJECT

The Quadrilatero Marche-Umbria Project features the construction of infrastructure, whose axes ideally represent the four sides of a quadrilateral.

The project consists of the completion and upgrading of two main highways; roads the Foligno-Civitanova Marche freeway (S.S.77) and the main roads Perugia-Ancona (S.S.76 and S.S.318). This new road system connects existing industrial areas and, more generally, improves and increases the access to the internal areas of these central Italian regions.

From a strategic infrastructure perspective, this project is part of the main arterial road system of Italy, reducing the infrastructure deficit experienced by Marche and Umbria and creating an efficient link with the surrounding regions and Europe.

Pale Tunnel

The new solution for the primary lining, made by B.ZERO-Tondo tubular steel ribs, has been applied in Pale Tunnels, which are currently under construction (Spring 2013).

The previous section described the Quadrilatero project and the Pale Tunnels are within the section from Foligno to Pontelatrava (Table 1- lot 1.2). This element is 35km long and includes 13 tunnels (Table 2), eight cut-and-cover sections and 16 viaducts. With 60 per cent of this section provided by tunnels, the result is a project with a lower environmental impact.

The Pale Tunnels are being excavated within the Massive Limestone rock mass with good mechanical characteristics (Figure 3). Within this type of rock mass a category A behaviour "stable core-face" (diagnosis phase, Lunardi, 2008) was expected.

The excavated tunnel section designed for this stretch corresponds to a section type Ac. This section is characterized by shotcrete reinforced by a traditional standard rib made of a single HEB 140 installed every 1.50m (single profile HEB 140, Steel Grade S275). The B.ZERO-Tondo Tubular Rib was selected to substitute the traditional system with a Tubular Hollow Section;

193.7mm diameter with 5mm wall thickness in steel Grade S275. The Tubular Rib Ultimate Strength Domain resistance domain is comparable to that one of Standard Rib (Figure 2).

The geological conditions are similar to those encountered in the field test (Figure 3). The project engineer designed a solution using tubular steel arches at 1.8m centres spacing with a pair of crossed chains as bracing between the arches. This connection between the two arches guarantees out of plane stability, because it works in the same way as a rigid bracing (Figure 4). Furthermore, this decision was taken on the evidence of the good results recorded during experimental activity carried out in the Varano Tunnel, characterized by similar geological condition (Zenti, et al. 2012).

Tubular Steel Arches Installation

The installation process for this new primary lining system are similar to the traditional approach. Tubular steel arch assembly and installation consists of the following phases:

- Component handling: one worker secures the components for lifting/ hoisting and indicates any obstacles along the route to the machine driver.
- Component carriage: during transportation components are lifted to the necessary height to overcome any obstacles if present.
- Pre-assembly: steel rib components are positioned in the final configuration using a mobile crane and linked together by bolted junction plates. This stage could be performed near to the excavation face or outside the tunnel, depending upon the job site management.
- Placement: Tubular steel arch, placed adjacent to the excavation face, lifted up and laid as close as possible to the excavation profile.
- Filling: The tubular steel arch is then filled with concrete, pumped into filling ports on the tubular profile.

The tubular rib has good compatibility with underground operational needs. The tubular rib is very stable and easy to handle during transportation and installation. The buckling risk during installation has been eliminated due to its high rigidity. This reduces the risk to operatives and is therefore safer to install than other less rigid support arches. The filling phase is rapid and functional to ensure the complete filling of the profile. The junction plates of the tubular arch are characterised by a central hole that

Table 2. Foligno-Pontelatrava tunnels

Tunnels S.S.77 Foligno - Pontelatrave	length [m]	
	North	South
Belfiore	1,100	1,109
Pale	2,319	2,045
Sostino	2,820	2,834
La Franca	1,052	1,075
Cupigliolo	2,182	2,100
La Palude	1,166	1,226
Varano	3,455	3,472
Serravalle	1,341	1,341
Bavareto	1,682	1,661
Muccia	2,126	2,223
Costafiore	565	552
Maddalena	670	550
Rocchetta	840	980

Source: Authors

This connection between the two arches **guarantees out of plane stability,** because it works in the same way as a rigid bracing

enables the creation of a continuous concrete arch within the tubular profile at the completion of the filling phase. This Tubular Arch System assures the effective collaboration between the steel circular hollow profile and the concrete filling, thereby produces a composite system with enhanced performance behaviour. The remaining operational phases necessary for tunnel construction remain unchanged.

Monitoring Results

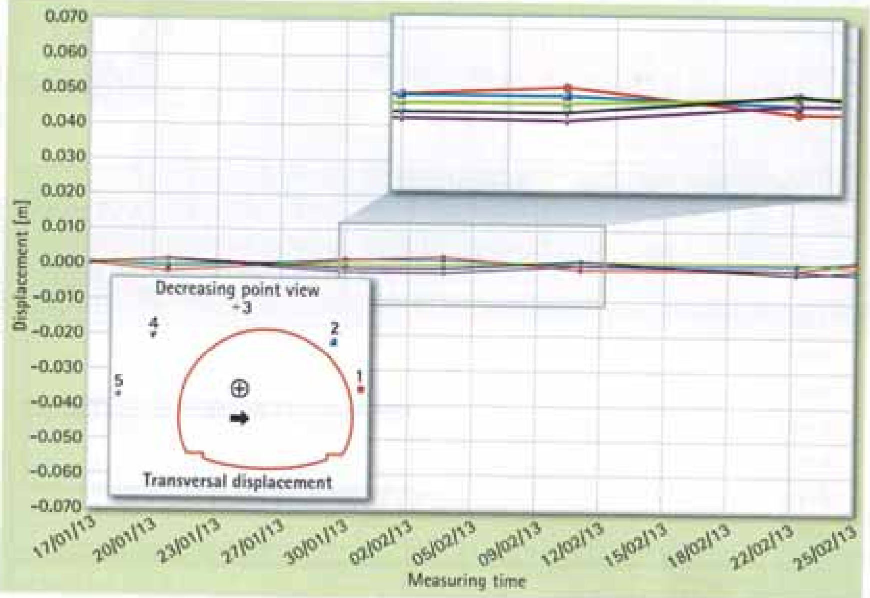
The mass presents homogeneous characteristics (Figure 3): this has been demonstrated by geological surveys carried out upon the face. The deformation in-plane response recorded was always within the elastic range, with displacement and convergence values below 0.5cm, in rapid stabilization.

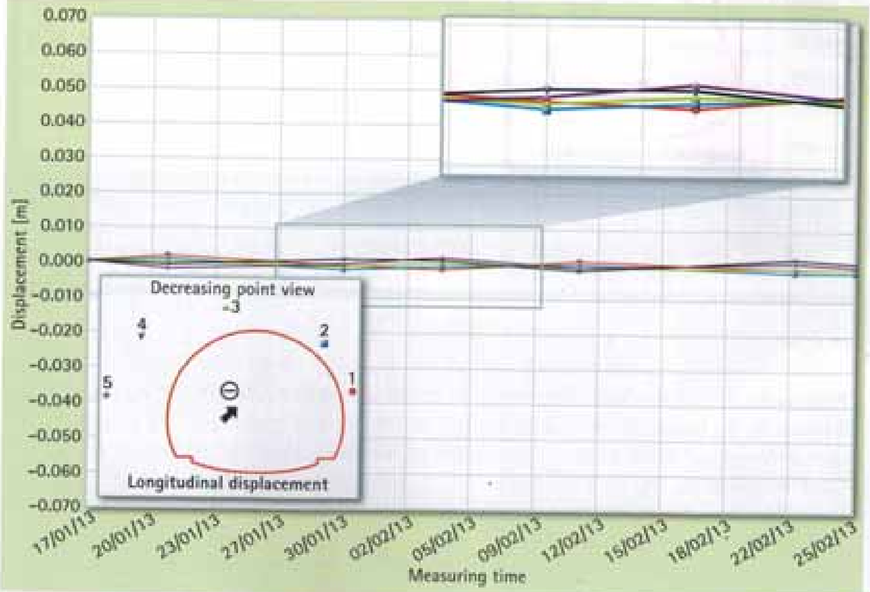
The difference between the behavior of traditional and tubular ribs can be underlined by the evaluation of transversal and longitudinal displacement. Figure 6 shows the transversal (Figure 6.a) and longitudinal (Figure 6.b) displacement of a single HEB 140 arch installed every 1.50m. Figure 7 shows the transversal (Figure 7.a) and longitudinal (Figure 7.b) displacement of a B.ZERO Tondo tubular arch (193.7mm-th.5mm) at 1.8m centres spacing with a pair of crossed chains as bracing between the arches. Evaluating the monitoring results (Figure 6.b and Figure 7.b), it is clear that the out of plane displacement affecting tubular ribs are lower than those corresponding to standard ribs. In the case of the tubular rib (Figure 7) after an initial movement due to the natural load stabilization, the displacement remains more or less constant. In the case of traditional the rib is not possible to record the same fact.

Table 3. Steel arches

Profile	Steel Arch Characteristics				1km Tunnel length		SAVES
	Steel	Length	Installation Step	Weigth	Number	Weigth	
	[Grade]	[m]	[m]	[kg]	[n°]	[tons]	111 ARCHES 16.7%
HEB 140	S275	27	1.5	1293	667	862	244 Steel Tons 28.3%
Diameter 193.7 - Th.5mm	S275	27	1.8	1112	556	618	

Source: Authors





With reference to transversal displacement (Figure 7.a) the constant response of the tubular rib is due to Composite Section behaviour, in which steel tubular hollow section and its concrete fill work together (Eurocode 4). This fact endows the system with the capability to accommodate axial and eccentric loads in any direction.

With reference to longitudinal displacement (Figure 7.b), it is possible to underline the benefits due to crossed chains as bracing between the arches, despite the significant increase in spacing between the arches, 1.5m for traditional system and 1.8m for B.Zero Tondo tubular Arch.

Above: Figures 6.a and 6.b, HEB arch installation

Next page: Figures 7.a and 7.b, tubular arch installation

Project Cost Analysis

The tubular rib installation offers numerous advantages, not only from the technical perspective , but also from an economic point of view.

In the Pale Tunnels, as a consequence of good geological conditions, it has been possible to increase the spacing of the ribs installation. It was increased from 1.5m (related to the standard solution using HEB 140) to 1.8m by using the tubular profile (external diameter of 193.7, thickness of 5mm) which has a greater resistance performance envelope when compared to the open sections originally proposed (single HEB 140), see Figure 2). Additionally, the new solution is lighter than the one offered by the HEB 140. The use of a lighter and more rigid profile enables the operatives to work in a rapid and safe way.

The savings within each kilometre of tunnel are summarized in Table 3. It is possible to save 111 steel arches, with a total weight of 244 steel tons. Immediate cost savings are possible due to the reduced steel and, as a consequence, it is possible to generate further saving due to the reduced operational work during the complete construction of the tunnel.

The application of this new Tunnel Lining System consisting of Tubular Arches with double-crossed bracing chains within a steel fibre reinforced sprayed concrete lining, in general, could increase the speed of installation from 10 per cent to 20 per cent, depending on local geological conditions.

Another important saving is due to the absence of rebound during the placement of shotcrete between the tubular profile arches.

From an operational point of view when an operator tries to fill the space between the webs of an open profile support arch, a significant rebound of 50 per cent (or more, in the case of coupled profiles) of the shotcrete has been recorded.

This problem does not occur in the

case of tubular profile arches and a complete shotcrete filling between the arches is possible.

CONCLUSIONS

The use of tubular steel ribs in tunnelling and underground mining operations offers numerous technical, operational, safety and cost benefits compared to traditional steel section arches. The tubular arch hollow sections accommodate axial and or eccentric loads applied from any direction, enhancing the performance of the support system and reducing the required number of supports over the tunnel length. The concrete fill to the steel arch forms a composite structural member. The rigidity of the tubular section arches also eases transportation and installation of the arches, improving the safety of the tunnel operatives.

Monitoring results confirm the "Composite Section" (Eurocode 4) behaviour of tubular hollow section filled with concrete and the effectiveness of bracing between the arches constituted by crossed chains, which ensures out of plane stability.

During shotcreting of the primary lining, tubular section arches dramatically reduce shotcrete rebound and "shadowing" where voids can occur behind traditional section support arches. The Pale Tunnel application, within the Quadrilatero Marche-Umbria Project, demonstrated the excellent performance of the system consisting of the Tubular Steel Arch, shotcrete (with blended accelerants) reinforced with steel mesh and or fibres

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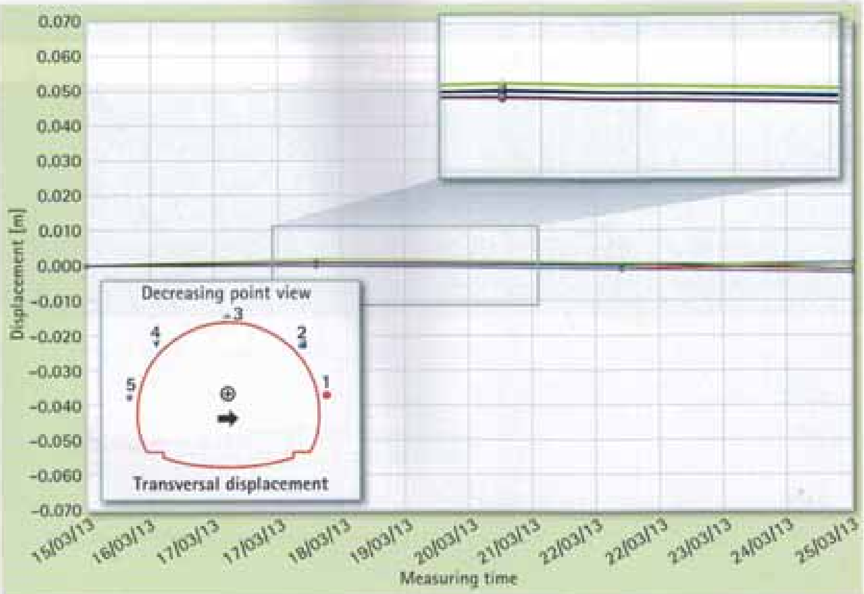

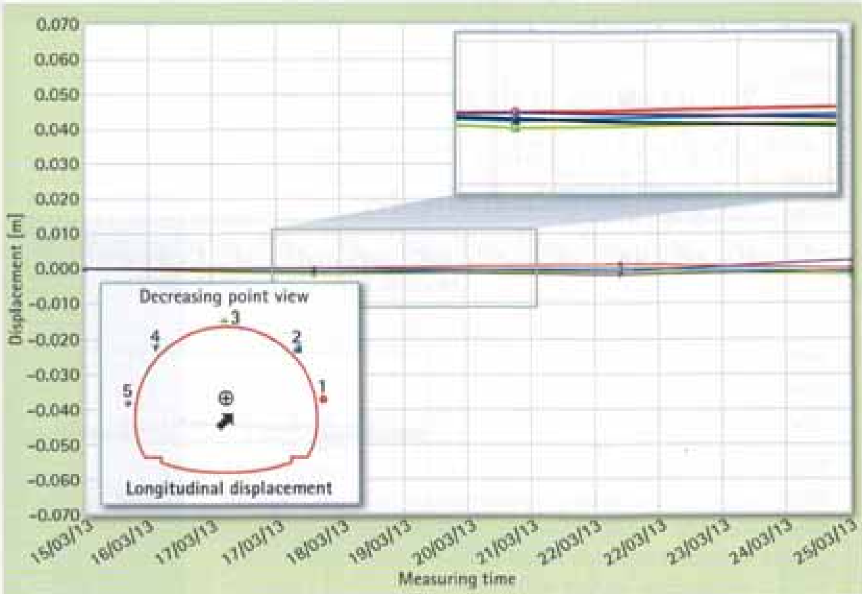

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