

# *Comparison of high speed rail tunnels in Korea with those on other high speed railways worldwide*

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## 1. Introduction

High-speed rail transportation has become increasingly popular throughout the world. Some of the primary countries where high-speed railways are operating, under construction or being designed include Korea, Japan, France, Germany, Taiwan and Spain. Completely new or modified existing lines are being utilized with infrastructure comprised of earthworks, viaducts and tunnels. This paper provides a comparison of the Korea High Speed Rail (KHSR) project with those in other countries with emphasis on the design and construction aspects of the bored tunnels (excludes cut & cover tunnels).

### *Korea*

The Korea High Speed Railway is being constructed by the Korean High Speed Rail Authority (KHRC). The line will run along the major transportation corridor between

Seoul and the southern port city of Pusan. Total length of the new route is 412km. The line is designed for high speed passenger transport utilizing rolling stock directly derived from the French TGV designs. Phase 1 works, to be completed by the end of 2003, includes new alignment from Seoul to Taegu and upgrade of the existing line from Taegu to Pusan. Phase 2 will include construction of a new line from Taegu to Pusan via the city of Kyungju. With completion of the Phase 2 work expected in 2010, the trip from Seoul to Pusan will be reduced to less than two hours from the present time of more than four hours. Additionally, freight traffic along the existing rail lines will be improved.

The new route crosses many of the major tectonic provinces of Korea with terrain that is characterized by numerous mountains. Thus, 191km (46%) of the alignment is in tunnels. There is a total of 84 tunnels along the route with nine tunnels more than 5km long. The longest continuous tunnel is Keumjeoung Tunnel at 18.5km in

length. The Taegu Tunnel is 20.2km long but is divided into two sections by the future underground Taegu Station. Construction is presently underway for the first phase of work from Seoul to Taegu where most of the 48 tunnels have been completed or are nearing completion. Maximum speed of the train designed for revenue service is 300km/hr for the first generation trains; however, the double-track tunnel internal cross-sectional area of 107m<sup>2</sup> is based on a design speed of 350km/hr.

### *Japan*

The Shinkansen High Speed Railway is operated by the Japan Railways Group. The Tokaido Shinkansen was the worlds first high speed railway line, opened in 1964 for passenger transport, and operated between the cities of Tokyo and Osaka over a distance of 515km. Presently, the high speed railway system consists of four main lines and is expanded to more than 1800km in length with an additional 830km planned or under construction. The maximum operating speed (Sanyo Shinkansen running between Okayama and Hakata) is 300km/hr with an average line speed of about 260km/hr. There are more than 550km of tunnels on the existing lines, many which are over 5km in length. The Sanyo Shinkansen runs mostly through mountainous terrain; thus, about 50 percent (277km) of the line is in tunnels. The Shimizu Tunnel, along the Joetsu Shinkansen, is the longest mountain tunnel in the world at 22.3km length. The Seikan Tunnel, connecting Honshu and Hokkaido, is 53.85km in length and excavated beneath the sea.

### *France*

The TGV (Train a Grande Vitesse) is the French high-speed train system. It is owned and operated by SNCF, the French National Railways. The first high-speed line opened

between Paris and Lyon in 1981. Presently there are three main trunk lines coming out of Paris. These include the Atlantique line, Sud-Est line and Nord-Europe line which connects the capital cities of Paris, Brussels and London through the Channel tunnel. The Mediterranean line, from Valence to Marseilles, is set to begin operations in June, 2001. This line includes the 8km long Marseille Tunnel, which is the longest tunnel on the French high-speed rail system. TGV trains operate largely on existing lines which have been improved for high speeds and tunnels are far fewer than other high-speed systems in Korea, Japan, Germany and Taiwan. Rolling stock consists of both single and double-deck vehicles. Postal TGV trains and those for carrying light freight also operate on the lines.

The Alpe Tunnel is a new 52km long tunnel along the proposed route connecting Lyon, France to Turin, Italy. This line will serve both passenger and freight traffic. The design includes twin tubes, each 8-meter diameter, separated by 30 to 50 meters and connected with cross passages.

### *Germany*

Since 1980, the German Railway has developed its high-speed rail system, the Inter City Express (ICE). Presently, the ICE operates on about 700km of lines. Because of the topography, there are approximately 200 tunnels constructed or under construction. Along the 327km long line from Hannover to Wurzburg, there are 76 tunnels totaling 153km. The ICE tunnels range in length from less than 0.5km to about 10km. Design criteria for tunnels has been modified over time based on experience gained from the earlier works.

Presently, work is in progress on the new 219km long Cologne-Rhine/Main line between Cologne and Frankfurt. This includes 23 tunnels to be driven by mining techniques. The Schulwald double-track tunnel is the longest tunnel on the line at 4.5km. The second longest tunnel, the

Niedernhausen Tunnel, is about 2.8km long with 664m of this length to be by cut-and-cover method.

### *Taiwan*

Taiwan is in the early stages of high-speed railway transportation. In the early 1990s, plans were first developed for a high-speed rail line between Taipei and Kaohsiung. Civil design is now nearing completion on the proposed line and a symbolic groundbreaking ceremony was held to signify the start of construction on the lines main depot. Total length of the new route is 345km. The design maximum speed is stipulated to be 350km/hr with a planned maximum operational speed of 300km/hr.

More than 85 percent of the total alignment will be comprised either of tunnel or viaduct. There are 36 bored tunnels totaling 39km in length. The line is designed for high-speed passenger transport using the latest Japanese rolling stock.

### *Spain*

The Alta Velocidad Espanola (AVE) high-speed line from Madrid to Seville, with total length of 471km, was completed in 1992. The maximum design train speed is 300km/hr. The AVE rolling stock comes directly from the French TGV while German technology is used for the operational controls system. Portions of the line follow over existing railway trackbed. Between Braztortas and Cordoba is completely new line which passes through the Sierra Morena mountains. There are at least 15 tunnels totaling about 15km. Currently, numerous tunnels are under construction or being planned for other extensions of the AVE railway system. An 8km long tunnel is included in the proposed line connecting Perpignan, France to Figueras, Spain.

## 2. Design and Construction Aspects of Tunnels

### *Geometry and Cross Sectional Area of Tunnels*

Factors which govern the geometry and cross sectional area of high speed rail tunnels include clearance requirements for the rolling stock, train velocity, aerodynamics, track spacing, minimum alignment curve radius, track gradient and service, maintenance and safety requirements.

Typically, the double-track tunnels for all the high-speed railways including Korea are horseshoe-shaped with flat or elliptical-shaped (arched) invert, depending on ground and groundwater conditions. The net internal cross-sectional area varies from 60 m<sup>2</sup> for the Shinkansen to 107 m<sup>2</sup> for the KHSR. The larger section for the Korean tunnels is based on train design speed of 350km/hr. Within Pusan City area, a portion of the Keumjeoung Tunnel will have a reduced section of 67 m<sup>2</sup> because train design speed is reduced here to 150km/hr as the train approaches the station. Within the Daejeon and Daegu areas, tunnel sections are also reduced due to lower train speeds allowed. Table 1 provides a general comparison of the various high-speed railways. Figures 1 thru 3 provide typical tunnel cross sections for the various railways.

In Taiwan, for tunnels exceeding 3km in length, sections of the tunnel within at least 20m of the portals are to be enlarged to at least 1.5 times that of the normal bored tunnel to mitigate aerodynamics effects of the moving trains.

Single-track tunnels are also present along a portion of the TGV and ICE lines. These include the two TGV single-track tunnels at Villejust. These tunnels are circular with an inside diameter of 9.25m. Along the Cologne-Rhine/Main line of the ICE are 1.65km of twin tube, shield-driven tunnels with a

Table 1. General Comparison of High Speed Railways

Item	Korea (KTX)	Japan (Shinkansen)	France (TGV)	Germany (ICE)	Taiwan	Spain (AVE)
Max. Speed in Revenue Service	300km/hr (first generation KTX trains) 350km/hr(design)	300km/hr (some sections, < 300km/hr)	230km/hr to 300km/hr (existing lines)  Mediterranean line, speed will be 350km/hr except in Marseille Tunnel where speed will be 230km/hr	300km/hr (tunnels along Hanover-Wurzburg line designed for 250km/hr)	300km/hr (operational) 350km/hr(design)	300km/hr
Track Gauge	1435 mm	1435 mm (1000 mm some)	1435 mm	1435 mm	1435 mm	1435 mm (some lines to accommodate du gage 1435/1668mm)
Min. Curve Radius	7000 m (400m along portion of Keumjeoung Tunnel within Pusan City limits)	4000m (300km/hr) (2510m on Tokaido line and 6500m for Seikan Tunnel)	5500 - 7100m	3450m (on Cologne -Rhine/Main line)  5000-7000m (on earlier ballast track lines)	5500 m (350km/hr)	4000 m
Max. Gradient	2.5 % (3.0% in Keumjeoung Tunnel within Pusan City limits)	1.5 % (2% on Tokaido line and 1.2% for Seikan Tunnel)	2.5 % design but can be increased up to 3.5% as for the Mediterranean line.	1.25 % (4 % on the Cologne -Rhine/Main line)	2.5 %	(unknown to author)
Track Spacing	5.0m (spacing required for potential wider vehicles to be manufactured in future)	4.3m (4.0m on Tokaido line)	4.2 m (Atlantique)  4.5m (Nord)  4.8 m (Mediterranean except 4.2m for Marseille Tunnel)	4.7m (4.5 m for Cologne -Rhine/Main line)	4.5m	4.3 m
Internal Sectional Area (doubletrack tunnel)	107m <sup>2</sup> (based on 350km/hr design speed)  75m <sup>2</sup> (within Daejeon and Daegu)  67m <sup>2</sup> (within Pusan City with max. speed of 150km/hr)	60m <sup>2</sup> (nominally larger for some tunnels)	100m <sup>2</sup> (300km/hr)  61-90m <sup>2</sup> (230-270km/hr)	82m <sup>2</sup> (92m <sup>2</sup> for Cologne -Rhine/Main line)	90m <sup>2</sup> (except vicinity of portals where enlarged to 1.5 times normal for aerodynamics)	75m <sup>2</sup>

104m<sup>2</sup> excavated area.

In France, single-track tunnels are now being considered for all future tunnels longer than 1km or for tunnels longer than 300m that have high traffic volume. Because of revised rescue/safety requirements, Germany is also considering that all future tunnels longer than 3km shall be single-track. Contracts were recently awarded for single-track tunnels in

Spain. These are to be circular with 8.5m finished diameter.

### Excavation Methods

For all of the high-speed railways, the bored double-track tunnels are excavated using drill-and-blast method or by mechanical excavators. Typically, NATM concept is followed and tunnels are excavated using heading, bench and

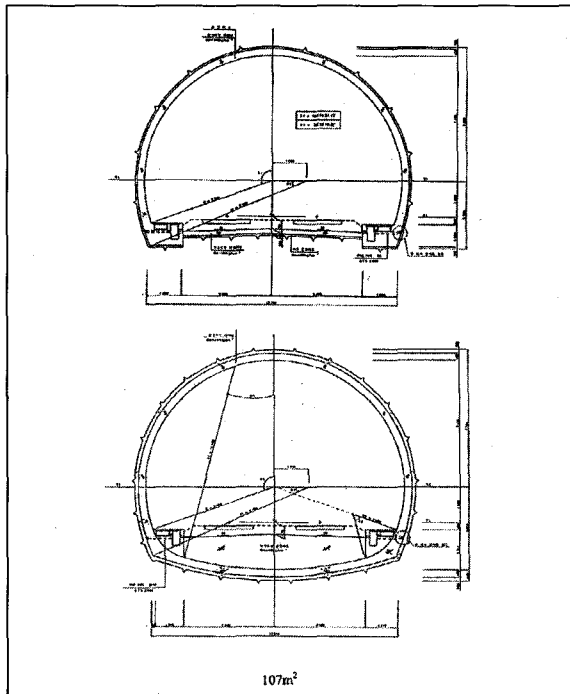


Figure 1. Typical Sections for Double-Track High Speed Rail Tunnels in Korea

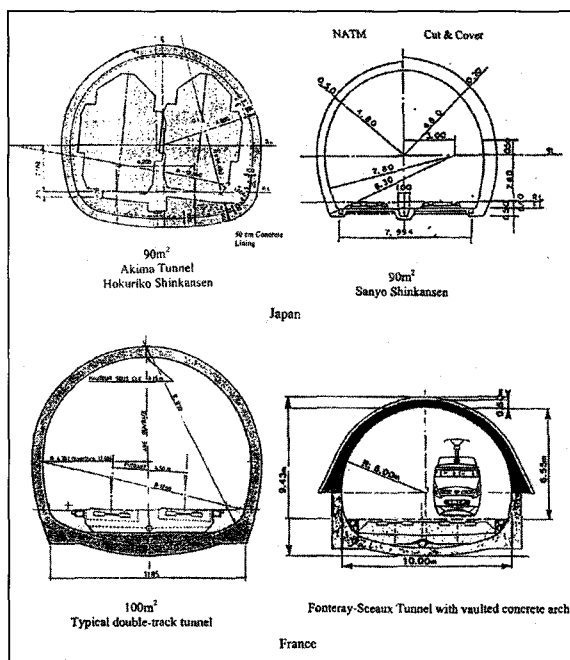


Figure 2. Typical Sections for Double-Track High Speed Rail Tunnels in Japan and France

invert (if arched) or multiphase sequence, depending on ground conditions, with explosives or mechanical excavators. Tunnels for the Taiwan HSR are expected to be excavated in similar fashion. Being a design/build project, the contractors are to propose the best construction method on a case-by-case basis.

Along the TGV Atlantique line at Fontenay and Sceaux, the marly ground conditions required construction of the tunnels to be done in two phases. Initially, a vaulted concrete arch was constructed with excavation performed using a mechanical excavator. Shotcrete and internal supports were used during the excavation. Following construction of the 45cm thick concrete vault, the tunnel was mechanically-excavated to invert and concrete side walls constructed. This was followed by excavation and closure of the arched concrete invert.

In Korea, mechanical excavators have typically only been

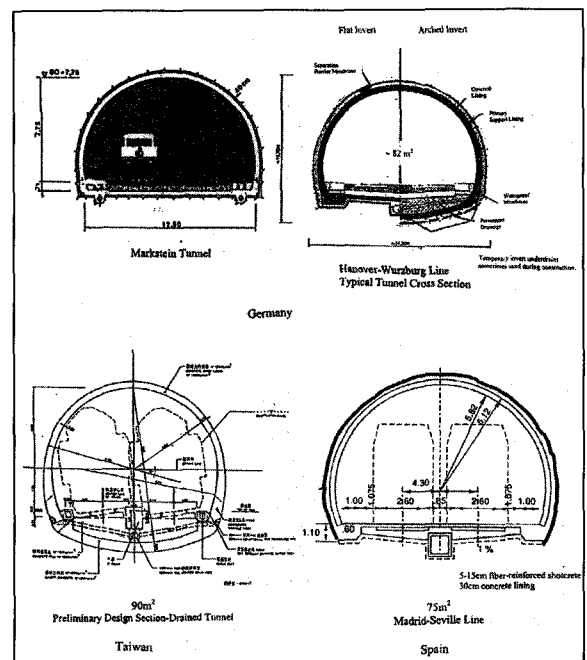


Figure 3. Typical Sections for Double-Track High Speed Rail Tunnels in Germany, Taiwan and Spain

used to develop the portal areas and start of the tunnel where ground conditions may be poor and blasting is restricted or not required. In France and Germany, some tunnels where rock was soft and very weak have been entirely excavated using only roadheaders or other mechanical excavators. In Spain, roadheaders have been used to partially excavate the Sagides Tunnel in mixed ground conditions. Blasting in Korea is done using only electric detonators. In France, both electric and non-electric detonators are specified.

Tunnel boring machines (TBM) have not yet been used for any of the high-speed rail tunnels in Korea. However, they may be utilized in future Phase 2 works to advance pilot tunnels along planned underground stations. The Hokuriku Shinkansen Akima tunnel in Japan is being shield-driven with outside dimensions of 8.92m height and 9.7m width. The tunneling machine is equipped with both digging arm and rotating cutting head.

In France, the twin single-track tunnels at Villejust were excavated using 9.25m diameter shield, earth pressure balance TBMs in ground consisting of fluid sand. Single-track, shield-driven tunnels have also been constructed in Germany as mentioned previously. In Spain, TBMs are being used on single-track tunnels. Here, the Paracyellos Tunnel was first advanced with a 4.7m diameter pilot drive. This is presently being reamed to 12.5m using a TBM. Pilot tunnels using TBMs are proposed for long tunnels in Taiwan.

Pilot tunnels, advanced by drill-and-blast or mechanical excavators, have been used in Germany to better define ground and groundwater conditions prior to advancing of the full-sized tunnels in difficult ground. Insitu testing, including plate load tests, swell tests on clayey rocks and monitoring of ground response, were performed in these pilot tunnels and results used in analyses for excavation and support design of the full-sized tunnels. Examples include the Rollenberg and

Burgberg Tunnels. A 3.4m diameter pilot tunnel was driven by pipe jacking above the crown of the main Siegaue Tunnel. This was later used for drilling dewatering wells and jet grouting.

Similarly, a pilot tunnel was advanced prior to excavation of the Seikan undersea tunnel in Japan. Initially, a TBM was used but the method had to be changed to drill-and-blast method using NATM due to the poor ground conditions.

Generally, there have not been any significant reported problems with groundwater inflow during excavation of the tunnels in Korea. During excavation of the Seikan undersea tunnel in Japan, the significant inflows of water were encountered when driving the initial pilot tunnel and the service tunnel parallel the main running tunnel. The pilot tunnel was used for drainage during driving of the main tunnel with pumps employed during construction. Grouting was done ahead of the working face during driving of the pilot, service and main tunnels along the undersea portion of the Seikan Tunnel to reduce seawater inflow and ensure safe tunneling.

In Germany, there have been cases where horizontal drain holes were drilled ahead of the face and vacuum pumps or vertical wells used for dewatering during construction. One example was the northern portion of Niederhausen Tunnel along the Cologne-Frankfurt line. In tunnels along the Hanover to Wurzburg line, groundwater inflows up to 400 l/s were encountered. The southern part of the Siegaue Tunnel required a groundwater lowering system consisting of deep wells drilled from within the pilot tunnel. Additionally, in the northern part of this tunnel jet grouting was done above the crown and the tunnel advanced using compressed air.

Monitoring of the tunnel excavation is an inherent part of the NATM concept used on the various high-speed railways. Typical monitoring includes convergence, deformation and stress measurements within the tunnels. On the surface,

levelling, extensometers, inclinometers and piezometers are sometimes utilized within portal areas, low cover areas or other areas where structures or facilities may cross over the tunnel.

### Primary Support

In Korea, generally five categories of primary excavation support are provided in the tunnel design based on the Rock Mass Rating (RMR) System. Support typically consists of a combination of untensioned rock bolts (25mm diameter, SD35 strength steel per KSD 3504), steel ribs and shotcrete with wire mesh reinforcement. To date, fiber-reinforced shotcrete and lattice girders have had limited use in Korea. Shotcrete is wet-mix type with a design strength of 210 kg/cm<sup>2</sup>. Forepoling, pipe roofing and pre-grouting are used in poorer ground conditions.

Typically, the primary support used in Japan includes rock bolts, shotcrete with wire mesh or fiber-reinforcement and steel sets or lattice girders. For the Seikan undersea tunnel, special measures had to be taken in difficult ground including extensive grouting ahead of the face, pipe roofing and excavation of a circular section.

In France, primary support consists of untensioned rock bolts (steel, metal tubes or fiberglass), steel ribs and shotcrete with wire mesh or fiber reinforcement. Minimum shotcrete strength is specified as 25MPa. Forepoling and pressure grouting is specified in poorer ground conditions.

In Germany, excavation/support categories are based on standard regulations 007 of the German Federal Railways. These categories include various excavation methods, driving concepts, timing of support installation, advance lengths and amount of support. This concept is similar to that used in Korea.

Shotcrete is typically reinforced with wire mesh and lattice girders. Fiber-reinforced shotcrete is used in some tunnels.

Shotcrete grade is B25 of 250 kg/cm<sup>2</sup> strength. Both wet and dry-mix type shotcrete has been used. Additional support is provided with rock bolts. Auxiliary measures, including face sealing, face bolting, widening of shotcrete footing for top heading stage, temporary shotcrete invert, spiling, forepoling and pipe roofing have been used according to the ground conditions encountered.

In Taiwan, rock materials are divided into various categories upon which the support and excavation methods are defined. Typically, a combination of untensioned rock bolts, lattice girders and shotcrete are envisaged.

For the double-track tunnels along the Madrid-Seville line, support consists of rock bolts, steel sets and a 5 to 15 cm layer of fiber-reinforced shotcrete applied using the dry-mix method.

Figure 4 shows typical primary support and multiple drift face excavation used in difficult ground conditions in Korea and Germany.

### Waterproofing and Drainage

Tunnels in Korea are defined as drained or undrained. In the larger urban areas, tunnels are required to be undrained and completely waterproofed since long-term lowering of GWL is not allowed. Most of the tunnels along the alignment are designed as drained tunnels which are partially waterproofed. The drainage system consists of a fleece layer (geotextile filter fabric), lying beneath the waterproofing membrane, and placed over the shotcrete surface of the tunnel roof and walls above the invert. Groundwater seepage can collect along this fleece layer and flow into longitudinal drains, consisting of perforated PVC pipes, along both sides of the tunnel. Transverse drain pipes connect the longitudinal drains into the main concrete drain channels running inside the tunnel along each of the invert haunches. The invert slab is covered with a vinyl sheet which acts as a

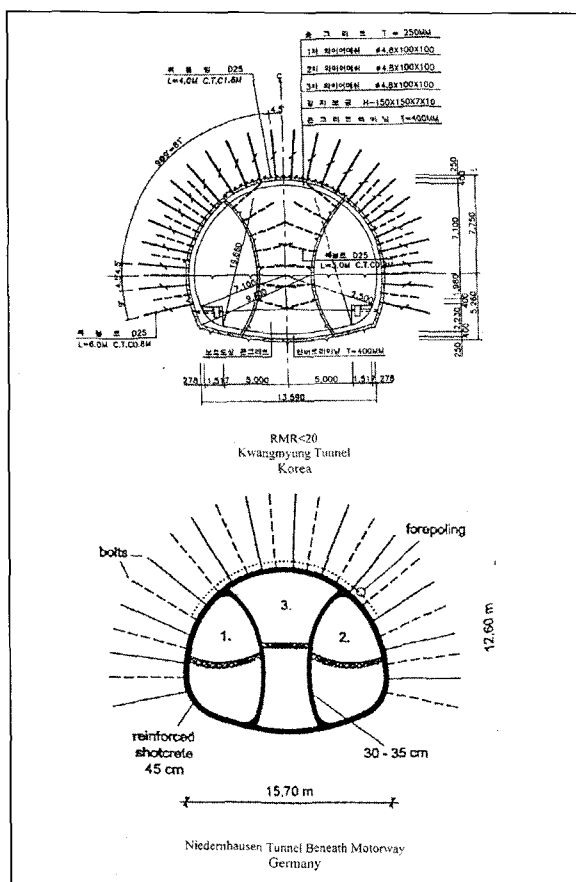


Figure 4: Primary Support and Multiple Drift Faces in Difficult Ground Conditions

moisture barrier. Figure 5 provides details of the typical drainage system used in Korea.

In France, a waterproof membrane is specified to be installed along the roof and walls of the tunnel within the area of the portal bell mouth and in areas of thin ground cover. For tunnels below the groundwater table, the waterproof membrane is typically placed completely around the lining. In areas of low water-bearing ground, the membrane is optional. If membranes are not used, the joints in the lining must be fitted with a grouting sheath or hydrophilic seal with water stop strip. Deeper tunnels are not required to be totally watertight.

In Germany, typically watertight concrete is used for the final tunnel lining. For tunnels along the line from Hannover to Wurzburg, a waterproof membrane with fleece layer is installed behind the final lining. Longitudinal perforated drain pipes along both sides of the tunnel connect to transverse drains which slope into a central drain pipe beneath the trackway running along centerline of tunnel (Figure 3). Due to water inflows encountered in the Rauheberg Tunnel, the the waterproofing membrane was completely wrapped around the tunnel section including the invert and the lining was designed for the full hydrostatic pressure. In some cases, a temporary central underdrain along centerline of the tunnel beneath the invert is used to control water inflow during construction.

Along the Cologne-Rhine/Main line, tunnels are undrained since long-term lowering of GWL is not allowed. The final lining is comprised of watertight concrete designed for full groundwater pressures. A waterproof membrane around the lining is also used where groundwater levels are more than 30m above the lowest edge of the tunnel structure.

For some ICE tunnels, such as the Markstein and Pulverdinger Tunnels, longitudinal underdrains are located beneath the invert on both sides of the tunnel trackway. These serve to drain groundwater seepage and operations-generated water from the tunnel. Transverse, slotted drains connect to the underdrains. To avoid buildup of water pressure behind the lining, a drainage mat is placed along the shotcrete/lining interface and water collected into perforated longitudinal pipes along bottom of the sidewalls. These pipes also connect to the main longitudinal underdrains (Figure 6). Inspection/maintenance manholes are located along the main drains.

In Taiwan, tunnels are defined as drained or undrained. Where long-term lowering of GWL is not allowed, undrained tunnels are required. These tunnels are to be

completely waterproofed using a waterproof membrane behind the concrete lining and invert slab. Only an internal drainage system, comprised of a semi-circular drainage gutter running longitudinally along both sides of the tunnel at track level and a rectangular drainage trough along centerline below track level, are provided for drainage (condensation, leakage and spillage) inside of the tunnel.

For the drained tunnels (Figure 3), the drainage system consists of a fleece layer (geotextile filter fabric) lying beneath the waterproofing membrane, and placed over the shotcrete surface of the tunnel above the invert. Groundwater seepage can collect along this fleece layer and flow into longitudinal drains, consisting of perforated PVC pipes along both sides of the tunnel. Transverse drain pipes connect the perforated pipes into a longitudinal reinforced concrete drain along tunnel centerline. The semi-circular side gutters and rectangular trough along centerline, as for the undrained tunnels, are provided to handle any water generated from inside of the tunnel. Cleaning access is provided at 50m intervals.

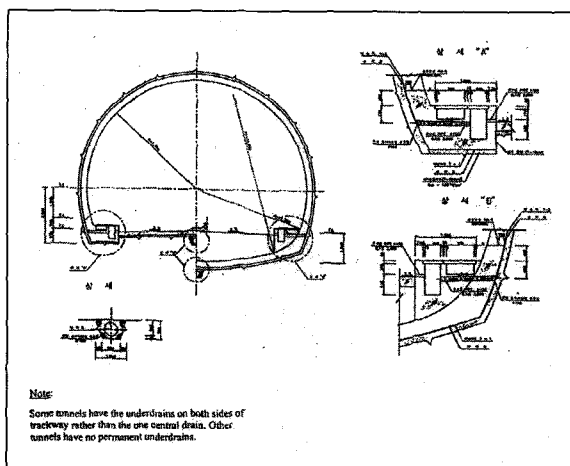


Figure 5. Typical Drainage Details for High Speed Rail Tunnels in Korea

## Final Lining

In Korea, the final lining consists of unreinforced cast-in-place concrete of nominal 400mm thickness. Concrete design strength is 240 kg/cm<sup>2</sup>. No fly ash is used in the concrete mix as is used in some of the TGV and ICE tunnels. Nominal reinforcement is provided within 150m of portals to prevent shrinkage cracking of concrete due to temperature fluctuations, in poorer quality ground (RMR<40) and within 15m of any cut-and-cover section. Locally, the lining has been designed to carry additional loads and therefore the lining consists of reinforced concrete up to 700mm thick.

After the concrete haunches have been placed, the movable form is set on these haunches and the complete ring for the walls and roof placed. The invert slab is placed last. Concrete is delivered to site in readi-mix trucks. Formwork consists of movable steel forms of nominal 10m or 12m lengths. Contact grouting using cement grout to fill voids behind the cast-in-place concrete lining along the tunnel crown is specified.

Tunnels in Japan have pre-cast concrete linings typically varying in thickness from 300 to 500mm. For the Seikan

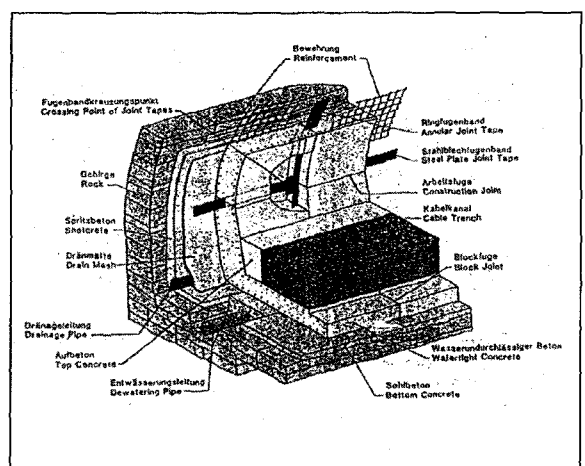


Figure 6. Construction Details of Lining and Drainage for Markstein Tunnel - Germany

undersea tunnel, which has a similar sectional area as the typical Shinkansen surface tunnels, the lining is up to 900mm thick. Further details on lining reinforcement were not available for HSR tunnels in Japan.

For the typical double-track tunnels in France, the lining consists of cast-in-place concrete of minimum 400mm thickness. Where ground conditions warrant, the thickness and configuration of the lining is modified as shown in the typical tunnel section (Figure 2) for the Fontenay and Sceaux tunnels. Grade B32 (320 kg/cm<sup>2</sup> strength) concrete is specified and fly ash allowed to be used in the mix. Concrete is delivered to site in readi-mix trucks. Typically, the invert is placed first and each section limited to 20m length. A complete ring for the walls and roof is then placed. Formwork consists of movable steel forms with length generally limited to 10m.

Need for reinforcement is determined by analyses. In any case, the first lining ring adjoining the portal structure is entirely reinforced. Contact grouting using cement grout to fill voids behind the cast-in-place concrete lining along the tunnel crown is specified.

Pre-cast reinforced concrete segments have been used in single-track TBM-bored tunnels such as those at Villejust.

For the typical German double-track tunnels, the final lining consists of reinforced cast-in-place concrete ranging in thickness from 300-600mm. Reinforcing steel quantity is approximately 80 kg/m<sup>3</sup>. Concrete is minimum Grade B25 and is designed to be watertight. Flyash is sometimes used in the mix. In some tunnels, slightly aggressive groundwater has required the use of low sulfate cement.

In many tunnels, a 2-3mm PVC membrane separates the concrete lining from the primary support to avoid local excess stresses at interface of shotcrete and lining; however, this does not act as a waterproof membrane. Concrete is placed in sections varying from 8.8 to 12m length.

Additional reinforcement within the construction joint areas is used to reduce cracking. The construction joints contain waterstops.

In Taiwan, a cast-in-place concrete lining with design strength of 280 kg/cm<sup>2</sup> is considered. Being a design/build project, the actual lining design is the responsibility of the Contractor who performs computer analyses. Therefore, details of the concrete lining are not defined in the current Directive Drawings.

Lining thickness is dependent on the ground conditions. In the tunnels of Lot 3 of the proposed alignment, where rock consists of soft sedimentary types, the concrete lining for drained tunnels varies from 280 to 560mm. For undrained tunnels, the thickness varies from 280 to 1350mm. The thickest concrete is along the tunnel invert.

### *Invert Type*

The tunnels in Korea typically are constructed with a flat, 25cm thick concrete invert slab. The slab has a 3% transverse gradient to facilitate drainage beneath ballast. In poorer ground (RMR<20), an elliptical-shaped (arched) invert slab is used.

The Japanese tunnels appear to use similar shaped inverts as in Korea. In France, all inverts appear to be arched, reinforced concrete with the amount of reinforcement determined based on finite element analyses. The German tunnels are constructed using both flat and arched inverts depending on ground and groundwater conditions. In very poor ground or where water pressures are high, a deep, reinforced arched invert of reinforced concrete is used.

The current design for the Taiwan tunnels indicates arched inverts for the standard double-track tunnels. Along the Madrid-Seville line in Spain, the double-track tunnels have a relatively flat invert; however, an arched invert is provided in poor ground.

## Ventilation

In Korea and the other countries mentioned in this paper, natural ventilation is provided in all tunnels with no mechanical ventilation systems in the present tunnel designs. The piston effect of the trains is relied upon to help move air into and out of the tunnels. The long undersea Seikan Tunnel in Japan uses eight work shafts for ventilation and emergency evacuation. A smaller service tunnel running parallel to the larger Seikan railway tunnel is provided with two refuge stations equipped with ventilation systems. No ventilation shafts are provided for the 8km long Marseille Tunnel in France. Along the new Cologne line, the tunnel cross section area of 92m<sup>2</sup> is the only ventilation requirement. Enlargement within the portal areas for long tunnels is not planned. In Taiwan, for tunnels greater than 3km long, pressure relief shafts are to be provided at portals and the tunnel has an enlarged section within at least 20m of the portals.

## Track Type

In Korea, ballast track has been used in all Phase 1 tunnels constructed to date. However, there are plans to use concrete slab-track in several of the remaining Phase 1 tunnels and slab-track will primarily be used for all future Phase 2 tunnels. The Tokaido Shinkansen uses ballast track; however, within the past 25 years most tunnels on the other lines have been constructed using predominantly slab-track. Tunnels along the TGV lines all have ballast track except for the 8km Marseille Tunnel, along the new Mediterranean line, where slab-track is used. In Germany, predominantly ballast track is used along the existing high speed lines. Slab-track systems have been used in some existing tunnels, including Muhlberg, Sengeberg and Sausenstein Tunnels, and the present philosophy is to use slab-track for future tunnels. Taiwan is planning to use slab-track in all of their tunnels.

The present AVE tunnels use ballast track but future tunnels may employ slab-track.

## Portals

Portal structures are typically adapted to the existing slope with environmental and aerodynamic considerations part of the design. In Korea, the portal structures, including the bell mouth and covered canopy, typically have reinforced concrete of 750mm thickness. The bell mouth design, standardized for all sections of the alignment, generally follows the German design. Plane of the collar is inclined toward the front of the portal. The sloping bell mouth section is typically about 14.6m long; however, the actual concrete portal structure sometimes extends much more than this beyond the NATM tunnel section in order to accommodate restoration of the slope.

In Germany, generally none or a minimal length of extended section is required. Along the Cologne ICE line, the portal is comprised of reinforced concrete with 800mm thickness. The portal face is inclined 30 degrees measured from the gradient line.

In Taiwan, the shape and type of tunnel portals are being developed in conjunction with the train supplier. In Section 230 of Lot 3, all portal bell mouth structures are to be inclined at least 45 degrees from vertical to mitigate aerodynamic effects.

## Safety Considerations

Safety facilities are an essential part of the KHSR. In all tunnels, handrails and walkways are provided on both sides of the tunnel. KHRC criteria requires proper lighting for safe train operations, convenience of passengers, evacuation and maintenance.

Inspection and maintenance is not planned to be performed during normal train operations; therefore, refuge

niches are not considered necessary. Electrical niches,  $4 \times 6 \times 4\text{m}$  size, are located at 2km intervals and communication niches,  $2.5 \times 2.5 \times 3\text{m}$ , are located every 500m along the tunnels.

For tunnels longer than 5km, inclined tunnels are provided and work shafts are to be equipped with stairways and used for passenger evacuation. Signboards and emergency phones are also to be provided in long tunnels. First aid equipment and vehicle turn-around areas are to be located at portals.

Japan provides life safety requirements for long tunnels. A long tunnel is defined as a continuous tunnel or combination of shorter tunnels, spaced less than 400m apart, that total 5km or more in length. There are more than 50 such tunnels on the Japan high-speed railway system. Some of the safety provisions inside the tunnel include recesses at 500m intervals along tunnels with telephone and safety equipment, fire extinguishers, lighting at 15m intervals and directional signs every 500m. On-train facilities include warning, fire and communication systems. The Seikan Tunnel uses work shafts for ventilation. The smaller service tunnel, which is parallel and 30m from the main railway tunnel, is used for ventilation, maintenance and emergency evacuation. Refuge areas are provided at two locations and equipped with fire extinguishers, first aid facilities, ventilation system and a fire location detection system. Cross passages between the two tunnels are provided at 600m to 1000m intervals. An earthquake warning monitoring system is also installed in the main running tunnel.

For all TGV tunnels, including the Marseille Tunnel, no other access is provided except for the portals. Tunnels are provided with walkways and trains are equipped with a radio system. Lighting is installed in tunnels for operations and passenger evacuation. Refuge bays are provided for safety in pairs facing each other every 25 to 30m.

For the Marseille Tunnel, recesses are located every 50m,

alternating on either side of the tunnel. Three large recesses ( $10\text{m} \times 10\text{m}$ ) are also constructed along the tunnel for refuge and maintenance. A continuous water supply pipe is located inside of the tunnel and safety equipment and facilities are provided at the portals. However, no special measures have been taken to handle smoke since probability of the scenario for a fire to occur and the train remaining inside of the tunnel is considered very low.

The French Ministry of Equipment, Transportation and Housing issued a technical instruction (Inter-Ministerial Technical Instruction No. 98-300 dated July, 1998) which provides safety guidelines for all future railway tunnels.

The French government (Tunnel Management International, October 2000) has recently issued a report for improving the safety of road and railway tunnels. This report includes four main recommendations:

- All new tunnels longer than 1km should be twin tubed.
- All new tunnels longer than 300m and planned for high traffic volume should be dualled.
- All tunnels longer than 3km should be continuously monitored for fire.
- Relief tunnels should be wide enough for emergency vehicles.

The report also urged that funding be made immediately available for research into better solutions for fire detection and control.

For the German tunnels, life safety, lighting and fire prevention features are defined by the following guideline: Anforderung des Brand- und Katastrophenschutzes an den Bau und Betrieb von Eisenbahntunneln. Tunnels longer than 15km are required to meet all the safety measures included in the guideline. In the double-track tunnels, an emergency tunnel or shaft less than 20m depth is to be located at 650m intervals.

Presently, most tunnels in Germany are double-track

tunnels. However, future tunnels that are longer than 3km are to be single-track design because of revised rescue/safety requirements. For future single-track tunnels, there will be a cross-over passage at 350m intervals.

Originally, double-track tunnels were constructed for the Spain AVE. However, the current understanding is that future tunnels are to be twin single-track tunnels of 8.5m diameter with cross passages located at 300m intervals. The reason for this change is due to safety and passenger evacuation considerations.

### 3. Summary

Most of the major aspects of the high speed rail tunnels in Korea, including such items as the tunnel geometry, excavation methods, primary support, final lining, drainage and waterproofing, are similar to the practices followed in other countries. The tunnels in Korea provide the largest net internal area (107 m<sup>2</sup>) as compared to the other countries addressed in this paper. The effective adaptation and modification of international practices and designs, combined with the integration of domestic practices, has resulted in the successful construction of these large tunnels.

The experience gained from the completed work to date on the high speed line in Korea, combined with international technology input, will help to ensure future tunnels are constructed in an efficient manner with adequate design measures implemented for the long-term operational life of the tunnels.

As has occurred in these other countries, further improvements and modifications to the Korea high-speed railway tunnels will occur as experience is gained and new technology develops.

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