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Design and Construction of InJe Tunnel, the Longest Road Tunnel of Korea

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ABSTRACT: Inje Tunnel, an 11 km-long twin-tunnel will be the longest road tunnel of Korea. Two parallel tunnels including two vertical shafts and one inclined shaft are under construction. Details of the tunnel design including geotechnical characteristics, cross-section of the excavation, reinforcement, drainage, ventilation operation, safety facility corresponding with a tunnel fire, and portal planning are introduced. Various analyses that systematically make comprehensive utilization of available data obtained from geotechnical investigations were applied for the optimal evaluation of ground conditions. The typical NATM excavation scheme by a combination of drilling, blasting and reinforcement has been undertaken. Steel-fiber mixed shotcrete, steel rib with Lattice girder, and rock bolt were designed for the reinforcement. Ventilation plan using the inclined shaft and vertical shafts are summarized considering traffic conditions and emergency situations. Current construction procedures are also briefly described.

1. INTRODUCTION

Inje Tunnel under construction is an 11 km long road tunnel beneath the Baekdu-Daegan mountainous region in Korea. The Baekdu-Daegan, the spine of the Korean Peninsula, is an eastern mountain range and watershed-crest-line from Baekdu Mountain (height 2,750 m) in the north to Jiri Mountain (height 1,917 m) in the south. It incorporates the Sobaek mountain range and most of the Taebaek mountain range. With a route length of 10,965 m and a total of 21,927 m of twin tunnels, it will be the longest road tunnel of Korea.

Inje Tunnel is a part of DongHongcheon-Yangyang Expressway (length 71.51 km) which will connect Chuncheon City and Yangyang County in Gangwon Province. It has been believed to enable balanced developments of the national land and to vitalize the tourism industry in the region. Route of the expressway and tunnel is shown in Figure 1. The project consists of two parallel tunnels, two vertical shafts, and one inclined shaft. Inclined shaft is for excavations during the construction and ventilations during the operation of the south tunnel. Vertical shafts are for ventilations of the north tunnel. Maintenance office buildings are planned to install at both ends. Construction of the tunnel was commenced on April 2009 and it will be completed on December 2015. Total construction cost is approximately estimated as 450 million USD.

Details of the tunnel design including geotechnical characteristics, cross-section of the excavation, reinforcement, drainage, ventilation analysis, safety system, and portal planning are introduced in this article. Construction procedures by NATM in current stage are also described in outline.

General information of Inje Tunnel is summarized in Table 1 and Figure 2 shows virtual aerial view of the tunnel.

Table 1 Outline of Inje Tunnel

Name	Explanation
Location	Begins at Girin, Inje County, Gangwon Province Ends at Seo, Yangyang County, Gangwon Province
Length	North tunnel (Chuncheon direction) : 10,965 m South tunnel (Yangyang direction) : 10,948 m [Distance between two tunnels : 33.28 m CTC] Vertical shaft : 207 m + 307 m ← height Inclined shaft : 1,394 m
Width	13.4 m (4 lanes for two-way traffics)
Excavation Method	New Austrian Tunnelling Method (NATM)
Portal type	Arch wall with reinforcement
Road Design	Design Speed : 100 km/hour Route alignment : R = 2,000 - 6,350 Vertical Alignment : (-)1.95 % Superelevation : (-)1 – (+)3 %
Ventilation	Jet fan + vertical shafts and inclined shaft
Emergency	57 cross passages for vehicle and people High-pressure water spray system
Utilities	Two maintenance office buildings Visitor's centre

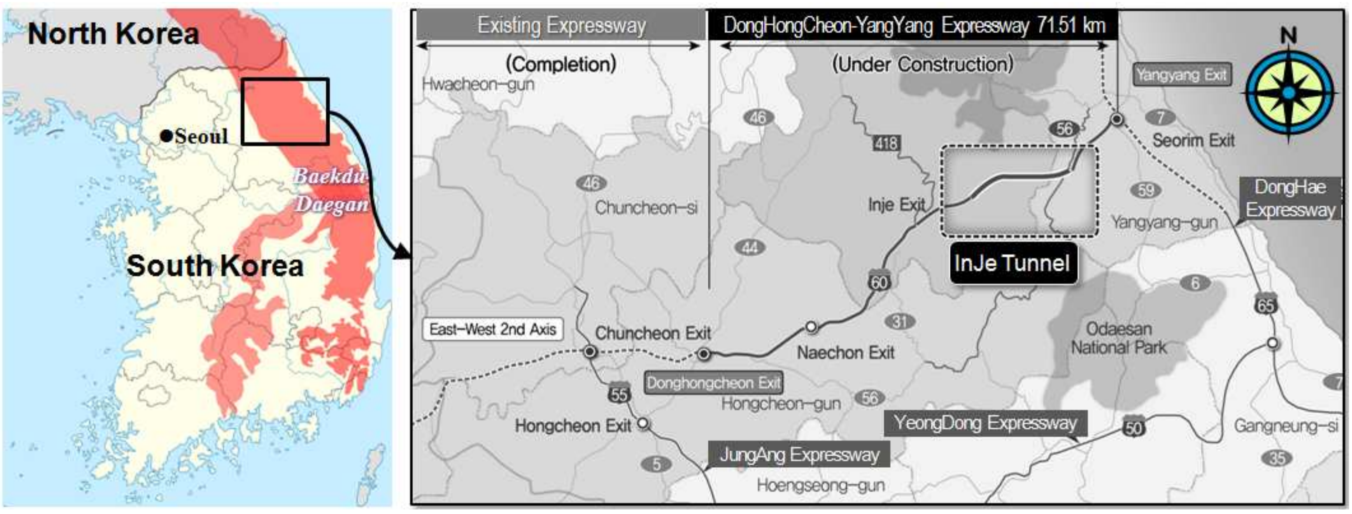


Figure 1 Route map of Inje Tunnel in DongHongcheon-Yangyang Expressway

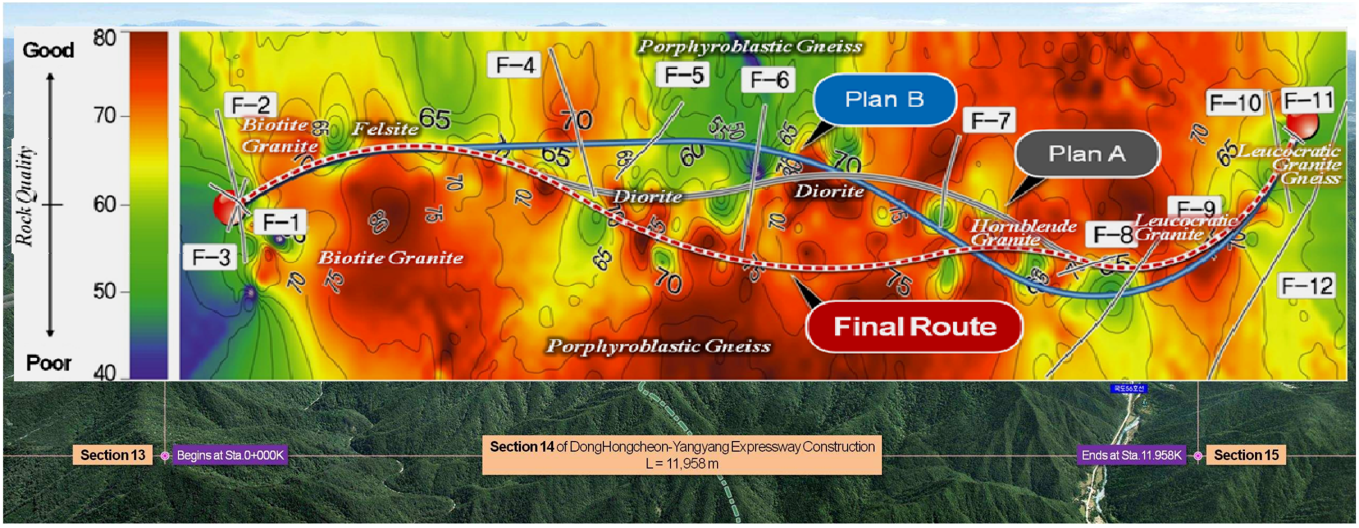


Figure 2 Aerial view of Inje Tunnel

Main reasons of choosing for very long tunnel instead of a long span bridge include protecting environment of the Baekdu-Daegan area (it contains natural forest, wildlife sanctuary and preserved water source), and also aesthetic purposes like as preserving the above-ground view, landscape, and scenery.

All domestic tunnels which are longer than 10 km are only for railways in Korea. For example, Geumjeong Tunnel for high speed railway (KTX) has a length of 20.3 km and is also under construction now. 24.5 km long Lærdal Tunnel of Norway is the longest road tunnel in the world (span width is 9 m).

2. ENGINEERING DESIGN OF THE TUNNEL

2.1 Geotechnical characteristics

Preliminary survey with geology map, satellite image, and existing information were performed to find out geomorphic development status and regional geological characteristics of the site. Many kinds of in-situ tests, boring, geophysical exploration, and laboratory tests were carried out to evaluate the geotechnical parameters for detailed design (Table 2).

Table 2 Site investigation methods for Inje Tunnel project

Types	Testing methods
Preliminary surveys	Literature review, Surface geological survey, Remote sensing with GPS
In-situ tests	Test boring, Standard penetration test (including efficiency measurements), Borehole shear test, Pressuremeter test (including Elastometer and Goodman jack), Permeability test, Groundwater flow test (well, pumping, velocity), Slug test, Hydraulic fracturing, Schmidt hammer test
Laboratory tests	Index properties test, Compaction test, California bearing ratio test, Shear test (direct, large-chamber, joint of rock), Triaxial compression test (including cyclic condition), Resonant column test (soil, rock), Unconfined compression test, Acoustic emission and Deformation rate analysis, Creep test (soil, rock), Point load test, Swelling/slaking test, Triaxial tension test (rock), X-ray diffraction analysis
Samplings	Test pit, Hand augering, Coring (double, triple barrel)
Geophysical surveys	Electrical resistivity survey, Electromagnetic survey (CSMAT), Seismic survey (surface refraction, MASW, tomography, down-hole), Sonic wave logging (suspension PS logging), Borehole density logging, Borehole image processing, Borehole televiewer

Colluvial soil layer, sedimentary soil layer, and weathered residual soil layer appears from the ground surface. Weathered rocks and bed rocks underlay these soil layers. N values from the ground surface to the weathered rock layer are shown in Figure 3. Deformation modulus (E_m) of ground at the centre point of the tunnel obtained from the Pressuremeter test (including Elastometer and Goodman jack) is depicted in Figure 4.

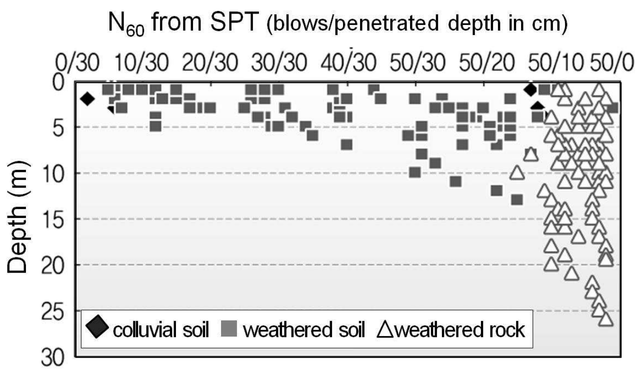


Figure 3 N-value from the SPT at the soil layers

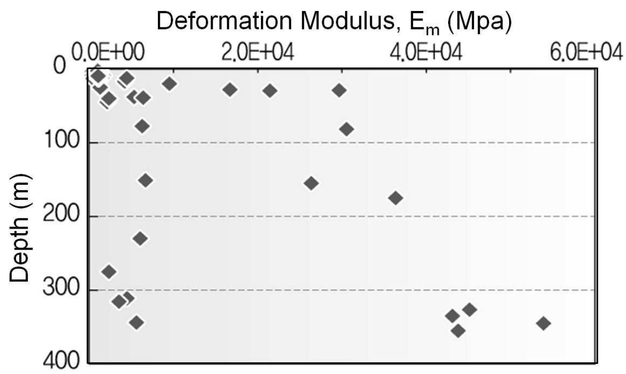


Figure 4 Deformation modulus of the ground

Bedrock of the ground consists of Precambrian metamorphic rocks and Jurassic granite which penetrated the metamorphic. Main rocks at the tunnel area are granite and gneiss (Figure 5). Geological boundary of each rock mass and major structural lines like as fault was established. Various methods which can systematically make the comprehensive utilization of available data obtained from investigations were applied for the optimal evaluation of ground

Figure 5 Geological map along the tunnel (Final route was selected among 3 candidate routes)

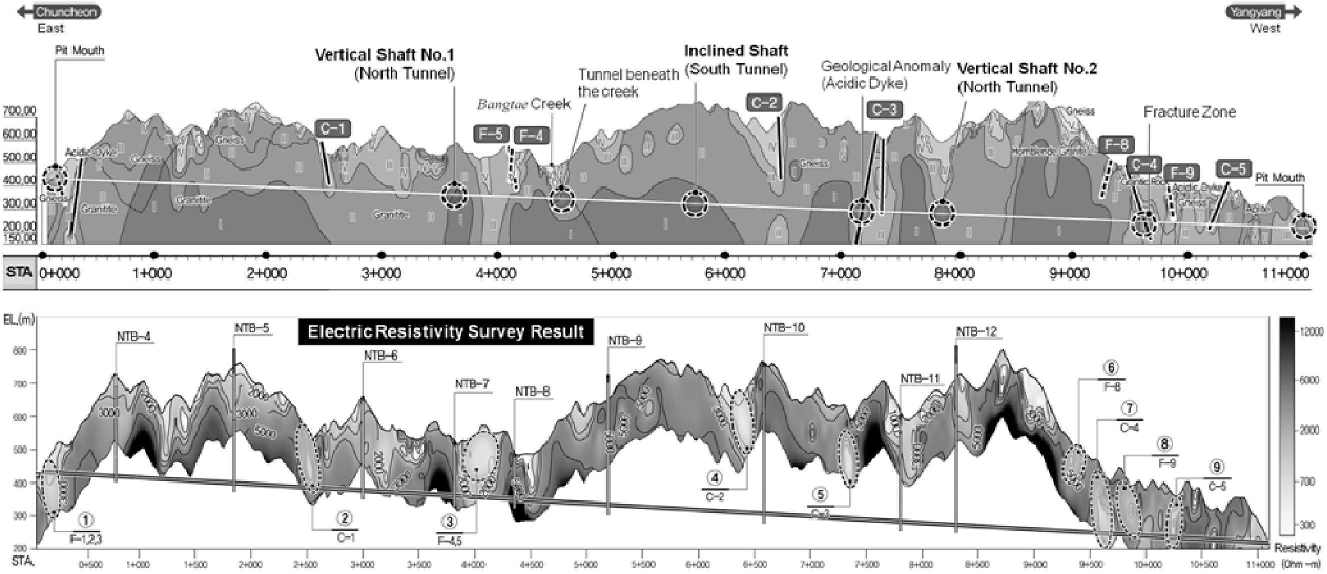


Figure 6 Ground profile, rock mass grades (from I to V), and electric resistivity distributions along the tunnel route

conditions in terms of rock mass class. Figure 6 shows the ground profile along the tunnel route and geological anomaly. This figure also contains the result of the electrical resistivity survey. Because discontinuous zone is expected to have low resistivity due to high porosity and small gain size, it has been known that the electrical resistivity is very useful property find out lineation, fault, and fracture zone in the ground. The electrical properties of rocks are strongly influenced by pore fluid; therefore, the subsurface electrical resistivity can be an important indicator of the existence of fluid and pores in the rock mass. With the electrical resistivity survey across the fault, vertical fracture zone which the tunnel has to face would be detected. Resistivity value of these anomaly areas measured as less than 1,200 Ω·m. The electromagnetic survey by CSMAT was also performed to investigate the geological characteristics at the deep ground. Cross-section of the ground obtained by these investigations along the route is shown in Figure 6. Six geological lineaments and nine faults were found in the site and the tunnel was designed to cross three faults. Figure 6 was split up into three figures from Figure 7 to Figure 9.

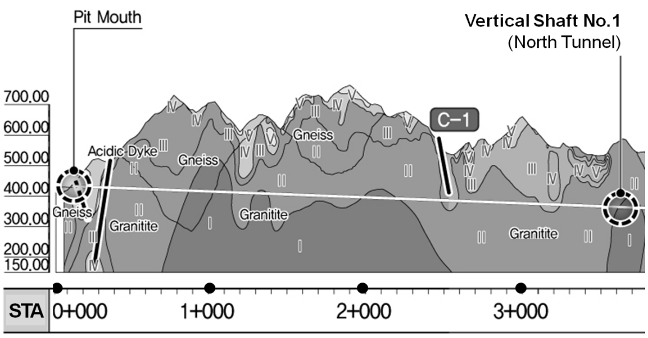


Figure 7 Ground profile: STA.0 - 3+800 (km)

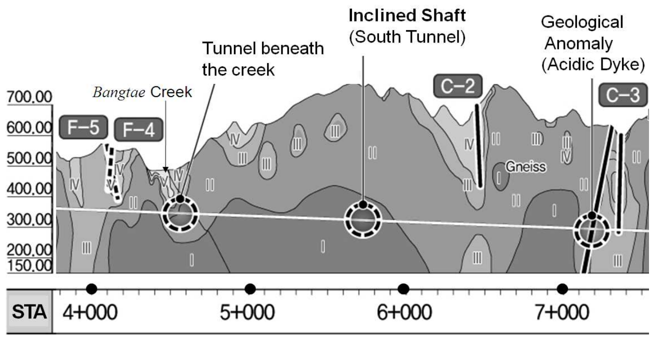


Figure 8 Ground profile: STA.3+800- 7+600 (km)

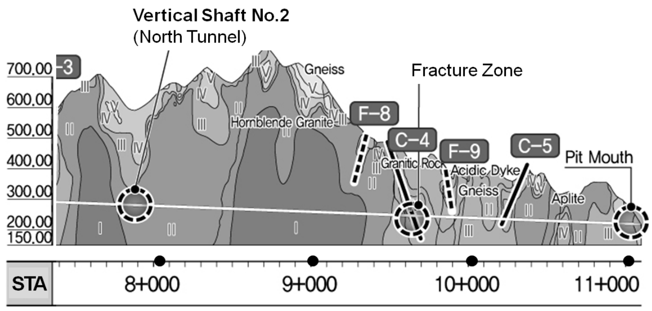
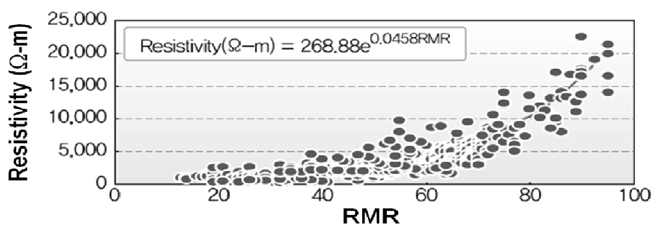


Figure 9 Ground profile: STA.7+600 - 11+000 (km)

Relation between Bieniawski's RMR (Rock Mass Rating) and electrical resistivity for the rock mass is shown in Figure 10. Every rock mass was classified into 5 groups from I-class to V-class. Uniaxial compressive strength of major rocks is shown in Figure 11.



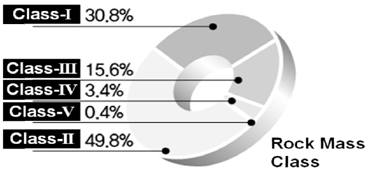


Figure 10 Relation between RMR and electrical resistivity of rock-mass, and percentage of each class

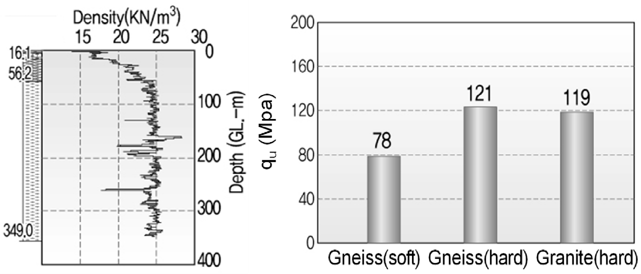


Figure 11 Density of the ground and the unconfined compressive strength of the rock

In-situ stress state of rock mass was evaluated by the hydraulic test. Vertical stress of the ground was in the range of 4.4-8.9 (Mpa) and horizontal stress distributed from 5.0 to 5.7 (Mpa). Coefficient of lateral earth pressure, K_0 from the hydraulic fracturing test was measured as 0.84-1.27 in longitudinal direction of the tunnel, and 0.70-1.05 in transverse direction (Figure 12).

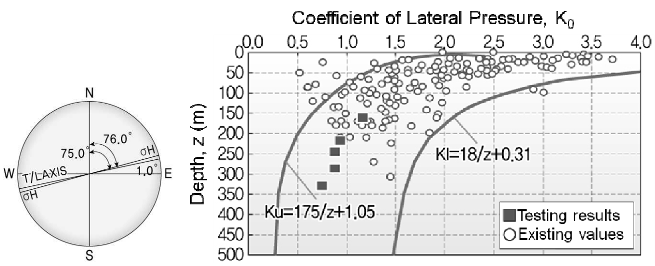


Figure 12 Direction of principal stress and K_0 value from the hydraulic fracturing test

Coefficient of lateral earth pressure of the bed rock also was obtained from the acoustic emission (AE), and deformation rate analysis (DRA). K^0 is depicted again in Figure 13 and it shows decreasing tendency according to the depth. Permeability of granite was estimated as $7.7{\times}10^{-8}$ m/sec. Groundwater table in the slope at the portal area was predicted by surface flow test and Pradel-Radd method.

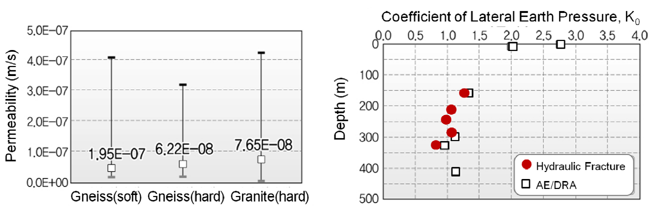


Figure 13 Permeability and K_0 value of the bed rock

Seismic surveys by subsurface refraction method, down-hole method, suspension method, and topographical method were performed. Shear wave velocity was measured averagely as 250 m/s at colluvial soil layers, 420 m/s at residual weathered soil, 570 m/s at weathered rock layer, 1,600 m/s at soft rock layer, and 2,600 m/s at hard rock layer. The velocity increased greatly at the deep rock-layer. Typical results at the central area of the tunnel using the down-hole method are summarized in Figure 14.

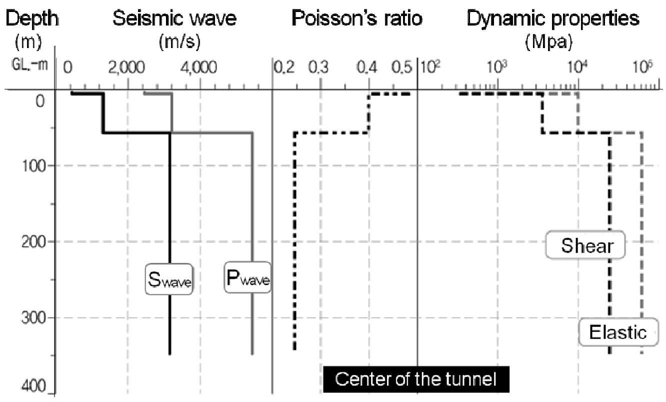
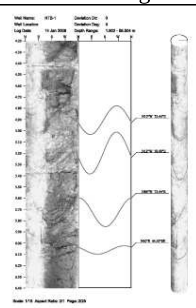
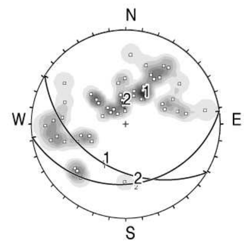
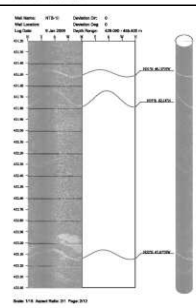
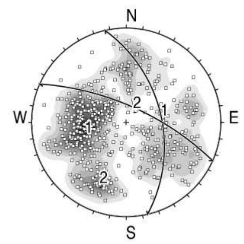


Figure 14 Seismic survey results

Characteristics of rock joint like as orientation, spacing, and roughness were analysed by image processing and televiewer survey during the test boring, and joint strength test using cored rock specimen. Table 2 presents typical image of the discontinuity of the rock captured during the drilling. Joint orientation was N10-60W at the entrance area, N10W-N20E at the center of the tunnel, and N30-50E at the ending area.

Table 2 Discontinuity properties (BIPS analysis)

Location	BIPS image	Discontinuity Contour
Entrance of tunnel		
Center of Tunnel		

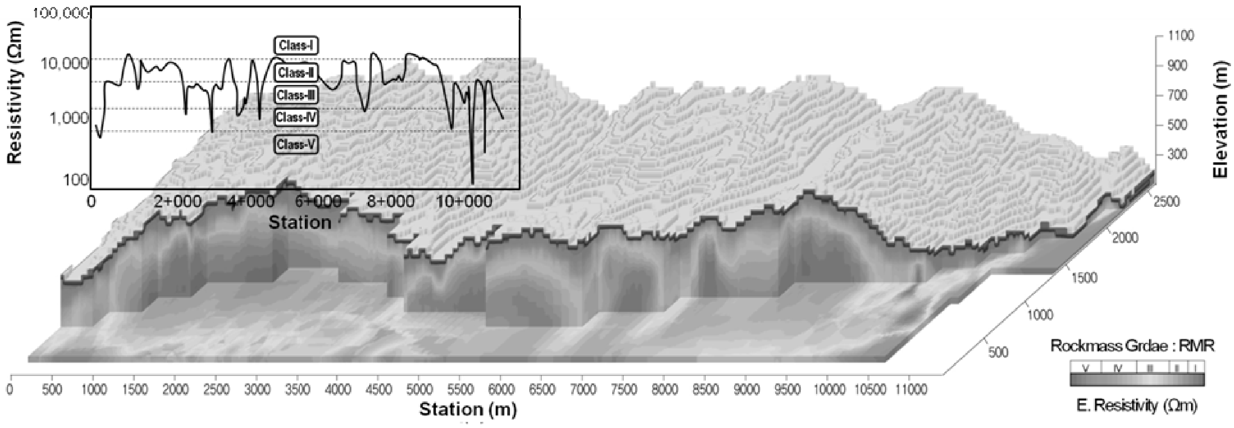


Figure 15 Three-dimensional distribution of the rock mass by the Kriging method

The indicator Kriging method was utilized to classify the rock mass using site investigation results. The result of three dimensional interpolations was shown in Figure 15.

As shown in Figure 7 and 9, both portals of the tunnel were installed at steep slope area. A section around the STA4+400 is directly under the Bangtae River (creek) and geological anomalies are appeared in the subsurface ground.

Geotechnical parameters of the rock mass which were decided for the design were summarized in Table 3.

Table 3 Geotechnical parameters of rock mass for design

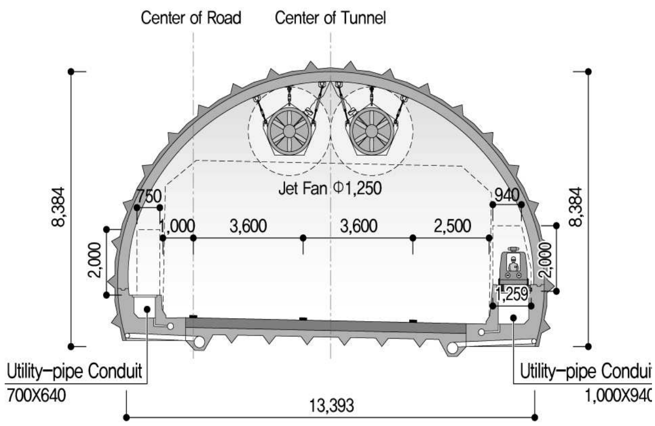
Parameters	Rock mass Grade				
	I	II	III	IV	V
Unit weight, kN/m^3	27	26	25	24	21
Cohesion, MPa	2.5	2.0	1.5	0.3	0.05
Friction angle, degree	50	48	40	35	33
Deformation Modulus, GPa	22	12	10	2	0.5
Poisson's ratio	0.20	0.22	0.25	0.27	0.30

2.2 Cross-section of the tunnel

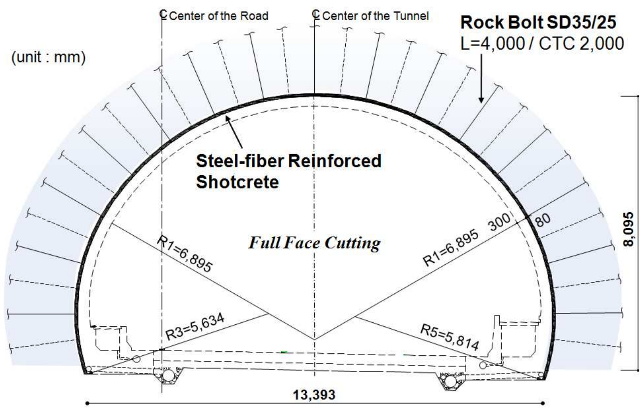
2.2.1 Main tunnel

The tunnel cross sections were determined considering design criteria, traffic volume, construction-ability, maintenance function, and requirements for safety. Figure 10 shows typical cross section of main tunnels (north and south). Span of the tunnel is 13.4 m and height is 8.4 m. Two regular lanes (width 3.6 m respectively) and one emergency lane (width 2.5 m) were planned. Two utility-pipe conduits were designed at both sides and patrol vehicle system with tires will be installed on the right-side conduit (Figure 16).

A typical NATM excavation scheme by combination of drilling, blasting and reinforcement was planned. Steel-fiber mixed shotcrete, steel rib with Lattice girder, and rock bolt were designed for the reinforcement. A pilot horizontal drilling investigation and TSP (tunnel seismic profiling/prediction) are necessary at the geological anomaly area prior to excavating. A steel-pipe reinforced multi-step grouting technique (diameter of 60.5 mm or 114 mm) as an umbrella arch method and the fore-polling are available for the reinforcement at this area. Umbrella arch method (UAM) has been widely used for reinforcements and water cut-offs in the tunnel construction with a shallow soil cover in cohesionless soils or highly weathered rocks.



(a) Dimension of cross section



(b) Model reinforcement plan

Figure 16 Cross-section of main tunnel

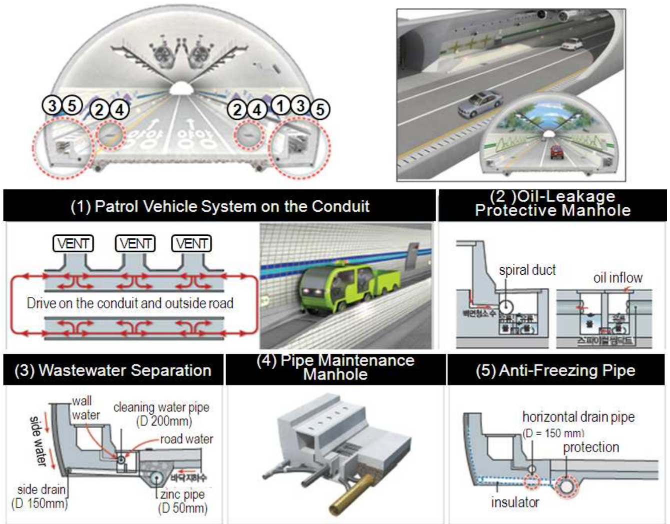


Figure 17 Tunnel section design at the conduit part

Drain pipe and optical communication line are to be installed separately in both directions. For drainage system, oil-fire dispersion preventing manhole and drain pipe for wastewater were planned. Groundwater from the wall and the bottom is drained simultaneously using perforated pipe system (diameter 350 mm). A maintain manhole for zinc-coated perforated pipe is applied. Runoff from the road and groundwater flow from the wall will be separated thanks to this system. Details of the drainage system in the tunnel are described in Figure 18. Construction workability has been improved by application of this unified cross-sectional system.

As shown in Figure 8 and 19, main tunnel intersects with Bangtae River and minimum vertical distance between the riverbed and top of the tunnel is 132 m. According to the seepage analysis at this area, advanced horizontal boring was planned to investigate the groundwater discharge possibility and geotechnical condition of the subsurface. Figure 20 indicates the pore water pressure distribution around the tunnel due to the underground excavation beneath the river.

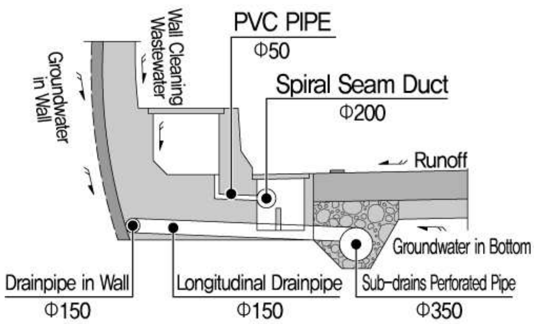


Figure 18 Drainage design at the conduit in the tunnel

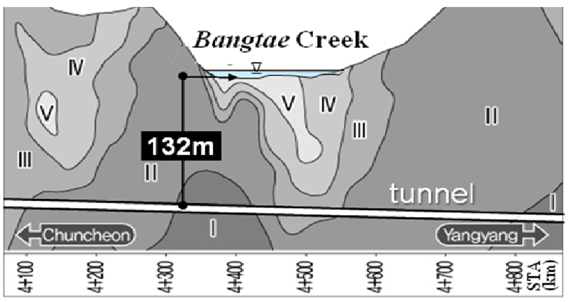


Figure 19 Tunnel beneath the creek

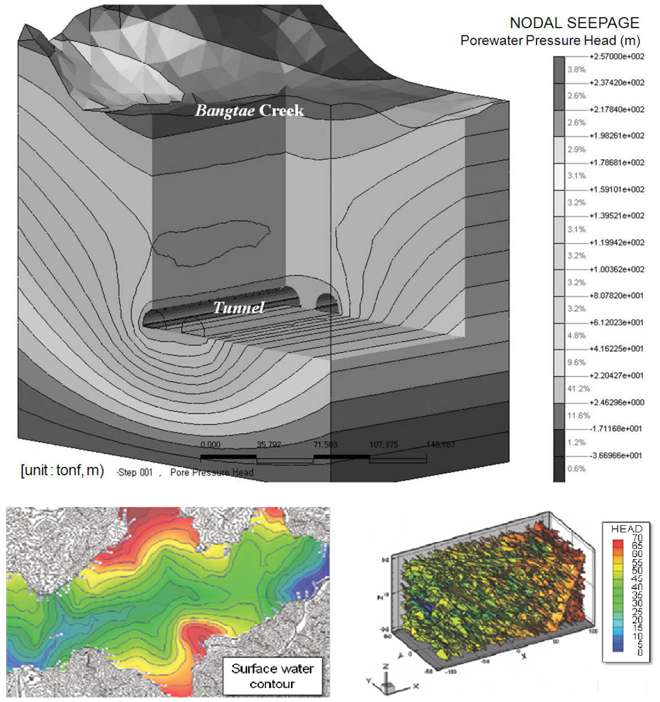


Figure 20 Groundwater behavior around the excavated tunnel beneath the creek (analysis of seepage and flow)

Cut-off grouting with micro-cement can be done for the case of groundwater discharge. Number of piezometer will be instrumented to monitor the groundwater behaviour during the excavations under the intersection point with the river (Figure 21).

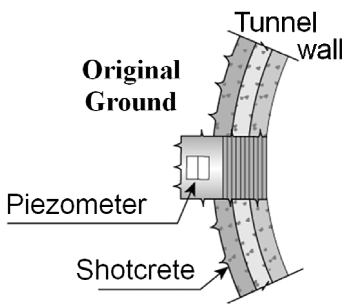


Figure 21 Piezometer installations for groundwater monitoring

2.2.2 Inclined shaft and vertical shaft

An inclined shaft and two vertical shafts are constructed at the south tunnel and the north tunnel respectively (Figure 22).

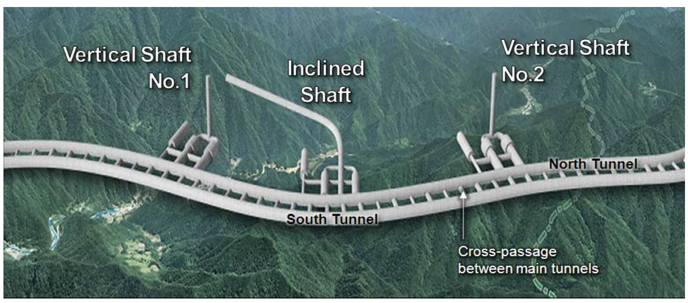


Figure 22 Inclined and vertical shafts

The inclined shaft at the south tunnel is being used for excavations and muck transportation after blasting and it will be used for ventilation and emergency rescue during traffic operation.

This shaft is very helpful to reduce the time for excavations of main tunnels. Span of the shaft is 9.6 m to allow the passing of two heavy trucks and the height is 6.7 m. Cross sections of the inclined shaft were shown in Figure 23.

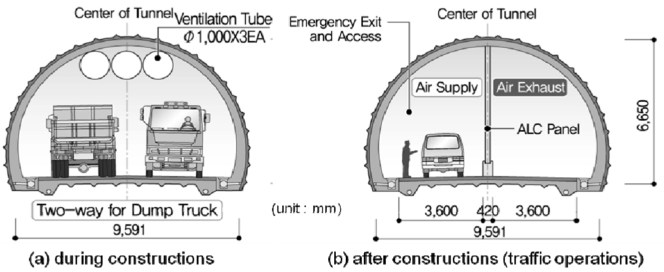


Figure 23 Cross section of the inclined shaft

Three ventilation tubes of 1 m in diameter were installed for ventilation during the construction. Turn-places for equipment driving during construction were built and a diaphragm wall, an ALC (autoclaved lightweight concrete) panel for separation of air-supply and exhaust in the shaft will be made. Thanks to this dual air-flow system, the inclined shaft will be used as evacuation facility. Ambulance can access the main tunnel using the shaft.

Two vertical shafts were designed for ventilation of the north tunnel and they have circular cross sections (Figure 24). A 30 cm thick diaphragm partition will be installed to separate the air-supply from the exhaust. The first shaft is 208 m high and the other is 303 m high. To satisfy the minimum required area of 64 m2, diameter of the shaft was decided as 9.7 m.

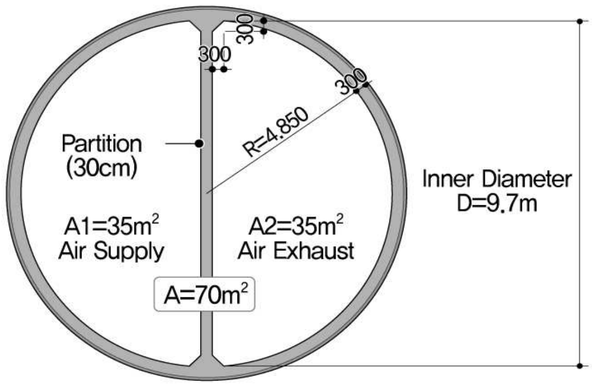


Figure 24 Cross section of the vertical shaft

2.3 Reinforcement at the portal area

Because both portals of the tunnel were made at steep slope area and had shallow ground cover, ground reinforcement had been required. Umbrella arch reinforcements as well as soil nailing were applied to minimize the environmental damage. A type of the portal was selected as a facing-wall to secure the tunnel against the rockslide and soil runoff from the above (Figure 25).

Figure 25 Portals at both ends of the tunnel

Soil nailing at the slope above the tunnel portal and umbrella arch reinforcement with steel pipe grouting at the roof of the portal were very effective for stability of the ground around the portal (Figure 26).

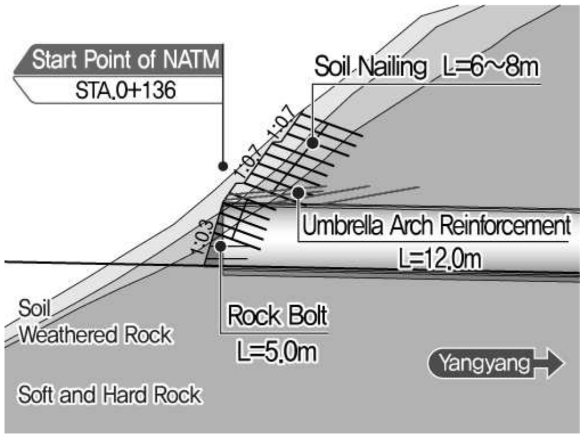


Figure 26 Reinforcement with soil nailing and UAM at portal area

And safety fence and wire-net was installed to prevent the rock falls. Kinetic energy of the fallen rock and rebound characteristics were analyzed using Rocfall program. Rebound height of the fallen rock at the toe of the slope was reduced to 0.4 m thanks to these measures (Figure 27).

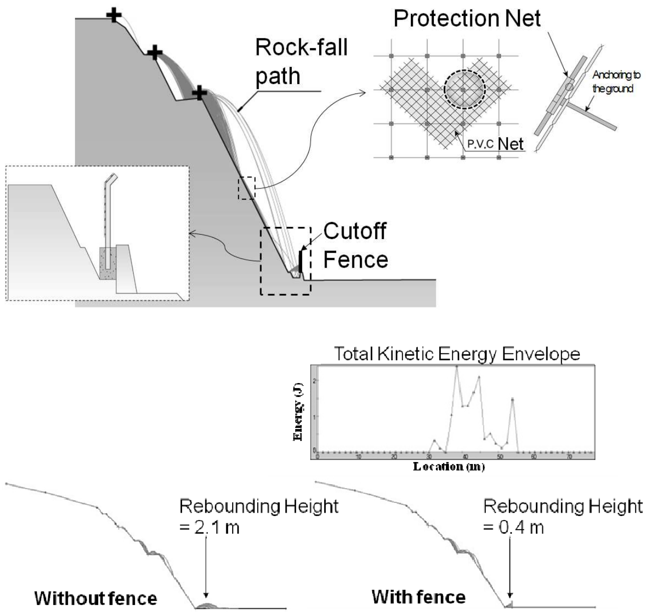
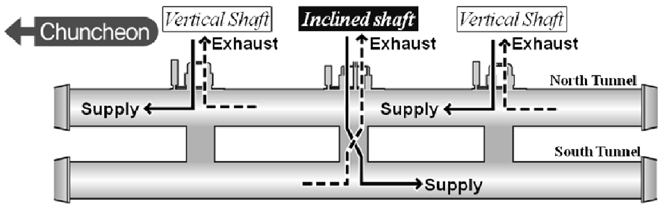


Figure 27 Analysis of rock-fall behavior and its countermeasures at the cut slope

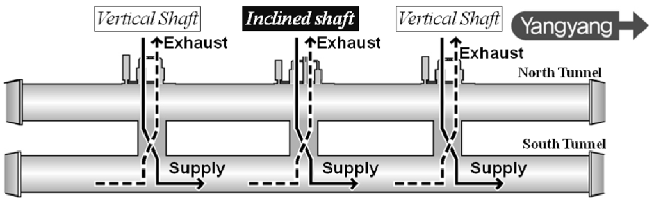
3. VENTILATION AND SAFETY

3.1 Ventilation designs

Inje Tunnel is very long and it traverses the Baekdu-Daegan nature reserve. Therefore, special ventilation system which enables minimizing the environment impact on the surrounding nature circumstance. Generally, tunnel ventilation system is divided into two groups; natural and mechanical. There are longitudinal type, transverse type, semi-transverse type, and combined type in the mechanical system. A longitudinal-mechanical ventilation system using jet-fan and vertical shaft was selected for Inje Tunnel.



(a) Ventilation plan at normal traffic condition for both tunnels



(b) Ventilation plan at busy-traffic condition for south tunnel

Figure 28 Ventilation operation examples according to traffic conditions

Figure 28 shows how to operate the ventilation system for the normal traffic condition and the busy traffic condition. Vehicle emission of an ascent road was 1.8 times more than that of a descent road in the tunnel. Because the south tunnel has a downward gradient of 1.95% along the route, ventilation by the inclined shaft is sufficient considering smaller amount of emissions. However, for the north tunnel with an upward gradient of 1.95%, two vertical shafts will be used to vent larger amount of emission. For the large traffic volume period like as weekend or holiday season, concentrated operation will be done (Figure 28 (b)).

Emergency ventilation plan to provide itself against a fire in the tunnel was also planned. Four ventilation sections were set to take immediate evacuation of the smoke. See Figure 29.

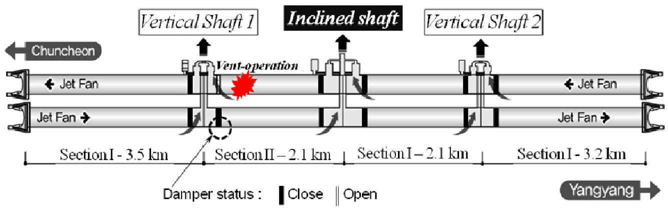


Figure 29 Ventilation plan for the fire in the tunnel

3.2 Safety designs

Safety facilities to prepare the emergency situations were designed. Various kinds of a model test and a simulation for a fire were carried out. Overall precautions against fire in the tunnel were established through a quantitive risk analysis (QRA). 57 cross passages (37 exits for people, 14 exits for small vehicle, 6 exits for large vehicle) between two tunnels were designed for emergency evacuation and for access of the rescue vehicle including the fire engine. A water-mist spray system at the wall and foam extinguishing system on the road will be installed to suppress the fire. The water-mist sprayed curtain is a swift tool for the down-drag effects on fire gases. Figure 30 and 31 shows an illustrative situation of the fire. Rescue vehicles can also move in the inclined shaft (See Figure 23).

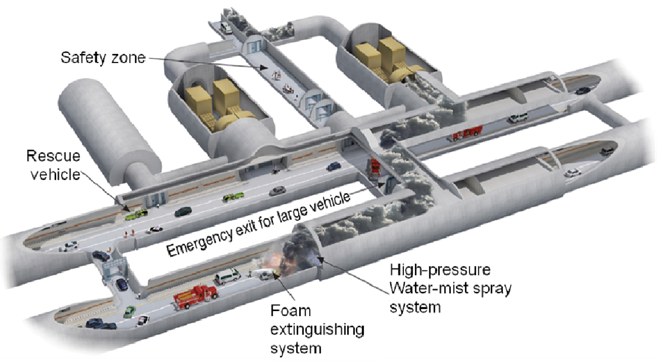


Figure 30 Illustration of the fire emergency situation

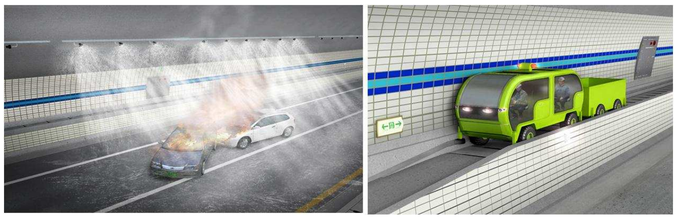


Figure 31 Water-mist fire extinguishing system and maintenance vehicle moving on the conduit

Aesthetic designs for the internal space of the tunnel to enhance the driving environment (Figure 32). Cozy and awakening atmosphere during the driving in very long tunnel is important to prevent the accident. All the safety actions will be controlled at the maintenance office located at the end of the tunnel (Figure 33).

Figure 32 Aesthetic designs of the tunnel

Figure 33 Maintenance building at the end of the tunnel

4. CONSTRUCTIONS

The construction in progress is scheduled to be finished by 2015. About 25 % of total excavation amount was accomplished so far.

1.4 km long inclined shaft was already completed and 5.4 km of main tunnels were also excavated in total. Vertical shafts will be set to excavate in 2013. The tunnel excavation was started from eight points of the route to keep the impending construction schedule74 months of construction period). Tunnel facings were opened at both ends of the tunnel and at two intersections with the inclined shaft. Figure 34 describes excavation directions from eight facing point. So, the inclined shaft is essential to reduce the construction time as well as to the ventilation function.

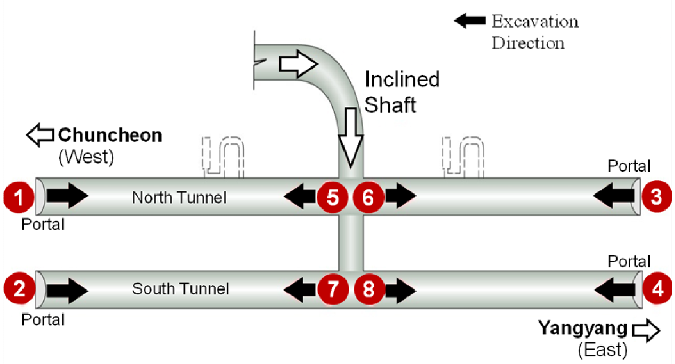


Figure 34 Excavation directions (8 points)

Main equipment and material for the tunnel excavation are listed in Table 4.

Table 4 Construction equipment and material

Usage		Model (Spec.)	Photo
Excavation Equipment	Jumbo drill	Boomer353ES - 3 booms	
	Charging car	SMKC-2500-A1104	
	Shotcrete pump machine	SSM20Plus	
Transport Equipment	Wheel Loader	Caterpillar 950H - bucket : 3.5 m^3	
	Backhoe	SORA210W-V - Tire 08	
	Dump truck	15 tonf : MD45DI 25 tonf : Benz 4144K 40 tonf : CAT 740B	
Major Material	Rock bolt	Deformed Steel Bar - Diameter 25mm - Length 3-5m	
	Steel support	Lattice Girder - 70×20×30 (mm) - 50×20×30 (mm)	
	Emulsion explosives	MegaMEX - detonation velocity = 6,000 m/sec	

Steep slope above the tunnel entrance and the roof of the tunnel at the portal area were reinforced by soil nailing and umbrella method (Figure 35).

(a) Soil nailing

(b) Umbrella reinforcement

Figure 35 Ground-reinforcement at the portal area including slope

Four sets of fan system for ventilation during the excavation were installed in the tunnel (Figure 36).

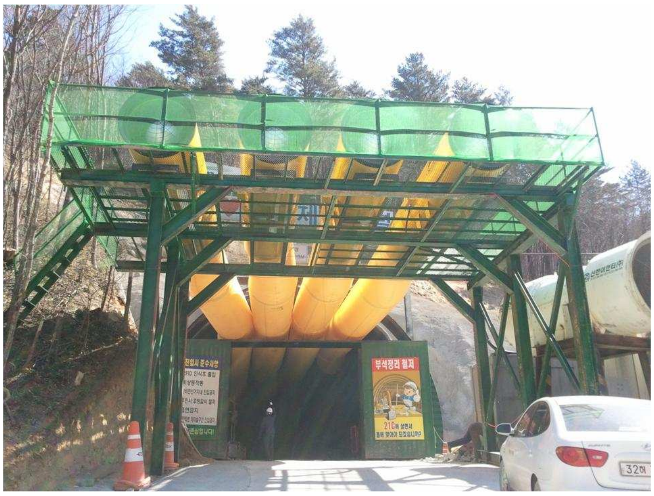


Figure 36 Ventilation tubes for construction (110 KW)

Major excavation works with reinforcement were shown in following figures (Figure 37, 38, 39, and 40).

Figure 37 Drilling works for the blasting

Figure 38 Shotcrete placements after the blasting

Figure 39 Rock bolt installations

Figure 40 Steel rib (Lattice girder) installations

5. CONCLUSION

The outlined information on the design and construction of Inje Tunnel, an 11 km long road tunnel of Korea is briefly introduced. This tunnel consists of two parallel main tunnels with 2 lanes respectively, one inclined shaft for excavation works and ventilation, and two vertical shafts for the ventilation control. New Austrian Tunnelling Method with blasting and reinforcement was applied and 25 % of total excavation amount has been completed.

6. ACKNOWLEDGEMENT

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