Planning and Detailed Design of the Longest Road Tunnel in Korea

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1. INTRODUCTION

There are more tunnels and bridges planned on roads passing mountainous areas by requests from environmental groups and local residents due to the problems of environmental damages by recent construction of roads. In Korea, the Inje tunnel was planned as a twin-tube tunnel with a length of 10.945 km because the entire site spreading out widely is planned as tunnel.

Initially, the plan was to minimize the tunnel length by constructing a straight tunnel. However, later, the plan was changed and a curved tunnel was decided upon. There were two reasons for the change: (1) the location of vertical shafts required by regulations on environmental damages and (2) preventing drivers from dozing off due to dullness from driving in tunnels for a long time.

Many plans were devised for preventing disasters so as to minimize casualties in accidents and for reducing the construction time.

Even though modern excavation methods have been developed for the construction of tunnels, various types of problems such as changes in groundwater distribution and transformation of geographical features still remain. In regions where there are mountain tunnels, it is not uncommon for private wells and small streams to be used in daily life. Tunnel excavation activities can cause serious social problems such as a decrease in the well water level. Therefore, we evaluated the quantity of water leakage into tunnels and groundwater drawdown area by performing simulations; numerical models such as MODFLOW and MAFIC were used in the simulations to examine ways to reduce the adverse effects on the environment.

The tunnel consists of two parallel double-lane tubes, each with a width of 14.5 m. The tubes are connected by cross tunnels every 250 and 750 m for use during emergencies. The gradient of the tunnel from Chuncheon to Yangyang is 1.95% downward. A 1.5-km-long inclined tunnel was designed for access to the excavation face and for use as an emergency escape tunnel. Table 1 shows a general overview of the tunnel.

<table>
<thead>
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<th>Table 1 - Specifications of Inje tunnel</th>
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<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Alignment/Gradient</td>
</tr>
<tr>
<td>Shape of portal</td>
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<tr>
<td>Traffic type</td>
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<td>Ventilation facilities</td>
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<td>Excavation method</td>
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<td>Emergency facilities</td>
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</table>
2. ALIGNMENT PLAN

Lines were compared by dividing broadly into straight tunnel and curved tunnel. A straight tunnel has a smaller length, but it is expected to decrease the speed of vehicles heading upward on inclined roads and increase exhaust emissions. A curved tunnel can increase construction costs since its length is larger, but it can be made to have reduced slopes and selecting locations for tunnel ventilations is easy.

The final selection of the tunnel line was made after a comprehensive review and an analysis of problems relating to routes in the basic design; thorough site examinations were performed and the feasibility of plans was researched by considering social and geographical conditions in the region together with changes in public sentiment and government policies.

![Fig. 1 Location of Inje tunnel and its vertical section profile](image1.png)

2.1 Major factors reviewed during selection of routes
- Route for minimizing environmental damages
- Types of ventilation within the tunnel and their location
- Safe driving by users (driving simulation)
- Preempting civil complaints during the construction of the tunnel

![Fig. 2 Simulation of drives in the tunnel](image2.png)

2.2 Driving simulation
The time taken to pass through the Inje tunnel is expected to be 6–7 min when driving at the maximum permitted speed. The possibility of major accidents due to dullness of drivers and a lower perception of speed by them while driving at high speed for a long time in the tunnel were investigated; thus, problems expected during actual driving were examined and reviewed through the simulation of tunnel structures on a computer. It was observed that safety is relatively increased when the tunnel comprises curves with a radius greater than $R = 2,000$ m.
3. GENERAL OVERVIEW OF TOPOLOGY AND GEOLOGICAL CONDITIONS

The dominant topographic features of the area include rugged mountains and a few streams. The western part of the area is lower in altitude and has more relief than the eastern part. This area shows an early mature stage in the geomorphologic cycle.

The area consists of Precambrian porphyroblastic gneiss, banded gneiss, and Jurassic biotite granite, two-mica granite, Cretaceous basic and acidic dikes, and Quaternary alluvium and diluvium (Fig. 3).

![Fig. 3 Geological features at the location of the Inje tunnel](image)

4. EXCAVATION METHODS

This route is part of a highway connecting Seoul, the capital city, located to the west, and Yangyang, located to the east, and the time for completing the entire route is expected to be decided by the length of the Inje tunnel. Therefore, the safety of the tunnel, ease of construction, and minimization of the construction period were considered when selecting the tunnel excavation methods. Comprehensive data from geographical and topographical studies on sections, obstructions, laws and regulations, and case studies were collected for the above purpose. Multiple boring and elastic wave studies were conducted for studying the geology of the entire section. In particular, very accurate information on the geological status was obtained by performing boring on sections expected of structures and in deep sections. A review of the obstacles to the tunnel showed that a few residential areas located in tunnel sections are sufficiently far and would not be affected by vibrations/noise caused by blasting; it also showed that developments on forest land on the routes are strictly restricted. Thus, it was inferred that there will be no major problem in utilizing other riverbeds or roadside sites. A topography study showed that there was no fault zone and there was no difference between the underground water level and surface, except in the case of bored holes near a river.

The results of boring and elastic wave studies showed that geological status throughout the entire section is satisfactory; a small fracture zone exists at the location of the river, but it is expected that there will be no adverse effect on tunnel sections. However, if there are aquifers (connected to rivers) crossing the main line of the fracture zone, they should be taken into account in the planning stage.

Next, the applicability of TBM (tunnel boring machine) excavation, which is widely used in the constructions of long tunnels throughout the world, and the most widely applied blasting methods are reviewed.
4.1 TBM
The TBM method has been widely used in constructing long tunnels because it is simple and fast. It was reviewed under various conditions before its selection for the Inje tunnel. First, the cross section required for selecting equipments was determined. The width of the entire tunnel as specified by Korea Highway Corporation is 9.95 m; this includes a lane with a width of 7.2 m (3.2 × 2), a side room with a width of 2.0~3.5 m (1.0 × 2), and a passage with a width of 0.75 m for inspectors; the height is 4.8 m and the TBM diameter satisfying those is 11.7~13.0 m. Subsequently, in the review, considerable information on the blast method, carried out after initial excavation with a small TBM diameter, for the required cross section was obtained from past records on domestic road tunnels. It was observed that there was no reduction in the construction time. In fact, it was found that it may delay construction by imposing restrictions and was thus excluded. The TBM is composed of a body, which consists of a cutter head, and an electronic motor for operating the cutter head attached to the body, and the TBM is accompanied by a trailer equipped with a hydraulic pump, and additional equipments for processing low-grade ores. A large space is required for moving/assembling/disassembling these equipments to apply TBM methods. But, the starting and ending points of this tunnel are located in narrow valleys and 10~20 m away from an actual bridge. Further, there is a possibility of causing major problems like flooding and equipment failure due to the inflow of a large quantity of underground water if there is an unconfined aquifer connected to a river at the base of the Bangtaecheon stream. It was judged that the TBM in this project was hardly useful, on the basis of the results of the comprehensive review on geographical characteristics, dangers of aquifers, lack of construction experience, and supply of equipments.

4.2 Drill and blast method
This is the most widely applied tunnel excavation method. The blast method has also been applied for the excavation of most tunnels in Korea. It was inferred that the drill and blast method is the most appropriate for constructing the Inje tunnel. Since the project area is a mountainous area and will suffer little damage from vibration/noise during blasting, it is possible to minimize the amount of soil excavated; this is especially true since an optimal section can be excavated and there are plenty of skilled engineers apart from of the method having been used in past constructions. However, since the speed of excavation was relatively low, a separate plan is required for reducing the construction period. The most popular method for reducing the construction period of a long tunnel is to increase the number of excavation tunnels through a separate tunnel connected to the main tunnel. A tunnel for the operation was planned at the center of the tunnel for the purpose and 1.5 km of inclined shaft with a 12.45% inclination was planned to overcome an altitude difference of 190 m between the main line.

The time required for the excavation was 60 months for an initial excavation speed of 90 m/month, but this period is expected to decrease to 40 months when the inclined shaft is built. The inclined shaft will not be closed, but utilized as an evacuation shaft for emergencies after the completion of the tunnel.

4.3 Vertical shaft excavation method
A large quantity of exhaust fumes is expected to be discharged by vehicles passing through the tunnel. Ventilation is essential for driver safety and for maintaining a healthy environment in the tunnel. A combination of jet fans and vertical shafts were selected as a result of ventilation simulation; two shafts and two fans were planned for each tube, giving a total of four underground ventilation plants and vertical shafts. The excavation of the vertical shaft is complicated; vertical excavation is different from excavation for general tunnels in the horizontal direction. This is a result of limitations such as narrow space and worker mobility. The process of purifying low-grade ores, ventilation, and water supply also contribute to the complicated nature of excavation. The height of the vertical shaft is large—200 to 300 m—since the height of the tunnel is large in mountainous areas. Therefore, the excavation method cannot be used for the main line through the vertical shaft, unlike an inclined shaft, since the efficiencies of inputing equipments and the discharge of low-grade ores are reduced. The excavation of the vertical shaft is to be completed after the completion of the main line and both the RC and RBM methods will be applied.
5. DISASTER PREVENTION PLAN

The best disaster prevention plan for a tunnel is to take precautions to avoid an accident. The risk of drifting away from the driving lane is higher in a long tunnel like the Inje tunnel because of the possibility of dozing off due to the dullness of the surrounding environment. Korea Highway Corporation has foreseen this problem and has recommended that the side room be increased to 2.5 m from 1.0 m, which is the existing standard for the tunnel. It is impossible to reduce the possibility of accidents to 0% despite this.

Accidents within the tunnel, unlike in the case of general road sections, have a high probability of developing into a major fire. Therefore, many studies have been carried out to devise ways to prevent major accidents.

Disaster prevention facilities in the Inje Tunnel have been divided into fire-fighting facilities, smoke control and ventilation facilities, evacuation facilities, and rescue facilities.

5.1 Fire fighting facilities
When a vehicle is on fire in the tunnel, it is important to extinguish the fire as soon as possible before taking any other steps. Fire hydrants installed on the walls of the lanes within tunnel are designed to be easily accessible to users near the accident site. However, the fire hydrant will hardly be useful in the case of an accident when there are very few vehicles in the tunnel, e.g., during late nights, or when the user is not familiar with the use of the fire hydrant. Thus, as an alternative, a sprinkler system will be installed at the top of tunnel to extinguish fires automatically. At present, the sprinkler system is designed to operate simultaneously for the two sections, each section being of 50-m width.

5.2 Smoke control and ventilation facilities
Smoke caused by fire is the major cause of human casualties since it causes difficulty in breathing and reduces visibility in the tunnel. If the early control of fire is not possible with the aforementioned fire fighting equipments, then the people in the tunnel should be evacuated to a safe area. At this time, it is necessary to control the direction of smoke, which obstructs the safe evacuation, or delay the spread of the fire. Thus, smoke control facilities like jet fans are required. It is necessary to quickly discharge smoke to control the fire and protect facilities during evacuation, and discharge outlets should be additionally planned at fixed intervals in the tunnel. That is, in the Inje tunnel, the direction of smoke can be controlled with jet fans, a smoke control facility, and expelling smoke through ventilation holes in vertical shafts or through the shafts at the ends of the tunnel.

<table>
<thead>
<tr>
<th>Smoke control</th>
<th>Ventilation</th>
<th>CFD(fire intensity 20MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
<td>- prevent backflow of air</td>
<td>- ventilation for good visibility in the tunnel</td>
</tr>
<tr>
<td></td>
<td>- provide safe escape conditions</td>
<td></td>
</tr>
<tr>
<td>Criteria</td>
<td>- Critical velocity to prevent</td>
<td>Velocity of ventilation = smoke control velocity + 1 m/s</td>
</tr>
<tr>
<td>Facilities planned</td>
<td>Jet fan 40 EA</td>
<td>Ventilation Shafts at intervals of 4 km</td>
</tr>
</tbody>
</table>
5.3 Evacuation facility

5.3.1 Evacuation shaft

The evacuation shaft is a facility for evacuating drivers and passengers during accidents like fire or in emergencies. It should be installed at adequate intervals by considering the rate of spread of fumes and the speed of evacuation. Casualties can be minimized by promptly arranging for ambulances and fire engines. The standard evacuation shaft interval specified by Korea Expressway Corporation and used in the Inje tunnel is shown in Table 3.

<table>
<thead>
<tr>
<th>Allowable escape time</th>
<th>Result of experiment in KIMM</th>
<th>Korea Expressway Corp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eureka test</td>
<td>Input: 1.0 m/s</td>
<td>360 m</td>
</tr>
<tr>
<td>Escape velocity of humans</td>
<td>Input: 0.85 m/s</td>
<td>204 m</td>
</tr>
</tbody>
</table>

Interval of escape cross tunnel: 750 m for vehicles and 250 m for humans

5.3.2 Evacuation guiding facilities

Various facilities like lightings are installed to provide a certain level of illumination for safe driving. However, there might be situations where these lightings do not function well either because of thick smoke or a break in cables during a disaster such as fire. There is also the possibility of people losing their way because they cannot detect exits easily in tunnels where illumination is poor. It is recognized that there is need for a separate plan to guide people toward tunnel exits even when the lightings fail. Normally delineators are widely used for vehicle guidance on highways; however, these only provide forward linear information upon being illuminated by headlights of vehicles and they are incapable of providing information about the rear side of vehicles, which is the direction of evacuation during accidents like fires.

In the Inje Tunnel, sight-guiding lights equipped with LEDs have been installed on both sides of guiding lights at both ends of the tunnel as a complementary measure for effective evacuation, and it will be help drivers recognize the width of roads.

5.3.3 Maintenance and vehicles for disaster prevention

The tunnel is too long for maintenance personnel to walk during maintenance activities, and the use of vehicles by them is bound to hinder traffic flow. Therefore, rails have been installed at the top of common areas on the sidewalls of the tunnel for the use of electronic vehicles. These vehicles are expected to be used when it is difficult for vehicles to enter through roads during accidents in the tunnel.

5.3.4 Preventing secondary accidents through TTMS (Tunnel Traffic Measurement System)

This system is used for controlling traffic in tunnels and it was introduced to minimize damages through the quick detection of accidents in the tunnel and promptly responding through a broadcasting and communication system. The system also helps prevent secondary accidents by suspending traffic. This system was installed by taking the concerned tunnel as well as dynamic relationships with other nearby tunnels into consideration.

Step 1: Quick accident detection plan

- Automatic accident detection system (Image detection system): Automatically detect accidents through motion tracking technology using a VDS (Vehicle Detector System) and CCTV (Being reviewed)
- Detect fire through fire sensors
- Receive information on accidents through wired/wireless communication equipments

Step 2: Prevent secondary accidents through quick response

- Notify status of accidents through LCS (Lane Control System), VMS (Variable Message Sign), radio re-broadcasting and tunnel
- Suspend the entry of vehicles into the tunnel (suspend traffic in both directions when fire breaks out; install a cutoff system at the entrances of the tunnel)
- Broadcast details of the accident within the tunnel
- Notify relevant government organizations like fire stations and police stations
6. EVALUATION OF INFLUENCE ON GROUNDWATER

The environmental assessment of the tunnel on the groundwater aims to forecast the drawdown of and variation in domestic groundwater levels near the planned routes due to tunnel excavation. As usual, numerical methods of groundwater flow modeling are used for the environmental impact assessment of the tunnel groundwater.

Different program packages are used for the modeling of the tunnel groundwater outflow, depending on the variation in the groundwater level throughout the tunnel or small-scale variations in the groundwater level in narrow fracture zones. Normally, continuous numerical model packages are commonly used for modeling large-scale groundwater flow variations, while fracture media models are applied for groundwater flow modeling in smaller zones composed of jointed rock aquifers [1,2,4].

Similarly, when we carry out the modeling of groundwater outflow, the MODFLOW package is commonly used for the numerical analysis of regional groundwater flows throughout the tunnel and for the analysis of the drainage, and MAFIC is applied for detailed groundwater modeling in small discrete zones in the tunnel [3].

In this study, two representative models are used to forecast the tunnel groundwater outflow pattern (Table 4).

Table 4 Details of groundwater flow modeling

<table>
<thead>
<tr>
<th>Program</th>
<th>MODFLOW</th>
<th>MAFIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3D continuous model</td>
<td>3D discontinuous model</td>
</tr>
<tr>
<td></td>
<td>(continuous media)</td>
<td>(fracture media)</td>
</tr>
<tr>
<td>Modelling section</td>
<td>Sta. (2 + 500)~(6 + 500)</td>
<td>Sta. (4 + 000)~(4 + 500)</td>
</tr>
</tbody>
</table>

The ground conditions of modeling section are of very good (rock type 1) to moderate (rock type 3) grade in terms of rock classification, and the rock layers of the tunnel under streams and valley areas are about 100 m or higher.

The MODFLOW result indicates that the drawdown of groundwater due to tunnel excavation is 1.92~3.29 m. This is a small amount in general, but its influence on groundwater systems around the tunnel is of concern. Therefore, we carried out a simulation for examining waterproof grouting with the aim of reducing water inflow into the rock mass of the tunnel.

The groundwater level at Sta. 5 + 000 will decrease to 2.03 m after tunnel excavation, and the water inflow rate per kilometer is 0.127 m$^3$/min. When waterproof grouting is performed on the ground near the tunnel, the drawdown of the groundwater level is 0.79 m and the water inflow rate per kilometer is 0.060 m$^3$/min. It can be noted that if waterproof grouting is performed in advance, the amount of groundwater inflow into the tunnel will decrease [3].
7. CONCLUSIONS

The construction of the Inje tunnel is facing some problems due to the tunnel’s length; these problems typically pertain to logistics during construction, ventilation, fire safety during an emergency, and environmental impacts. It is very important to decide the excavation method so as to decrease the construction duration. Logistics becomes even more demanding if excavation is to be performed not only over long horizontal distances but also for vertical distances, which is the case at Inje tunnel where four 300 m deep ventilation shafts will be constructed. We examined the use of mechanized excavation for very long tunnels under adverse conditions. As a safety measure, we considered various escape tunnels such as an escape connecting tunnel and service tunnel. We performed investigations and numerical analysis to evaluate the influence of tunnel excavation in mountainous areas on the groundwater.

8. REFERENCES


