New Design Standard for Urban Railway Shotcrete Tunnels

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Application of shotcrete tunneling has increased in urban areas of Japan as a result of technological development, such as that of large-scale fore-piling method, and counter-measure work. However, there had been no well-established design methods for urban shotcrete tunnels. Then, a new design standard for them was established in March 2002, based on the investigation and analysis of several design and construction experiences. This paper describes the concept and some aspects of this new design standard.

Keywords : NATM (New Austrian Tunneling Method), shotcrete tunnel, urban area, design standard, reinforced-concrete lining, limit state design method

1. INTRODUCTION

With advances in tunnel excavation technology, the application of "shotcrete tunneling method" has gradually increased in urban areas, taking the place of open-cut and shield tunneling method that had usually been adopted. The shotcrete tunneling becomes economically viable when the tunnel cross section shape changes or the tunnel length is short. On the other hand, the excavation technology of shotcrete tunnels in such location must overcome the problem of unstable tunnel faces caused by soft ground conditions, ground settlement and sinking of groundwater level. Therefore, it is important to make careful geological surveys and to make the design and construction match ground conditions.

In Japan, there had been no well-established design methods for urban shotcrete tunnels, although dozens of tunnels had been constructed. Moreover, new techniques, such as the large-scale fore-piling method, have gradually been introduced. Accordingly, we investigated and analyzed several examples of design and construction. Then, a new design standard for urban railway shotcrete tunnels was published in March 2002. Its principles are described in this paper.

2. GROUND CLASSIFICATION CRITERIA FOR URBAN AREAS

In designing a tunnel, the ground profile is identified first based on the geological survey in accordance with established ground classification criteria. The identified ground profile is directly used for both tunnel support and lining designs. For railway tunnel construction, the criteria in "Mountain tunnel design and construction indices," developed by the Japanese National Railways in 1983, are well-known and have been applied to a number of construction experiences. However, these criteria were developed specifically for mountain tunnels and do not

Table 1 Ground classification criteria for clayey soil

Class of ground profile	Competence factor (C_f)	Degree of slaking
I_N	$C_f \geq 2.0$	
I_{LC}	$1.5 \leq C_f < 2.0$	
	$0.5 \leq C_f < 1.5$	A ~ C
Special-LC	$C_f < 0.5$	D

- 1) If the content of particles of smaller than $2 \mu\text{m}$ is higher than 30% and the liquid limit is more than 100%, demote to one lower rank.
- 2) The ground condition shows the degree of self-support of the tunnel face in clayey soil.
- 3) $C_f = \sigma_c / \gamma H$ σ_c : Axial compressive strength of the ground
 γ : unit weight H : Overburden

Table 2 Ground classification criteria for sandy soil

Class of ground profile	Relative density (D_r) [%]	Fine fraction content (F_c) [%]
I_N	$D_r \geq 80$	$F_c \geq 10$
I_{LS}		$F_c < 10$
Special-LS	$D_r < 80$	

- 1) The fine fraction content is the ratio of particles smaller than $75 \mu\text{m}$.

cover tunnels in the unconsolidated ground such as sandy and clayey soils which generally exist in urban areas. Then, new ground classification criteria for such soils were proposed, in which clayey soil was classified by the competence factor and slaking tests, while sandy soil by its relative density and the fine fraction content. See Tables 1 and 2.

3. DESIGN PRINCIPLES

3.1 General design

In the construction of urban shotcrete tunnels, unlike the tunnels constructed in mountainous regions, the following aspects shall be considered.

Table 3 Design items for the basic and detailed design stages

Design items	Basic design	Detailed design
(1) Shape of tunnel cross section	✓	
(2) Excavation method	✓	
(3) Countermeasures	✓	
(4) Fore-piling method	✓	
(5) Tunnel supports	(✓)	✓
(6) Lining and invert concrete	(✓)	✓
(7) Waterproofing and drainage		✓
(8) Portal		✓
(9) Observation		✓

Note ✓: Essential (✓): Optional

- Sufficient survey work must be conducted before designing.
- It is difficult to modify the design, to any large extent, once construction starts.
- Some countermeasures are usually conducted in order to reduce the influence of tunnel construction on surrounding areas.

Therefore, it is necessary to determine an outline of shape, size and countermeasures before urban shotcrete tunnels are designed. Then, according to this new standard, the design is divided into two stages, basic design and detailed design. Table 3 shows a list of design items to construct urban shotcrete tunnels. Items (1) to (4) are assessed at the basic design stage, while (5) to (9) are at the detailed design stage.

3.2 Basic Design

The basic design is conducted at an early stage for urban shotcrete tunnels. The main design items at the basic design stage are the shape of the tunnel section, excavation methods and countermeasure works. The application of countermeasures should be studied at an early

Fig. 1 Relationship between ground settlement and overburden

stage to reduce the influence on surrounding areas because the ground in urban areas predominantly consists of the unconsolidated ground.

Figure 1 shows the relationship between ground settlement and overburden regarding the urban shotcrete tunnels and shows the fact that the application of appropriate countermeasures reduces the ground settlement to less than 50mm, in cases where the overburden is deeper than 10m or almost equal to the outer diameter of the tunnel section.

3.3 Detailed design

The detailed design is conducted after the shape of the tunnel cross section, excavation methods and countermeasure work are determined at the basic design stage. The main design items at the detailed design stage are tunnel supports, lining, invert concrete, waterproofing, drainage, portal and observation. The details of tunnel support design are described in Chapter 4, while those of lining and invert concrete are in Chapter 5.

3.4 Design methods

Tunnel design methods are classified into three types: one imitates past designs, one adopts the standard design, and one conducts numerical analysis. In the design of urban shotcrete tunnels, one design method is adopted independently or combined with others. This type of tunnel designing is carried out according to the flowchart shown in Fig. 2.

Past designs of other tunnels are imitated, when the ground condition, the shape of tunnel cross section and the limitation of influence on surrounding areas are similar. Suitability is verified by observation, measurement and other means. This type of design is called "the design based on similar conditions." If similarity and suitability are sufficient, this design requires the least time and effort and is the safest of the three.

The standard design is adopted by applying a standard tunnel cross section that has already been determined. The standard section is determined based on the

Fig. 2 Flow chart of the application of design methods

Table 4 Applicable conditions for the standard design

Overall	(1) Shape of tunnel cross section	Standard single-track, double-track and Shinkansen cross section
	(2) Geographical features	Not located on unstable, sloping ground
	(3) Overburden	Deeper than the outline of tunnel section
Support	(4) Countermeasures	Not necessary to use pre-support or special countermeasures.
	(5) Influence on surrounding areas	Limitation of ground settlement and sinking of groundwater level not rigid
Lining and invert	(6) Drainage	Waterproof tunnel
	(7) Water pressure	Groundwater level not 10 m higher than tunnel crown.
	(8) Other loads	Influence of earth pressure with earthquakes not considered.

analysis of past construction experiences. It is possible to adopt the standard design for the supports, if (1) to (5) mentioned in Table 4 are wholly satisfied. On the other hand, the standard design can be adopted for lining and invert if (1) through (3) and (6) through (8) are wholly satisfied.

Numerical analysis is conducted, when it is impossible to adopt the design based on similar conditions or the standard design. This type of design is called "the design by analytical methods." FEM analysis that can calculate ground settlement and displacement of adjacent structures is used to design supports, while simple frame analysis is used to design lining. In the design standard, methods to create analytical models and determine characteristic values are shown in order to unify analytical methods.

4. DESIGN OF TUNNEL SUPPORT

Tunnel supports are constructed to stabilize the excavated tunnels in cooperation with the surrounding ground. The components of tunnel supports are normally shotcrete, steel rib supports and rock bolts. The design based on similar conditions, the standard design or the design by analytical methods is applied independently or combined with others in order to design the patterns of tunnel support. "Standard tunnel support patterns" are proposed for every class of ground profile (I_N , I_{LC} and I_{LS}) determined by the ground classification criteria mentioned in Chapter 2. See Table 5.

The supports of urban shotcrete tunnel are applied to resist the loosening of the ground and prevent the influence on surrounding areas where a number of structures and buildings exist. The performance of supports is slightly limited when compared with those in mountainous areas as shown in Table 6. Rock bolts in the unconsolidated ground, for example, are effective in the reinforcement of arch legs and tunnel faces but do not perform the ground arch action, unlike the tunnels constructed in mountainous regions.

Table 5 Standard tunnel support patterns for double-track tunnels

Class of ground profile*		I_N	I_{LC}	I_{LS}
Shotcrete	Thickness	200mm	250mm	250mm
Steel rib support	Space	1m	1m	1m
	Size of steel rib	125H	150H	150H
Rock bolt	Length	3m	3m	3m
	Number of rock bolts / every steel rib support	12	10	10
Short pre-support**	Length	2m	3m	3m
	Space in the circumferential direction	0.6m	0.6m	0.6m

* Class of ground profile is determined by Table 1 or 2.

** Installed where necessary.

Table 6 Performance of tunnel supports in the unconsolidated ground

Performance of tunnel supports	- Support against loosening earth pressure - Effect of internal pressure - Reduction of settlement
Essential tunnel supports	- Shotcrete - Steel rib support
Optional tunnel support	- Rock bolt - Short pre-support - Wire netting with shotcrete

5. DESIGN OF LINING AND INVERT CONCRETE

5.1 General

The lining and invert concrete of urban shotcrete tunnels have the following features:

- They are constructed as waterproof tunnels to prevent the influence on surrounding areas.
- It is conceivable that tunnels are influenced by the construction in the adjacent areas.
- As shotcrete tunnels are normally constructed in places where the overburden is shallow and the ground strength is small, they are subject to the influence of earthquake.

In the new design standard, therefore, the waterproof reinforced concrete lining is regarded as the standard lining structure, and the construction of invert concrete and the closing of section are regarded as essential items, because shotcrete tunnels are normally constructed in the unconsolidated ground. The lining and invert concrete are designed by either the standard design or the design by analytical methods.

5.2 Standard design

The new design standard proposes "standard lining design patterns," in which the thickness of lining and invert concrete and the amount of reinforcement have been already determined. Table 7 shows those for Shinkansen double track tunnels. Designers can determine the lining and invert concrete by selecting a pattern according to the ground profile and ground water level from the tunnel crown.

Table 7 Standard lining design patterns for Shinkansen tunnels

Standard design pattern	Class of ground profile*	Groundwater level from tunnel crown [m]	Standard design				Note
			Secondary lining		Invert concrete		Waterproofing and drainage structure
			Thick-ness[mm]	Amount of reinforcement	Thick-ness[mm]	Amount of rein-forcement	
I _{NL-}	I _N	—	500	D19@250mm	500	D19@250mm	Drainage type
I _{NL0}		0m	500	D19@250mm	500	D19@250mm	Waterproofing type
I _{NL5}		5m	500	D19@250mm	500	D22@125mm	
I _{NL10}		10m	600	D19@250mm	600	D25@125mm	
I _{LL-}	I _{LC} , I _{LS}	—	500	D19@250mm	500	D19@250mm	Drainage type
I _{LL0}		0m	500	D19@250mm	500	D22@250mm	Waterproofing type
I _{LL5}		5m	500	D19@250mm	500	D25@125mm	
I _{LL10}		10m	650	D19@250mm	650	D22@125mm	

* Class of ground profile is determined by Table 1 or 2.

Table 8 Criteria for load increase and decrease by adjacent execution for Shinkansen tunnels

Standard design pattern	Class of ground profile	Water pressure level from tunnel crown [m]	Note	
			Criteria for adjacent execution	
			Upper load σ_{vmax} [kPa]	Removed load h_{min}/H
I _{NL-}	I _N	-----	40	0.9
I _{NL0}		0	95	0.8
I _{NL5}		5	125	0.7
I _{NL10}		10	150	0.7
I _{LL-}	I _L	-----	15	0.9
I _{LL0}		0	60	0.9
I _{LL5}		5	75	0.9
I _{LL10}		10	55	0.9

The thickness of lining and the amount of reinforcement have been determined by applying the limit state design method to the past construction experiences. Essential design loads are self weight and water pressure.

Table 8 shows the criteria on the increases in the load by adjacent construction that can be resisted within the serviceability limit state. The embankment is limited by the vertical stress increment σ_{vmax} at the tunnel crown as shown in Fig. 3 (a). The value of σ_{vmax} is calculated by a frame analysis. On the other hand, the cutting is limited by the permissible value of remaining overburden rate (h_{min}/H) as shown in Fig. 3 (b). The permissible value of remaining overburden rate h_{min}/H is calculated by FEM and frame analyses.

Fig. 3 Limitation of embankment and cutting

5.3 Design by analytical method

5.3.1 Limit state design method

Tunnel lining and invert concrete are designed by the limit state design method in the case of the design by the analytical methods. There are two limit states that must be checked in the design of lining and invert concrete. One is the ultimate limit state and the other is the serviceability limit state. Both limit states are defined in Table 9.

In such an arched structure as the tunnel lining, even if the rigidity of one section is reduced by the occurrence of a tensile crack or yielding of reinforcing bar, bending moments are distributed to surrounding sections whose rigidity has not reduced yet. Therefore, it can be thought that the loss of one section does not directly cause the destruction of the whole structure. In other words, structural integrity is normally maintained until the strain on the concrete reaches the ultimate strain which corresponds to Point C in the relationship between load and displacement shown in Fig. 4. The structure maintains the bearing capacity for loads until the concrete strain

Table 9 Limit states of secondary lining and invert concrete

Name	Definition
Ultimate limit state	Stability and functions are lost under loads that rarely occur except for earthquake loads, such as unusual rises of water pressure.
Serviceability limit state	Serviceability and durability are lost under long-term and continuous loads, such as water pressure and adjacent loads.

Fig. 4 Relationship between load and displacement

reaches Point D. On the basis of these features, the ultimate limit state is defined as the compressive failure of concrete.

In the case of reinforced concrete with cracks, air and water supplied through cracks cause the corrosion of reinforcing bars, which may cause the spalling of concrete piece. Then, the allowance crack width must be checked to prevent the corrosion of reinforcing bars. The serviceability limit state of lining is defined as the allowance crack width because the spalling of tunnel lining concrete poses a serious problem. On the other hand, that of invert concrete is defined as the yielding of the reinforcing bars because the spalling of concrete piece can be ignored.

5.3.2 Loads

The loads acting on the lining and invert concrete of urban shotcrete tunnels are normally the self weight, water pressure, loads caused by construction in adjacent areas and earthquake loads. The lining and invert concrete are constructed after the excavation is finished and the ground conditions are stable. Therefore, the earth pressure acting at the excavation is not considered in the design of urban shotcrete tunnels. Table 10 shows an example of the combination of loads considered in the design.

Table 10 Example of the combination of loads

Loads \ Limit state		Serviceability limit state					Ultimate* limit state	Notes
Self weight		✓	✓	✓	✓	✓	✓	
Earth pressure								Considered if increases in the load are expected after completion.
Water pressure	Low water level		✓		✓			
	High water level	✓		✓		✓		
	High water level						✓	Extraordinary conditions
Adjacent load	Long term		✓	✓			✓	Remains after adjacent construction
	Short term				✓	✓		During adjacent construction
Other loads								Considered if necessary. Internal loads, freezing loads and upper loads
Note		Continuous or longterm stable loads					Except for earthquake	

5.3.3 Check of serviceability limit state

The check of serviceability limit state for the urban shotcrete tunnel is the same as those for ordinary reinforced concrete structures, except that the serviceability limit state for invert concrete is defined as the yielding of the reinforcing bar.

5.3.4 Check of the ultimate limit state

The check of ultimate limit state of lining and invert concrete is determined by the compressive failure of the concrete. Design becomes excessive unless the re-distribution of bending moment caused by the yielding of a reinforcing bar is considered appropriately.

Then, the following methods are proposed in this new design standard:

- (1) The design forces are calculated by means of nonlinear analysis, in consideration of the reduction of bending rigidity caused by the yielding of a reinforcing bar and the re-distribution of the bending moment.
- (2) The M-N curve is modified in consideration of the rotation of cracks caused by the yielding of a reinforcing bar. The design forces obtained by linear frame analysis are checked according to the modified M-N curve.

The calculation of the method (2) is simpler than the

Fig. 5 Check of ultimate limit state according to modified M-N curve

method (1), because it is easy to calculate the design forces according to linear frame analysis. Figure 5 shows a flow chart of the analysis and modification of M-N curve according to the method (2).

6. CONCLUSION

A new design standard for Japanese urban railway shotcrete tunnels has recently been established. This design standard proposes new ground classification criteria for the unconsolidated ground and a standard design of support and lining. In addition, the limit state design method is introduced into the design of lining and invert after their limit state is defined in consideration of the characteristics of arched structure.

The essentials in this paper can be applied not only to railway tunnels but also to a number of other tunnels.

We expect that this design standard will widely be adopted for the design of urban shotcrete tunnels.

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