NATM Tunnel Designs in Taiwan High Speed Rail Project
대만 고속전철에 적용한 NATM 터널설계

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ABSTRACT

현대건설㈜는 사업 주관사로서 해외 업체와 대만고속전철 턴키 공사를 2000 년 1 월에 공동으로 수주하였다. 고속전철의 총 연장 길이는 약 326 km 이며, 정거장 10 개소, Depot 및 야적장으로 구성되어 있다. 이번에 수주한 공구는 2 개의 연속된 공구 (C230, C240) 이며, 본 논문은 총 연장 23.6 km 인 C230 공구에 대한 설계 과정을 수록하였다. C230 공구는 NATM 터널 (6.2 km), Cut-and-Cover 터널 (0.5 km), 교량 (7.8 km) 및 토공 구간 (9.1 km) 으로 구성되어 있다. 전 구간의 지반조건은 "매우" 취약한 매질로 구성되어 있으며, 층리나 절리는 거의 발달되어 있지 않다.

따라서 화약발파에 의한 터널 굴착은 기계식 굴착 (Back-hoe Excavation) 방법에 비하여 현실성이 없는 것으로 분석되었다. 취약한 지반에서 계측 결과를 기준으로 굴착 공간을 안전하게 유지할 수 있는 NATM 보강 설계가 현지 암반조건에 가장 이상적인 방법으로 제시되었다. 특히, NATM 설계는 대형 아파트 지역과 파쇄대 및 지하수 침투 예상지역을 통과하기 위하여 계측에 의한 Feed-back 과정을 탄력적으로 적용하도록 계획하였다.

1. Introduction

A portion of concession to construct Taiwan High Speed Rail (THSR) has been awarded to the international joint venture of Hyundai *via* the Taiwan High Speed Rail Consortium at the early year 2000. THSR project consists of approximately 326 km of High Speed Rail (HSR) incorporating about 10 stations plus depot and storage areas. Hyundai has won two consecutive sections (C230 and C240). The current paper will describe C230 (Lot 3 Section) section of 23.6 km in sum, which consists of 6.2 km tunnels, 0.5 km cut-and-cover tunnels, 7.8 km bridges and 9.1 km embankments. The ground conditions along the project area are classified as "unusually" soft, and very few joints are found on the bedding plane exposed to the environment. Lot 3 section runs from Shin-Chu to Miao-Li where is approximately 120 km south of Taipei City.

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The mainline design speed for HSR tracks is 350 km/h and the maximum operating speed is 300 km/h with an operating schedule with a minimum headway of 4 min. HSR service will be offered with 90 min. between Taipei and Kaoshiung with one stop at Taichung, but ultimately 10 stations will be built with three depots. Train has a seating capacity of 1,100 ~ 1,400 people and has a carrying capacity of 420,000 people/day with two tracks.

The design and construction works shall have a minimum service life of 100 years. Any service elements shall be designed not less than the Clients' requirements, such as 100 years for tunnel structures, 100 years for cuttings and grade, 35 years for movement joints, 15 years for waterproofing, and 100 years for drainage.

A conventional drill-and-blasting method is far from cost-effective relative to a mechanical excavation method. Carefully controlled NATM design and construction approach is the best solution to acquire the stable condition for both underground and aboveground structures. This paper is focused on introducing a straightforward NATM approach, which has been successfully applied to all mined tunnels in very soft "rock-like" ground conditions.

2. Geotechnical Aspects

2.1 Geology

Geological conditions in the project area are covered with relatively superficial deposits of alluvium and Terrace deposits which comprise unconsolidated and unsorted gravels, sand and clays, which overlie alternating sandstone and mudstone successions of the Cholan and Toukoshan formations. Superficial deposits are encountered in valley sides and on alluvial plains. The consistency of these deposits is loose to medium dense in the upper few meters (typically less than 5m). Below this, the deposits generally become very dense ($N > 50$) passing quickly onto solid formations. Groundwater level varies along the depth of the route, but can be anticipated to be close to ground level on alluvial plains.

From the results of investigation, there is no obvious activity in fault zone areas. However, they may cause some influence to the bearing capacity, settlement variation, and stabilization of slope excavation in the soft geological materials areas where HSR route passes.

2.2 Rock Classification

According to the results of field geological investigation, the rock materials of tunnels are divided into sandstone, sandstone intercalated with mudstone, alternations of sandstone and mudstone, and so on. Details of geotechnical information are summarized in Table 1. In overall, the rock in this section is soft rock whose unconfined uniaxial compressive strength varies from less than one (1) MPa to slightly greater than 10 MPa. But mostly its value is approximately 5 MPa. The discontinuities are not well developed.

The rock materials of tunnels are divided into four categories (Type I, Type II, Type III and Type IV). Engineering rock classification is characterized and summarized in Table 1.

2.3 Engineering Geology along HSR Route

For the most part, it is classified to bear three types in this section, Type I for 43%, Type II for 12%, Type IV for 45%. Type I has a uniaxial compressive strength of 5 MPa to 10 MPa, and bearing angle of 20 ~ 27 in degree. It is mostly of sandstone and some of the part is intercalated with mudstone. Type II has a uniaxial compressive strength of 2 MPa to 11 MPa, and bearing angle of 19 ~ 24 in degree. It has an altered sandstone and altered mudstone and characterized similar geotechnical property to Type I in their rock engineering parameters. Type III is assigned to the "weak" strength and the sandstone has a swelling potential by water. Type IV is a highly weathered and fractured rock of Type I and Type II.

Table 1. Rock classification with its formation and characteristics

Rock Type	Rock Formation	Characteristics
Type I	Sandstone intercalated with mudstone	The characters of rock mass in engineering are medium strength and well self-supported. The influence of groundwater is smaller for the tunnel excavation than other
Type II	Alternations of sandstone and mudstone	The strength of rock material is medium weak, The sandstone is medium permeable and the mudstone is impermeable. The quantity of groundwater will influence the stability of tunnel.
Type III	Sandstone and mudstone intercalated with sandstone	The strength of rock is weak. The sandstone will soften by water and poorly self-supported, the mudstone will swell by water, and influence the supporting system of tunnel.
Type IV	Fault / fracture zones & full of groundwater, soft rock	It is likely to squeeze and slide in tunnel excavation. The portals of tunnel, overburden less than 20m, and highly weathered rock are classified into type V

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The groundwater will reduce the strength of rock mass and make a rock fall happen easily in alternations of sandstone and mudstone. The mudstone is impermeable, which may accumulate groundwater to build up water pressure, and may have a swelling potential by water also.

3. Tunneling Method

Since ground condition (soil and rock) along the project area can be classified as "unusually" soft, very few joints can be found on the bedding plane exposed to the environment A straightforward NATM design and construction approach has been adopted for the best solution to acquire the stable condition for both underground and aboveground structures.

Soft ground and groundwater conditions require the immediate support of the ground after each excavation for stability of the excavation and control of ground settlement. Ground treatment is carefully chosen in all cases where unstable area is met such as heavily weathered zone, temporary slopes, groundwater ingress zone, settlement control area, and tunnel exits. Jet-grouting is extensively proposed as required.

4. Tunnel Cross Section

The Clients set the tunnel dimension of $90m^2$, illustrated in Fig. 1. This is smaller than in Europe, where the SNCF recommends 100 m^2 for 300 km/hr and 114 m^2 for 320km/hr. The requirements for tunnel dimension are in general depend on many factors including train shape. The discussion of train impact on the tunnel dimension including M&E parts is beyond the purpose of this paper.

The optimization of cross-sectional area of tunnel is determined based on the following parameters: (a) aerodynamic effect on tunnel structure when train enters and exits tunnels, (b) clearances, (c) maintenance considerations, (d) service requirements, and (e) safety requirements. Besides the general portal design considerations, the Clients have brought a special attention to minimizing the extent of portal excavations and temporary and permanent slopes, so as to minimize land requirements, environmental impacts, maintenance to increase safety.

To mitigate aerodynamic effects, especially the so-called sonic boom, all portal structures are inclined at least 45° from the vertical. For tunnels longer than 3 km, the portal structure for pressure relief is implemented at each portal. The open cross-sectional area of the pressure relief structure is at least 1.5 times that of mined section. The pressure relief structure is set at least 20 m in length with an adequate opening arrangement: two openings at the crown or on one sidewall of minimum area 10 m^2 for each.

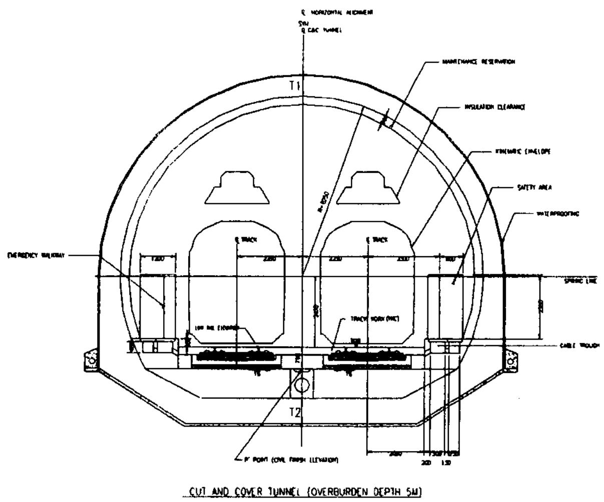

Fig. 1. Typical cross-sectional dimension

5. FEM Numerical Modeling

Tunnel cross-section is modeled as a frame element supported by a spring perpendicular to the ground. The model combination is considered on the plane strain condition which means a longitudinal displacement is constrained. The stiffness of soil spring is adjusted by a unit width calculated by an N-value, and by eliminating the extension spring element the iteration of calculation will be performed.

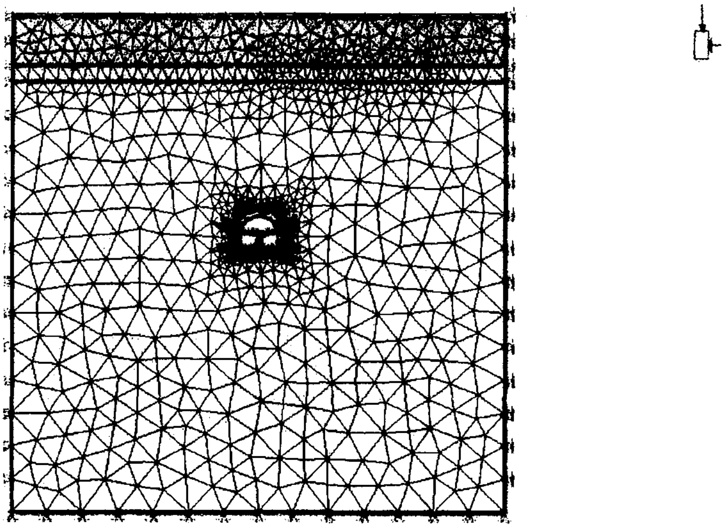

Fig. 2. Typical FEM model for Type I ground condition with 60 m overburden height

6. Lining Design

In general, earth pressure load in the "very" soft ground conditions is estimated by the empirical stress ratio of K (the ratio of horizontal to vertical stresses) determined by soil depth multiplied with its unit weight. Very often, this approach overestimates the actual earth pressure acting on the deep underground structure. The current design employs two different design schemes to overcome this problem.

For Case I, all reaction forces which are used in the lining design are computed with the total load, earth pressure load, hydrostatic pressure and self-weight by SAP2000. For Case II, the reaction forces of the lining for the earth pressure load are independently calculated with the PHASE II software. And reaction forces for the hydrostatic pressure and self-weight are computed with SAP2000 program. Peak values of each result are summed at every joint in the mesh as total loads. This sum is fed to estimate the dimension of an inner (concrete) lining.

Each case is compared for the two parts of the drained and undrained tunnels, respectively. Iterative calculations are preformed to determine the optimized section dimension. Case II seems to be more significant because earth pressure load has a significant impact on the underground structure. Fig. 3 illustrates a typical

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inner lining dimension tabulated in Table 2.

6.1 Outer Lining Design

Following preliminary calculations with a simplified analytical method, a detailed analysis of the ground-structure interaction is carried out by using the two-dimensional PHASE II FEM program (Hoek, 1988). The structural design of the tunnel outer lining was based on the ACI 318-99. With PHASE-II program, the entire tunnel construction process is modeled in a two-dimensional state of equilibrium, starting with the pre-deformation of ground ahead of the tunnel face (simulated by a stress relaxation of the two-dimensional model) until the final re-adjustment of ground stresses after completion of tunnel excavation.

The outer shotcrete lining and its associated support elements like rock bolts and lattice girders are regarded as a temporary structure. The design of the outer lining was carried out for a number of representative calculation cases, which cover most of the situations encountered during tunnel construction.

6.2 Inner Lining Design

Design of the inner lining is performed based on plane strain conditions with SAP2000 software. Numerical analyses are carried out with the ground loading conditions, load/displacement characteristics for a reasonable range of ground and groundwater conditions. Fig. 3 shows basic model of the calculations adapted.

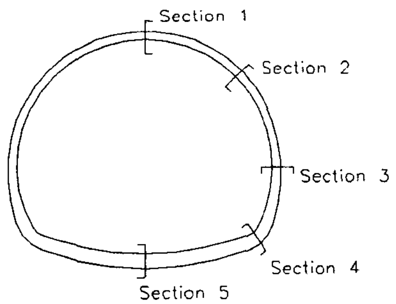

Fig. 3. Sectional location of the inner lining

7. Tunnel Construction Types

7.1 Undrained Watertight Tunnel

When a tunnel sits below the water table, the full circumference of tunnel is designed with a waterproofing system to prevent groundwater leakage into the tunnel. A circumferential waterproofing system is applied between the outer and the inner lining. The tunnel has an internal drainage system only to collect condensation, leakage, spilled water and other flows. The inner pipe diameter of 300 mm accommodates possible water seepage. The drainage pipe is accessible at a maximum of 50 m interval. T15 Toufeng No. 1 Tunnel (Chainage 91K+909 ~ 93K+154) is the longest tunnel in C230 section and its total length is approximately 1,245 m. Toufeng No. 1 tunnel is designed as a watertight tunnel which can withstand the full hydrostatic pressure.

Table 2. Typical sectional dimension with F_c = 280 kg/cm^2

(unit: mm)

Section	TYPE I		TYPE II		TYPE III		TYPE IV-a		TYPE IV-b	
	D	UD	D	UD	D	UD	D	UD	D	UD
1	350	440	350	440	300	320	380	480	280	280
2	380	480	380	480	300	320	510	630	300	300
3	330	420	330	420	330	350	330	430	420	320
4	330	1100	330	1100	370	1100	480	1100	560	1000
5	320	1200	320	1250	300	1250	300	1350	300	1380

Legend : D (Drained Tunnel), UD (Undrained Tunnel)

7.2 Drained Tunnel

The lining of each drained tunnel includes a drainage system to collect any groundwater inflow passing through the tunnel walls into the geotextile around the outer surface of the membrane. The drainage system is properly designed so as to prevent the loss of fine particles from the ground and to prevent long term blockage of the drainage system. Longitudinal drains accommodate a 300-mm diameter pipe. Access to the cleaning is provided at a maximum of 50 m interval. Lining thickness of the drained tunnel is slightly thinner than the undrained watertight tunnel. Seven out of eight tunnels are designed as a drained tunnel, because the groundwater table was observed lower than the spring line of tunnel.

8. Summary

The Clients, Taiwan High Speed Rail Committee, has prepared the overall project for little more than ten years and compiled all the tender documents for turnkey invitation to the contractors, very well. It is interesting to note that although they had utilized all the technical data related to the train, the Clients had changed the type of train to Japanese Shingansen from French TZB at the end of 1999, while maintaining the cross-sectional dimension of tunnel of 90 m^2. It would be very interesting for Korean tunnel designer to review a recent tunnel dimension adapted to the recent turnkey project and Korean High Speed Rail project as well.

Reference

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