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Design of twin-tube tunnel through soft rock

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ABSTRACT: Deformation control is utmost important to ensure stability and cost-effectiveness in twin-tube tunnelling through soft rock. The effective control of twin-tube tunnel deformation includes keeping safe width of the pillar, appropriate excavation sequence and timely installation of sufficient support system. A case history illustrating the importance and effectiveness of deformation control is presented in this paper.

1. INTRODUCTION

Rapid economic growth has been given rise to an urgent demand for more traffic infrastructure in Taiwan, especially for freeway with high capacity. Taiwan, a mountainous island situated on the western rim of the Pacific ocean, encompasses many kinds of soft rock, such as highly fractured shale, mudstone, conglomerate and widely distributed faulted area. Therefore, more and more twin-tube tunnels through soft rock have been designed and constructed during the last decade. Some problems have been revealed in the course of construction from the past experience, such as unacceptable deformation, instability, collapse of heading and large amount of groundwater inflow etc. Among these phenomena, the most frequent trouble is the large deformation which make remining work inevitable. The remining work is always costly and time-consuming which involves wasting lots of money and delaying the schedule. Thus, controlling deformation becomes the most important issue when tunnelling through soft rock

The mechanism of deformation of tunnels is extremely complex. In-situ stress, quality of rock mass, excavation sequence, support installation timing and geometry of tunnel are all major factors affecting the deformation of tunnels. A twin-tube three-lane tunnel is selected to illustrate the importance of twin-tube effect, excavation sequence and support systems.

2. DESIGN CONSIDERATION FOR TWIN-TUBE TUNNEL

2. 1 *Pillar width*

If the spacing between twin-tube tunnel is significantly larger than the diameters of the tunnels, then the two tunnels can be regarded as two isolated tunnels. The degree of twin-tube effect is strongly determined by the in-situ stress and the rock mass strength, in turn, by the ratio of pillar width to tunnel diameter.

It can be shown that the average pillar stress S_p can be approximately expressed as follows [1]:

$$S_p = \gamma H\left(1 + \frac{B}{w}\right)$$

where γ : unit weight of rock mass
H : tunnel depth below surface
B : tunnel width
w : pillar width

The uniaxial compressive strength of the pillar σ_p can be estimated as follows:

$$\sigma_p = \frac{2c\cos\phi}{1-\sin\phi}$$

in which c, ϕ respectively represent cohesion and angle of internal friction of rock mass. Therefore, the factor of safety (S.F.) against initial yield of the pillar is:

$$S.F. = \frac{\sigma_p}{S_p}$$

Figure 1 shows the ratio of w/B vs the pillar strength normalized by overburden pressure with S.F. ranging from 1~3. In design, ample factor of safety should be provided.

What is the appropriate spacing of twin-tube tunnel depending on strength of the pillar, i.e., after tunnel excavation, even the pillar was initial yield, the overall stress of the pillar S_p should be kept within strength σ_p. If the spacing is hard to be satisfied because of nontechnical reasons, such as limited by the right of way, then the support systems have to be reinforced

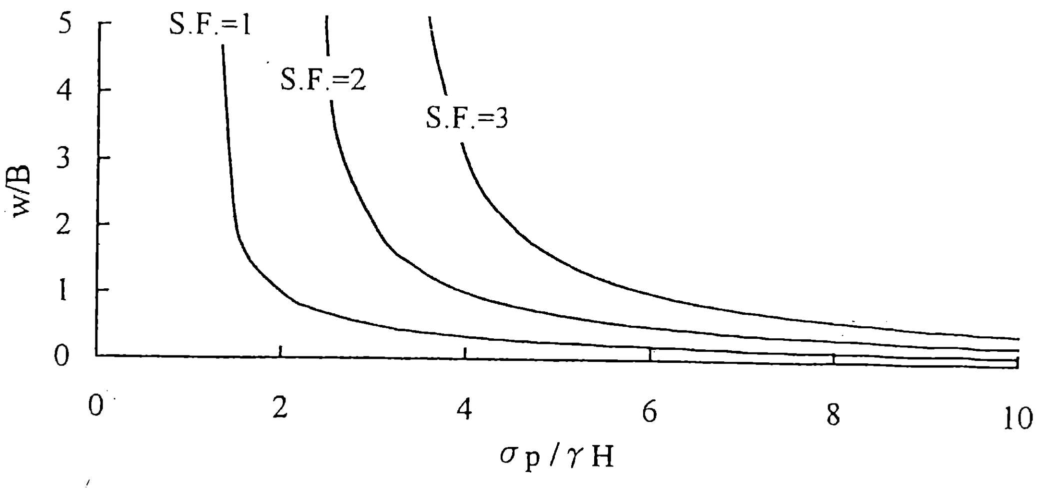

Figure 1. The ratio of w/B vs the pillar strength normalized by overburden pressure.

based upon the real condition which is other than those obtained from empirical support design. As an example, the pillar can be strengthened by prestressed tendons fastened at both sides of the pillar. The contribution of such anchors can be as demonstrated in Figure 2. It can be seen from Figure 2 that the strength of the rock mass in pillar is converted from uniaxial compressive strength to triaxial strength.

2.2 *Excavation sequence*

If the stress states of the rock mass around the tunnels do not exceed the yield limit, then the deformation of tunnels would make no difference between different excavation sequence. The deformation is independent of stress path in elastic state, which means no plastic zone exists after excavation. But for soft rock, it is almost impossible that the plastic zone would not exist after excavation is completed, thus excavation sequence highly influences the deformation.

Different excavation sequence means different unloading rate of tunnel. It can be appreciated that full face excavation is the fastest unloading process so as to cause the largest deformation. For soft ground, it is better to divide the face into several stages to excavate so as to ensure stability and small deformation.

The popular excavation method can be categorized into two groups; benching cutting and side gallery cutting. The side gallery cutting is suitable for wide span, poor rock tunnels, especially for those tunnels where deformation should be strictly controlled. Empirically, the settlement of tunnel using side gallery cutting with timely support is about half of that by benching cutting. The numerical analysis as shown in Figure 3 presents two different excavation sequence which indicates a significant reduction of roof displacements for side gallery excavation as compared with the full span top heading and bench excavation.

It can be shown that to excavate each tunnel of twin-tube tunnel simultaneously is less favorable than excavating them one by one. The former case would cause sudden loosening of the surrounding rock, which might yield unexpectable large and everlasting deformations.

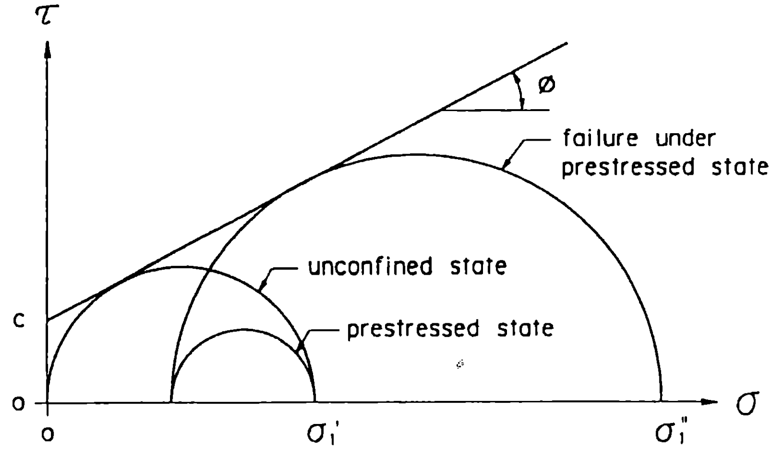

Figure 2. Stress state of rock mass around the tunnels before and after prestressed tendons applied. [2]

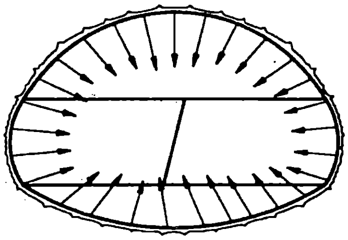

Figure 3a. Displacements induced by mining a 16m span tunnel in fault zone material by full top heading and benching.

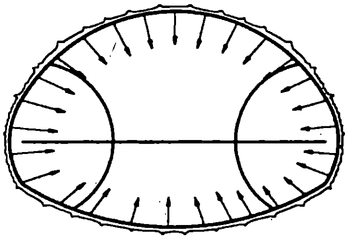

Figure 3b. Displacements induced by mining a 16m span tunnel in fault zone material by side galleries and benching.

2.3 *Support system*

In the case of soft rock twin-tube tunnelling in high in-situ stress, the deformation of tunnels usually reveals long duration and squeezing characteristics and therefore the traditional flexible tunnel supports can hardly provide enough bearing capacity and stiffness in time to ensure stability and controlled deformation. For instance, rock bolts are effective to form bearing arch to resist rock load if the surrounding rock around tunnels is moderately jointed, but for highly fractured rock, it is difficult to form a continuum by rock bolts. For stability concerns, it is more effective to timely apply rigid support such as concrete lining or shotcrete to confine deformation.

3. CASE HISTORY

3. 1 *Project description*

The 1.85 km long, 16m wide and 11m high twin-tube freeway tunnels were excavated simultaneously from both the southern and the northern portals, see Figure 4. From the northern portals, the two tunnels were excavated through rocks of the Miocene Nan-Chuang formation. The Nan-Chuang formation consists of a sequence of alternating sandstones and shales which strike roughly perpendicular to the tunnel alignment and dip to the southwest at approximately 20 to 40 degrees. Sandstones usually predominate, with beds typically 50 cm thick alternating with 10 cm siltstone beds. Away from the portals, the intact rock is generally fresh although the surfaces of joints from the two major joint sets are usually weathered, but not softened.

From the southern portals, the tunnels were excavated through older Miocene rocks of the Ta-Liao formation which is a similar sequence of sandstones and shales, although lenticular tuffs are sometimes encountered in the Ta-Liao rocks.

The boundary between the Nan-Chuang and Ta-Liao formations is a major thrust fault called Wantan Fault with the same general orientation as given above for bedding. The coverage of the tunnel in the faulted section is about 120m. On the line of the tunnel, the fault zone is approximately 60-70m thick, with a 30cm thickness of clay gouge present on the northern, lower contact and a 10cm thick gouge present on the southern upper contact. Between the two, conditions are highly variable, with several other gouge filled planes and various zones of fractured sandstone, siltstone and tuff. The faulted zone is generally dry and during excavation through the fault zone, the tunnel faces were generally stable.

3.2 *Problems encountered*

Three phases of excavation of a top heading, bench and invert have been performed in both the northbound and the southbound tunnels. Large deformations of the rock mass (more than 7% of excavation span) in the vicinity of Wantan Fault were developed when tunnelling through and beyond the fault. Additional rock bolts and local shotcrete repairs have been undertaken immediately when the excessive crown settlements were observed and the excavation works were then temporarily suspended. It is obvious that the temporary cessation has resulted in slowing down the deformation rate. During the summer of 1993, some additional prestressed tendons were installed in the crown with each row of tendons spaced at 1. 5m along the tunnel and each row having three tendons in the haunch and two in the other, excavation then recommenced away from the fault zone. However the deformations continued when the excavation recommenced, see Figure 5. To enhance the pillar, three rows of tendons as shown in Figure 6 were installed and the deformation was effectively controlled .

The largest settlement was up to 1.2m and cracked shotcrete and deformed steel ribs were repaired several times. Before remining works begun, additional rock bolts were used to prevent local failure.

3.3 *Remedy measurement*

The designed allowable deformation was 25cm for the extremely poor rock mass. Thus several hundred

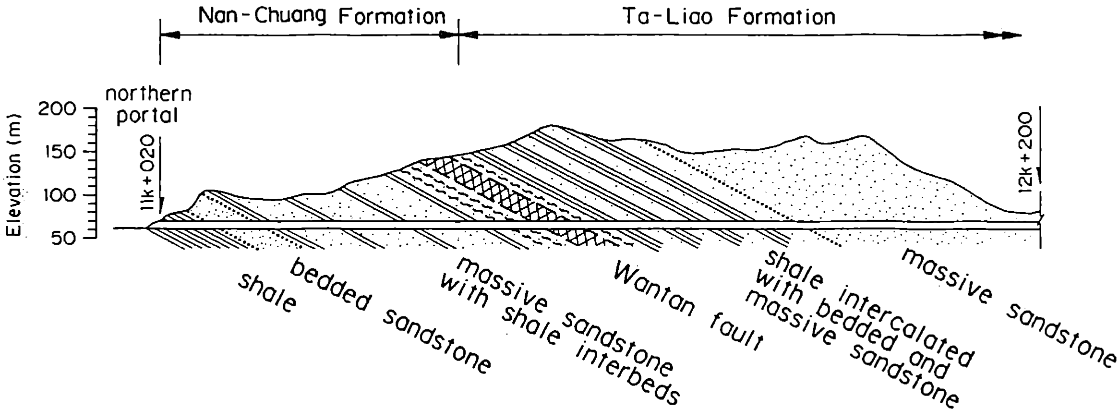

Figure 4. Geological profile of the northern part of tunnel. [3]

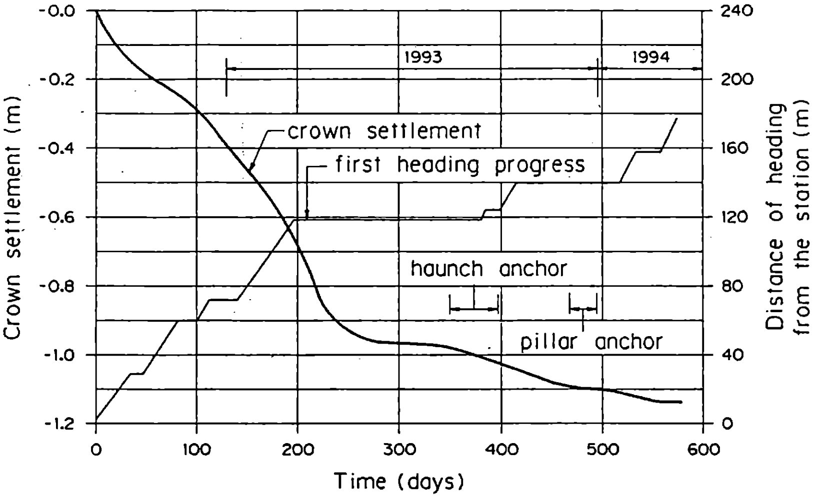

Figure 5. Crown settlement with respect to excavation process. [3]

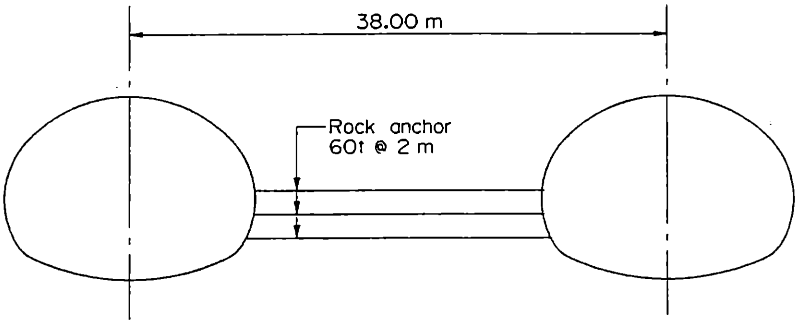

Figure 6. Rock pillar reinforced with prestressed tendons. [2]

meters in length of twin-tube tunnel had to be remined. Based on the monitored data and observed tunnel performance, supports were reinforced where required, especially in the weak pillar where additional prestressed tendons were adopted to tie up the pillar, and 15m long cables on a 2. 5*2. 5m grid spacing were placed in the crown and sidewall. Remining work progressed in 1m lengths and new supports followed. Each advance was remined in four stages. The concrete lining was redesigned to resist higher rock load so that it could be installed as soon as possible ignoring the potential additional deformation of the remined sections. In other words, secondary lining was regarded as part of primary support in this case. Consequently, the tunnel was successfully stabilized after the concrete lining placed.

4. DISCUSSION & RECOMMENDATION

The most important considerations of tunnel design are stability and defomation control. The purpose of support is to prevent failure and to maintain as much strength as possible in the rock mass during tunnelling operation. A safe width of pillar, appropriate excavation sequence and timely support installation are crucial to the behavior of tunnels through soft rock. To evaluate the interaction between each tube and rock load for a twin-tube tunnel is very difficult but important. If the width of pillar is wide enough, the twin-tube effect can be neglected. But for closely spaced twin-tube tunnel, it is of interest to note that by applying a confining pressure to the rock mass of pillar so as to convert from unconfined compressive stress state to triaxial compressive stress state had a great contribution to the stabilization of the twin-tube tunnel. It is worthwhile to point out that the deformation control should be better to rely on stiff rigid supports and be installed timely in soft rock tunneling with $\sigma_p/\gamma H<2$ as shown in Figure 1 since the non-rigid supports such as rockbolts or prestressed tendons provide very little stiffness as compared with that of the surrounding rock and have no significant contribution to control deformation. The remining work would cost more money and consume much time if more deformation than estimated occurred. Moreover, sequential excavation is safer than full face cut and the side gallery method is almost imperative for wide span tunnels in soft rock.

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