Risk Control Strategy for Large Slurry Shield Crossing the Soil at Shallow Depth below Airport Taxiway

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1 Background

Hongqiao International Airport is the second largest airport in Shanghai. It is predicted that the aircraft movements will reach 26 thousand per year and the passenger throughput will reach 30-40 million by the year 2015. To meet the demand, a new runway and a new terminal will be built on the west. At the same time, high-speed railways, maglev lines, metro lines etc., are under construction to link with the airport. Hongqiao airport will become the largest Integrated Transportation Hub in China. R10 metro line, the main passenger transit between the east and west terminals, extends from the existing east aircraft stands to the west. R2 and R13 metro lines are also linked with the hub in the west. The newly-built two road tunnels, Yingbin road tunnel and the west Xianxia road tunnel will undertake luggage transportation between the two terminals, and serve as the passenger transportation corridors between Hongqiao Transport Hub and the downtown areas (Fig.1).

![Fig.1 General plan of Hongqiao Airport](image)

The newly-built west Xianxia road tunnel is located in the north end of the Hongqiao Transport Hub and will be constructed using a slurry shield. It is 11.36m in diameter, 1.7km in length, shallow buried to a depth of between 6.5-13m and 110m away from the end of runway (Fig.2). The ground consists of mainly saturated soft clay with the lower layer interpenetrated with an artesian water bearing strata. The shield machines will pass under the important
facilities of the airport including taxiways both in the east and the west, the parking aprons, aircraft stands and navigation light columns, etc. (Fig. 2, 3).

Fig. 2 Section 1-1

Fig. 3 Longitudinal section of West Xianxia road tunnel

The most critical risk of the airport crossing is the settlement, which may cause damage to the airport pavements due to the shield tunneling below. A similar project, Airside road tunnel crossing at London Heathrow, airport taxiway, adopted an curved alignment to reduce the number of aircraft stands in the exclusion zones, in order to avoid localized excessive settlement [1].

In the research field, the achievements in tunnel risk management have been improving since 1990s [2,3,4]. A so-called “safety chain” is proposed to take measures for different stages [5]. Soren Degn Eskesen et al. proposed ITA guidelines for the entire process control [6]. But research on the inter-correlation and evolution of risks at and between different stages, which is the substantial aspect to make risk complex, has not yet been noticed or attracted much attention.

2 Risk descriptions for different phases of the airport crossing project

2.1 Risk at early planning and design phase

Planning and design is the first phase of risk identification, and it determines the total risk degree of the whole project to a large extent. At this phase, risk is based on the drawings prepared at the offices, they are usually predicated and far from the actual state. Risk can be caused by neglect, ignorance and defects in design. More attention should be paid to the risk’s migration from the design to the construction phase and its evolution which will probably make
the risk magnified and thus overburden the construction phase, especially when the construction contractor is not so qualified or experienced.

2.1.1 Risk of arrangements for parallel projects
Hongqiao airport crossing project is a part of the Hongqiao Hub project, which includes several projects undergoing concurrently. Under these circumstances, the time sequence of key activities, new pavement and its foundation treatment, renovation and maintenance of existing pavement etc., must be arranged carefully in order to minimize their interactions. For example, if the often-used roller compaction method is chosen for ground treatment, it is feasible to implement the tunnel crossing first. While in case of the deep mixing method, the tunnel crossing is preferred to be executed prior to ground treatment. But there still exists a question as to when the permanent pavement will be constructed? It has to be left until the settlement of its foundation stabilizes.

2.1.2 Risk of tunnel design options
The main risk arising from planning and design includes alignment of tunnel( including plane and vertical profile featuring with curvature, minimum depth etc.), relative location of cross passages and working shafts to airport pavement, waterproof grade of the tunnel, ground reinforcement method for the launching and receiving of shield, etc.. And above all, the protection standard for airport pavement is the foundation of this and the following phases.

Plane alignment of tunnel
The alignment design of west Xian Xia road tunnel must be consistent with the general plan of Hongqiao Transport Hub. The alignment is constrained by
- location of critical infrastructures (runways, aircraft stands, etc.),
- link requirement with existing city transportation network,
- intersection angle with airport pavement alignment,
- allowable minimum radius for shield driving,
- allowable maximum settlement for navigation facilities of the airport,
- underground obstacles (pipelines, abandoned foundations and piles, etc.).

In order to reduce the risk of the shield crossing as much of the airport pavement as possible, the location of the tunnel is planned at the end of the flight area to avoid runways, and the line is designed to the smallest curvature and nearly perpendicular to the pavement, as shown in Figure 4. The cross passages should be positioned far enough away from the airport pavement and other facilities in order to avoid excessive settlement during construction.

Vertical alignment and minimum depth of tunnel
The minimum depth and the longitudinal profile of the tunnel should be determined by hydrological and geological profiles, and ground layer characteristics, the distribution of infrastructures and underground obstacles as well as construction methods (Fig.5). Sharp curvature and steep gradients should be avoided. In order to avoid steep gradients, west Xianxia road tunnel has to be laid at a shallow depth, at a minimum cover of 6.5m. The shallow cover depth of the tunnel results in difficulty to the control of the shield.

**Tunnel lining section**

The extent of the ground deformation depends not only on the disturbance during construction phase, but also on the deformation and water-proof of tunnel lining. Inappropriate section design may result in water ingress and excessive consolidation settlement of the ground. Remedial measures for construction and operations should also be taken into consideration in the design phase, e.g. pre-embedded holes for compensation grouting on the segmental lining at the crossing zone in case of unexpected settlement.

### 2.2 Risk at construction phase

Most of the risks are usually intended to be left for the contractors to tackle at the construction stage. Risk control at this phase, on one hand, is to abide by the design principles and implement countermeasures made in the design phase; on the other hand, it is to adjust or adopt additional measures based on the judgments of the construction. These changes in the measures, by the construction contractors and the implementation of risk prevention measures will affect the composition and magnitude of risk, therefore re-identifying and re-defining risk is required at this stage.

**Constraints on working hour and working area**

According to the requirements issued by the Shanghai Airport Authority, the construction work in the exclusion zone must be scheduled in the morning between 00:00 ~ 6:00 am and all equipment must be removed 1 hour before the operation of the airport. With respect to the provisions of China's international airports; no ground operations are allowed within 150m of both sides of the runway and there is a strict restriction on headroom of plant and equipment. These constraints indicate that no ground treatment or shield working shafts for tunneling are allowed in this area.

**Shield machine type and its reliability**

Compared to the short distance crossing cases, long distance crossing may encounter much higher probability of shield machine failures. It is impossible to prevent the shield machine from any faults in the one kilometer’s length tunneling process at shallow depth. But severe problems, such as total breakdown, grouting system congestion, slurry cabinet and pipe blocking, should be avoided by careful check and immediate onsite repair. This is the basic requirement of the shield machine reliability for the project.
The launching and receiving of shield
The launching and receiving of shield is risky when the working shaft is near the airport pavement. During the construction phase, the following accidents are prone to happen: soil destabilization around the tunnel portal, shield posture out of control, etc. Another great concern is the inappropriate soil reinforcement method at tunnel portals may result in serious blocking of the slurry pipe system, and even frequent inverse circulating of slurry.

Construction of cross passage
The cross passages are generally located in the middle of the tunnel, at the lowest point of the line. The freezing method is often used for the construction of the cross passages. Apart from the common risks of this method, the deformation caused by the frost expansion and thawing is critical, especially as defrosting will continue for at least a year or more, which will increase the long-term settlement. Therefore, essential monitoring and a “defrost-tracing grouting” are essential elements in the construction of cross passages.

Long-term settlement consideration
The ground disturbance caused by shield tunneling and the ground defrosting at the construction phase will lead to long-term consolidation settlement during the operation period. Therefore, the construction contractors must be aware that the allowable settlement at the construction phase is only a small part of the total allowable settlement. It’s reasonable to inform them the share of the total settlement allowed at the construction phase (see section 4).

2.3 Risk at operation phase
The main risk at the operation phase is that the excessive localized settlement of the ground can result in the crazing or even sudden subsidence of the airport pavement imposed by the dynamic load of aircrafts. Obviously this risk has close relationships with the rationality of design and the quality of construction.

Long-term settlement risk factors
Long-term settlement of the ground at the operation phase originates from the ground strata restoring from the disturbance caused by the shield tunneling, and it determines the extent of subsequent development of settlement at the operation phase. Besides, the water ingress induced by the design defects and the invalidation of waterproof material may also increase the long-term settlement during the operation period, which will lessen the safety of airport pavement and the facilities on it. Timely repair and grouting for the tunnel are critical tasks for risk mitigation and elimination at this phase.

Tunnel fire or explosion
A tunnel fire or explosion may result in not only the loss of life and severe damage to the tunnel but also the collapse of the tunnel structure under the airport, which may in turn induce a collapse of the ground cover, thus reducing the safety of the airport facilities. Catastrophic consequences of the tunnel fires (e.g., the Mont Blanc tunnel, 1999 and the Swiss St. Gotthard tunnel, 2001) also result in great concerns for the fire-life safety protection in road tunnels. Structural damage or collapse may not result in a severe problem on the surface in a rock zone, but completely contrary in soft ground zone, especially in the case of sensitive buildings existing above the tunnel.

3 Inter-correlations and evolution of risks
Traditional risk analysis methods, such as fault tree, event tree and decision tree, usually
define the distribution and evaluate the probability of risk statically. The complexity of risk evolvement, i.e., the risk changing from one phase to another, is ignored in the traditional risk analysis.

In order to research the evolvement of risk between different phases, the propagation and evolvement mechanism of virus can be used for reference. In the typical virus propagation model of SIR (Fig 6), there are three states of organism: \( S \) (Susceptible), \( I \) (Infectious) and \( R \) (Removed). The symbols \( (\alpha, \beta, \gamma) \) in Fig.6 are used to illustrate the transfer relationship between the three states. These can be regarded as similar to the engineering risk states in different phases.

Enlightened by this idea, we assume five evolvement types for engineering risks: Retaining (R), Aggravating (A), Weakening (W), Disappearance (D), Variance or Aberrance (V). The former three states (R,A,W) are often easy-to-see, but the latter two (D and V) are prone to be neglected, which are needed to be traced, rechecked or even re-defined at the following phases. Fig.7 shows an example of concepitive illustration of evolvement among risks of \( R_1, R_2, R_3, R_4, R_5, R_6 \). The different geometrical shapes of risks in the figure represent their changing forms consisting of intension and extension of their definitions.

**Evolvement of risks between design and construction phases**

The risks identified in the design phase may be weakened or aggravated or disappear or vary in the construction phase due to the changing conditions imposed by the ground geology and contractors. For example, in the design phase, the ground reinforcement at tunnel portals is designed to high strength and impermeability of the ground. But, during construction, the actual state of reinforced ground may impede shield driving and even causes breakdown as well as endless blocking faults of the machine. Therefore, the contractors face quite different or “unexpected” risks in their own phase due to the evolvement of risks.

**Evolvement of risks between construction and operation phases**

For instance, the ground loss caused by shield tunneling in construction phase brings about temporary settlement which can be measured by the surface monitoring equipments. Besides, it may develop into local cavity deep in the ground or just below the taxiway during the operation phase, which may stand temporarily but not observed, will develop into collapse after a long time of operation, especially when imposed by the dynamic load of aircrafts on the pavement surface.
**Evolvement of risks between design and operation phases**
The design rationality and construction quality will be verified by and reflected in the airport pavement state in the operation phase, and fed back for establishing protection standard.

Changes of operation conditions may cause the aberrance of the risks defined in the design phase. For example, waterproofing design defects may result in leakage of tunnel and consolidation settlement or even ground collapse in the operation phase. Unexpected changes of the movement frequency of aircrafts in the operation phase, possibly lead to over-estimation of the bearing capacity of airport pavement and also of the tunnel structure itself in the design phase.

4 Discussion on crucial issues related to the risk control

4.1 Deformation control criterion

The long-term deformation of the airport pavement built on soft ground is relatively large and generally uniform. But the deformation of the pavement above the tunnel would become non-uniform, and this may result in cracks of the pavement or unsuitable smoothness for the landing and sliding of aircrafts.

There exist contact and non-contact states between the pavement and the ground due to the deformation compatibility. The state of non-contact occurs with large settlement and will be more risky for the pavement than the contact state (Fig.8).

For the contact state, the allowable foundation deformation \((Sc)\) for crack resistance is calculated with the elastic foundation beam theory. As for the non-contact state, i.e., the cavity between the pavement and the ground (Fig.8) is assumed, the allowable deformation of the foundation can be obtained as \(Sw\).

In addition, to meet the requirements of smoothness for aircraft landing and sliding, the localized allowable maximum settlement of the pavement can be deduced as \(Sn\) based on the allowable smallest curvature \(1/R\) and settlement slope \(k\). Furthermore, in order to assure the accuracy of navigation lights, the allowable deformation of the light column base should be determined case by case as \(Sp\). Then, the maximum permissible settlement of the pavement is finalized as: \(S_{max}=Min(Sc, Sw, Sn, Sp)/K\), where, \(K\) is a safety factor.

4.2 Settlement share between construction and operation periods

The total settlement of the airport pavement is caused by many factors both in the construction and operation phases, it will develop covering the entire life of the tunnel and the airport pavement. In order to make the respective responsibilities of all partners clear and avoid litigation, it is necessary to divide the total allowable deformation into the construction and operation phases according to the normal construction control level and the long-term settlement characteristic of the soft soil in Shanghai. This forms the basis of the settlement control strategy so as to achieve explicit and determinate goals.
5 Summary

The entire process risk control remains a conception to some extent. It is important to be aware of the complexity of the risk evolution between different stages induced by the uncertain changes of conditions such as negotiations, mitigation measures, ignorance and other time dependent factors. Anyway, setting up an organization consisting of all partners, which is aimed at managing risks and coordinating to assure that it works since the beginning, is vital to check and re-identify the risks and to make clear their own responsibilities of all partners involved in the project.

This paper focuses on the risk characteristics and risk management strategy of the tunnels crossing airport at shallow depth below taxiway by slurry shield. It creatively uses the propagation, evolution and variation mechanism of virus for reference to illuminate the complexity and discipline of the evolution of the risks in civil work. It offers a new idea for the analyzing and managing of the risks of high-level-risk and complex construction.

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References