State-of-the-Art of the Tunnel Maintenance in Taiwan and Challenges to Sustainable Development

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ABSTRACT: Tunnel construction of Taiwan started early in late nineteenth century. Within 125 years, tunnel maintenance in Taiwan went through several stages. In early days, engineers meant tunnel excavation. Tunnel inspections, repairs and reinforcement were performed only when serious damage was observed. As the number of damaged tunnels increased, investigations of the most frequently recurring anomalies revealed that the degradation of tunnels in Taiwan was inevitable and usually occurred in an exceptionally shot period. Frequent earthquakes, a high ground water level and poorly cemented rock masses provides a severe environment for engineering structures. Hence, to adapt more effectively to the environment, tunnel maintenance started to consider the entire life cycle of a tunnel. Recently proposed monitoring technologies and anomaly cause diagnosis methods of Taiwan have been demonstrated to be useful in supporting the sustainable operation of tunnels.

KEYWORDS: Tunnel, Tunnel maintenance, Tunnel inspection, Tunnel repair, Tunnel reinforcement

1. INTRODUCTION

The purpose of infrastructure is to provide stable public services. To utilize resources and budgets effectively, all infrastructures should achieve sustainable development, a goal that can only be reached by intricate and careful maintenance. As an important components of infrastructures, tunnels are excavated to connect locations by undergone water and ground, or pass through mountains. Tunnels are expensive to construct. The maintenance of operational tunnels was overlooked until they are damaged. Tunnel maintenance used to be reactions to tunnel anomalies rather than supervision at all times. The traditional method of tunneling adopts strong and heavy structures to bear external loads, so damage is likely to occur if local stress exceeds material strength. New Austrian Tunneling Method (NATM), which has been the most widely used excavation technique since the 1960s, involves an adequate primary support, such that rock mass that surrounds tunnel can form a bearing ring, causing tunnel deformation eventually to converge at an equilibrium. A tunnel lining is installed to give additional protection and visual appeal. Recently, as instances of damage have attracted international attention to the issue of the long-term stability of tunnels, people are becoming increasingly aware that tunnel degradation does not end after construction, studies of the entire tunnel lifespan of a tunnel should be performed to ensure its sustainable operation.

This manuscript describes the natural and cultural background of tunnel engineering in Taiwan. Since the late 19th century, over 1,000 tunnels with a total length of over 1,000 km have been constructed. Based on data about tunnel damage, inspection and repair, Taiwan has transformed its tunnel maintenance strategy from breakdown maintenance, preventive maintenance to proactive maintenance. Challenges and potential solutions related to life-cycle tunnel maintenance are presented herein.

2. EXPERIENCES OF TUNNEL MAINTENANCE IN TAIWAN

2.1 History of tunnel excavation, inspection and repair

The history of tunnel engineering in Taiwan can be separated into four stages, the initial stage, the growth stage, the thriving stage and the maintenance stage, as shown in Table 1 (Cheng, 1993; Huang, 2007).

(1). Initial stage (before mid-1950s): Most early constructed tunnels in Taiwan were hydraulic. Primitive design concepts and construction technology, and large variations among engineering materials allowed severe lining damage by water abrasion. The function and purpose of those tunnels are no longer acceptable. Many of the hydraulic tunnels that were built in this stage are either close to failure, or have been reinforced repeatedly but still fail to function properly. Some have been abandoned. Their structural evolution is hard to assess because records of excavation, operation and repair are missing, and inspecting hydraulic tunnels is difficult.

Table 1 Brief history of tunnel engineering in Taiwan

Period	Main construction
Initial stage (~ mid-1950s)	Mainly hydroelectric and agr Period icultural irrigation tunnels, such as those at Guishan, Wulai, Sun Moon Lake and Tianlun, as well as Wushanling tunnel, Wushe hydroelectric tunnel and Taoyuan Canal tunnel.
Growing stage (Mid-1950s ~ late 1970s)	Large hydroelectric and traffic tunnels, like tunnels for Shimen and Tsengwen Reservoir, the Guguan and Deji hydroelectric systems, and those on Freeway No.1 and the north-link railway line.
Thriving stage (Late 1970s ~ late 1990s)	Tunnels for reservoir, pumped-storage power plants, roads and sewer. Representative tunnels include those for the Feicui Reservoir, Mingtan and Minghu pumped-storage hydroelectric plant, New Tianlun hydraulic power plant, and the south-link railway line, the north-link railway line as part of the east railway reconstruction project, metro Taipei, the north section of Freeway No.3 and Freeway No.5.
Maintenance stage (Late 1990s till now)	Tunnels in Kaohsiung rapid transit, metro Taipei, Taiwan high speed railway, freeways, expressways, and some hydraulic tunnels, including tunnels in the central and south sections of Freeway No.3, Freeway No.5, Freeway No.6, Suhua improvement Engineering (under construction), and Tsengwen sediment-sluice tunnel (under construction).

Railway tunnels that were built at this time were not water proofed, many of them suffer from leakage. However, leaking is not an issue before 1980 because all locomotives were powered by steam, diesel or diesel-electric, instead of electric as now. Most damage was repaired without being recording, except in cases of earthquake- induced damage and serious spalling that is caused by material deterioration.

(2). Growth stage (mid-1950s ~ late 1970s): Taiwan railway administration had the western railway line electrified from 1975 to 1979 (Figure 1). The project involved the installation of overhead wiring in tunnel roofs, imposing requirements on vibration capacity and water-proofing, which are challenges to the over 70 years, masonry supported tunnels. Along with electrification, lining around overhead wires in parts of the tunnels was reinforced; in other tunnels, all lining was reinforced. Some of the reinforcements can still be found in abandoned railway tunnels from Zhunan to Changhua (Figure 1). The purpose of the electrification project was to increase the traffic volume. Very little documentation about tunnel reinforcements remains. Most highway tunnels in Taiwan were constructed after 1960. The tunnels constructed in this stage are short and have small cross-sections, they pass under steep slopes, including the ones in Suhua and Central Cross-lsland Highway (Figure 1).

(3). Thriving stage (late 1970s ~ late 1990s): Once the railway electrification project was completed in 1979, larger locomotives and higher driving speeds increase the loading on the roadbed and tunnel structures. The Taiwan railway administration frequently carried out maintenance on the roadbed and ballast, and started to pay attentions to the maintenance of bridges and tunnels. In 1988, after the railway had been operated for 97 years, the Ministry of Transportation and Communications (MOTC) published "Maintenance Regulations for Bridges and Tunnels on 1067 mm Gauge Track" in the railway category of the engineering section of the Traffic Technical Standard Specifications, Taiwan. These regulations were the first official regulations for inspection and maintenance of railway bridges and tunnels in Taiwan with the purpose of ensuring structural safety, and they have since been amended several times, until the latest version was published in 2014 (MOTC, 2014), setting items and frequency of inspection, and requiring the systematic documentation of the results of those inspections.

Some of the highway tunnels that were built in the growth stage were abandoned in a series of traffic construction projects during 1970-1990, when Taiwan's economy was boosting. Some other tunnels were ruined by slope instability. The remainder are used today following extensive repairs. The construction of Freeway No.3 and No.5 (see Figure 1 for the location) begun in the late 1980s to early 1990s, when a succession of three-lane large cross-sectional tunnels were excavated using NATM, including an extremely difficult case, Xueshan tunnel, which took 13 years to complete. The excavation of metro Taipei initiated in 1998 denoted the beginning of shield tunnels in Taiwan. At this time, tunnel engineering had reached unprecedented peaks in mechanical theory, numerical simulation, construction appliance, engineering techniques, and quality control.

(4). Maintenance stage (late 1990s till now): In 1995, as part of the Yilan and north-link railway line electrification project which began in 1993, novel scanning instruments were used to capture images of the surfaces of tunnel linings. Digital records of inspection outcomes are a reliable basis for pre-electrification reinforcement design and for maintenance hereafter. Records of lining surfaces reveal that rock tunnels are not as durable as people used to believe. Periodic inspections and maintenance are essential to ensuring normal function. The structural inspections on Sanyi No. 1 Tunnel at the western railway line in 2001, tunnels on the south-link railway line in 2006-2011, and the south-link railway line again on 2014 for the purposes of electrification all involved scanning to capture images of lining surfaces, investigations of structural integrity and probing for holes behind the lining. Tunnel engineering in Taiwan is moving toward better maintenance of structural safety and increases service life, based on over one hundred years of experience.

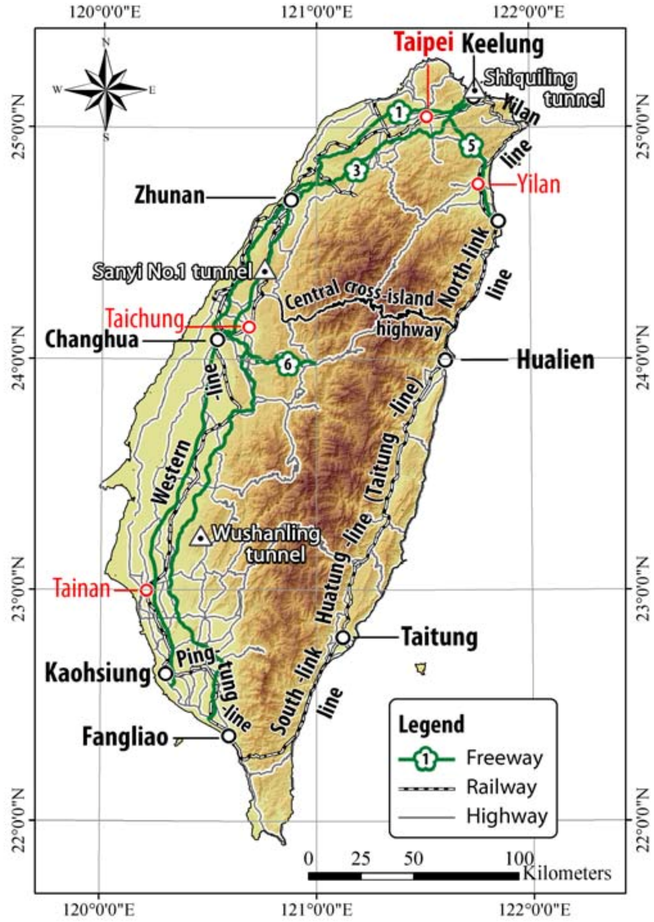

Figure 1Traffic network map of Taiwan

2.2 Damaged tunnels

Significant aging and deterioration were observed in several operational tunnels in Taiwan. Many inspections since 1993 revealed cracks, spalling, leakage.

The Shiqiling tunnel was built in 1887-1890, and abandoned after only seven years of operation because the deep slope and sharp turns of tunnel alignment is unfavorable to railway. The tunnel is built by masonry bricks and stones in Keelung City (Figure 1). The masonry lining flaked off, leaving undulating surface and cracks parallel to tunnel rim (Figure 2). The continued flaking was first observed and treated in 1990, 100 years after the tunnel was completed. Chiu *et al*. (2014a) concluded that the high precipitation and rocks that are prone to weathering were responsible for the tunnel anomalies.

The Chi-Chi earthquake with a Ritcher magnitude of 7.3 seriously damaged the Sanyi No.1 railway tunnel (Figure 1) in Miaoli County, which was approximately 58 km from the epicenter. Longitudinal cracks in tunnel roof and the spring line, circumferential cracks, inclined cracks (Figure 3a), invert heaving (Figure 3b) and spalling were all found in the tunnel. The earthquake damaged 53 other tunnels. Lining cracks, portal failure and lining spalling are the three most common anomalies in the damaged tunnels (Wang *et al*., 2001).

(a)

(b)

Figure 2 (a) Full view and (b) close-up of undulating surface of masonry lining in Shiqiling Tunnel

(a)

(b)

Figure 3 Anomalies in Sanyi Tunnel following Chi-Chi Earthquake in 1999; (a) inclined cracks and (b) invert heaving

Completed in 1920s, the Wushanling hydraulic tunnel in Tainan City (Figure 1) has been rehabilitated three times in the late 1950s, the early 1970s and the mid-2000s. None of these rehabilitations fully recover its design function and performance. Cracked lining and corroded rebar (Figure 4a) were found after the inspection in 2004. Surrounding rocks behind the tunnel lining are visible in some seriously cracked and spalling area. Along the displaced lining, water leaked (Figure 4b) and efflorescence occured due to water abrasion. The Chia-Nan Irrigation Association is now planning to build a new Wushanling tunnel to ensure the water supply to Wushantou Reservoir.

(a)

(b)

Figure 4 (a) Corroded rebar and (b) leaking water, at Wushanling Tunnel in 2004

3. DIFFICULTIES AND LESSONS LEARNED FROM TUNNEL MAINTENANCE

Taiwan is located at the inclined convergent plate boundary between the Eurasian Plate and the Philippine Sea Plate. The persistent movement of plates brings about a highly variable geology, young strata, and rock masses that are unfavorable from an engineering perspective. The subtropical climate produces moist and rainy weather, so the groundwater level is high. Operational tunnels in Taiwan may suffer from long-term rock mass loading, groundwater abrasion, aging lining, and shaking during earthquake (Chen *et al.*, 2011; Chen *et al.*, 2012) (Figure 5). The costs of repair, reinforcement and reconstruction are very large.

Since tunnels in Taiwan are prone to deteriorate rapidly, the principle according to the NATM that tunnel deformation stopped before lining construction is not effective here. Early tunnel inspections in Taiwan were carried out to identify construction defects. Provided with only a few inspection items and limited time, engineers were required to safety and reinforce zones of low safety.

The general idea is to inspect, design and implement reinforcement work once and for all. Tunnel maintenance was previously a response to tunnel damages, little attentions had been paid in the absence of visible damage. The "Maintenance Regulation for Bridges and Tunnels on 1067 mm Gauge Track", published in 1988, introduced periodic tunnel inspections in Taiwan. In the late 2000s, a wide range anomalies were identified in the large cross-sectional tunnels that were constructed based on modern mechanical theories of tunnel engineering. After only 20-30 years of operation, these strictly quality-controlled tunnels started to degrade in distinctive ways to a degree that also varied with time. The failure of the NATM to provide long-term tunnel stability in Taiwan initiated recent innovation in tunnel maintenance.

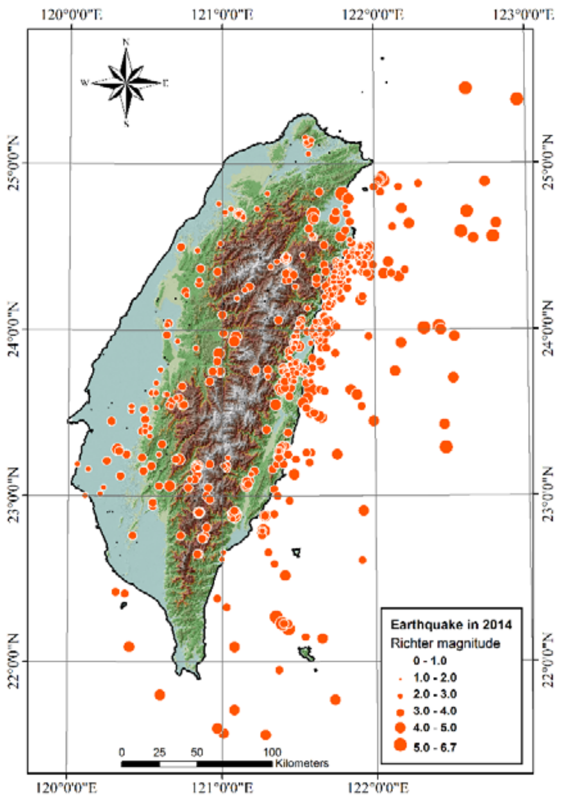

Figure 5 Earthquake events near Taiwan in 2014, after the records of the Central Weather Bureau, Taiwan

4. STATE-OF-THE-ART OF TUNNEL MAINTENANCE

4.1 Regulations concerning tunnel maintenance

On account of the requirements in Taiwan tunnel engineering, a tunnel inspection procedure is suggested as shown in Figure 6 (Huang *et al.*, 2008). The procedure establishes a hierarchy of several types of tunnel inspection. The first inspection should be carried out right after tunnel has been constructed. During normal operation, administrative personnel conduct ordinary patrols and regular checks periodically. Immediate checks should be performed under several emergent conditions. The main types of inspections are normal inspections and detailed inspections, which involve most of the inspection items and inference of anomaly causes. Normal and detailed inspection be conducted by professional engineering consultants, whereas administrative personnel can conduct ordinary patrols and regular checks.

Most of the directions concerning the inspection of tunnels follow the hierarchy that is shown in Figure 6. With respect to road tunnels, the traffic technical standard specifications "Road Maintenance Regulations" under the road category, road engineering section announced by MOTC in 2012 (MOTC, 2012), specifies that tunnel inspections should include tunnel patrols, regular inspections and special inspections. Tunnel patrols comprise ordinary patrol, regular patrols and special patrol. The first regular inspection should typically be conducted six years after the tunnel is built, and at least once every two years thereafter. Special inspections are performed following a catastrophic accident, or when the administration of the tunnel decide to initiate one after the patrol has identified anomalies. Railway tunnels must be inspected annually (MOTC, 2014). The ordinary patrol of freeway tunnels comprise daytime and night time patrols (Taiwan Area National Freeway Bureau, 2011). Two men in a car visually detect anomalies and fill out forms. Daytime ordinary patrols are carried out daily. Nighttime ordinary patrols performed at least once a month. Special patrols are conducted 1) after or during torrential rainfall (350 mm in 24 hours), 2) as seismic intensity exceeds level four (25-80 gal), 3) after a catastrophic traffic accident, fire accident, explosion, or natural emergency that is likely to have damaged tunnel structure has occurred, or 4) other special circumstances. Regular inspections are performed annually in freeway tunnels. The Directorate General of Highways, MOTC (2012) requires that for highway tunnels, ordinary patrols are carried out weekly and special patrols are performed before and after a typhoon, heavy rain, a flood, earthquakes with a seismic intensity of higher than level four, or after catastrophic traffic accidents. Regular checks are performed once a year.

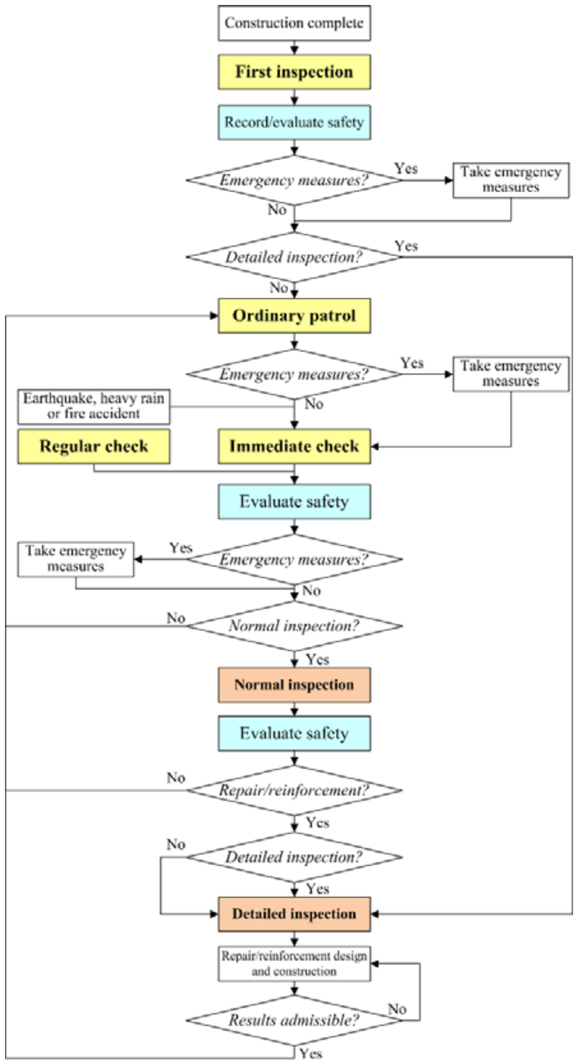

Figure 6 Tunnel inspection procedure used in Taiwan (translated from Huang *et al*., 2008)

4.2 Transition from preventive to proactive maintenance

Owing to the development of non-destructive technology, the number of available inspection items associated with lining integrity and cavities behind linings has increased rapidly in the past two decades. As the effectiveness of and accuracy of detection have improved, structural safety inspections for operational tunnels have been transformed from the checking for cracks at lining surfaces to the integrity inspections both on and beneath lining surfaces. Novel methods of tunnel inspection and maintenance focus on long-term stability (Wang *et al*., 2010). Micro-displacement monitoring technology is highly precise, involving absolute coordinates obtained using a Global Positioning System (GPS) (Chiu *et al*., 2012), enabling traces and displacements of monitored points to be recorded over a long time. The characteristic matrix method that was presented by Chiu (2014) and Chiu et al. (2014b) decomposes tunnel displacements into characteristic modes, which are displacement modes that involve translation, rotation and various degrees of deformation. This method enhances the identification of anomaly causes by tunnel displacements. Wang (2010a) used the layout of anomalies in several tunnels, acquired from image-mosaic technology (Lee *et al*., 2013) to characterize the patterns of cracks in tunnel lining and associate them with shear deformation of unstable neighboring slopes. Lee (2013) collected the inspection and reinforcement files of 266 tunnels, and developed a technique for diagnosing eight causes of lining anomalies (Lee and Wang, 2014). The results of applying these methods to several tunnels for monitoring, diagnosis, repair and evaluation of repair effectiveness reveal satisfactory outcomes. The structural behavior and failure patterns of tunnels can be elucidated by comprehensive inspections and follow-up monitoring. The concept of “once and for all” safety inspections now given way to “disaster prevention” and “life extension”. Periodic inspections and monitoring extends the lifespan of tunnels causes them to serve better.

Recently, in response to the regulations on preventive maintenance, large tunnel inspection projects, such as those involving the Taipei metro, south-link railway line and the north section of Freeway No. 3 have revealed the symptoms of displacement that may affect the structural behavior and normal operation of tunnels. Effective monitoring technology is utilized to examine long-term variations of tunnel sections. For example, experience has revealed that shield tunnel anomalies in metro Taipei are generally caused by differential subsidence related to adjacent constructions (Hwang et al., 2011; Chang *et al*., 2012). Metro research and inspection reports indicate that three-dimensional displacements of precast linings in absolute coordinates represents the structural evolution of the tunnels (Chiu *et al*., 2015). Anomalies of common types and at common locations are broadly under control. The main anomalies causes of tunnels in Taiwan include time-dependent variations of the surrounding rocks and soils, deterioration of the lining materials, and long-term loading on tunnels (such as by slope creeping, shear associated with faults, cyclic hydraulic pressure, vibrations caused by trains, water abrasion, environmental changes including those caused adjacent construction, and sudden external forces, such as those caused by earthquakes, landslides, or fire accident).

5. PROSPECTS FOR SUSTAINABLE DEVELOPMENT AND RELATED CHALLENGES

At the core of sustainable infrastructure operation is consideration of the lifecycles of its components. A facility should be considered from its proposal, through its feasibility evaluation, planning, related investigations, design, construction, project completion, operation, maintenance and life extension, until it is either modified for other purposes, or abandoned. Proactive maintenance, also known as lifecycle-based maintenance, is concerned with maximizing the economic and financial benefits of infrastructure while minimizing energy consumption.

Tunnel anomalies resemble the symptoms of human disease in many ways. Modern medicine treats diseases based on experience gained over a long period using systematic methodologies that have been developed in response to a considerable number of cases of illness throughout human history. For instance, the nature and timing of remedies are determined in response to symptoms, and the findings of physical and pathological examinations, as shown in Figure 7. The concept of tunnel maintenance as a means of keeping tunnels “healthy” was introduced to Taiwan as an analogy to the keeping of the human body healthy. As part of an ongoing plan, the maintenance of operational tunnels involves safety inspections, diagnoses of causes of anomalies, monitoring, safety evaluation and repairs. Tunnel safety inspections involve tasks as part of a standard procedure. To diagnose causes of anomalies and evaluate tunnel safety, the reason why structural behavior deviates from designed behavior and the degree to which that deviation influences tunnel stability must be known. Appropriate repair and reinforcement should return those insufficiently safe sections to their initial function and performance (Wang, 2010b, 2013, 2015; Wang *et al.*, 2015).

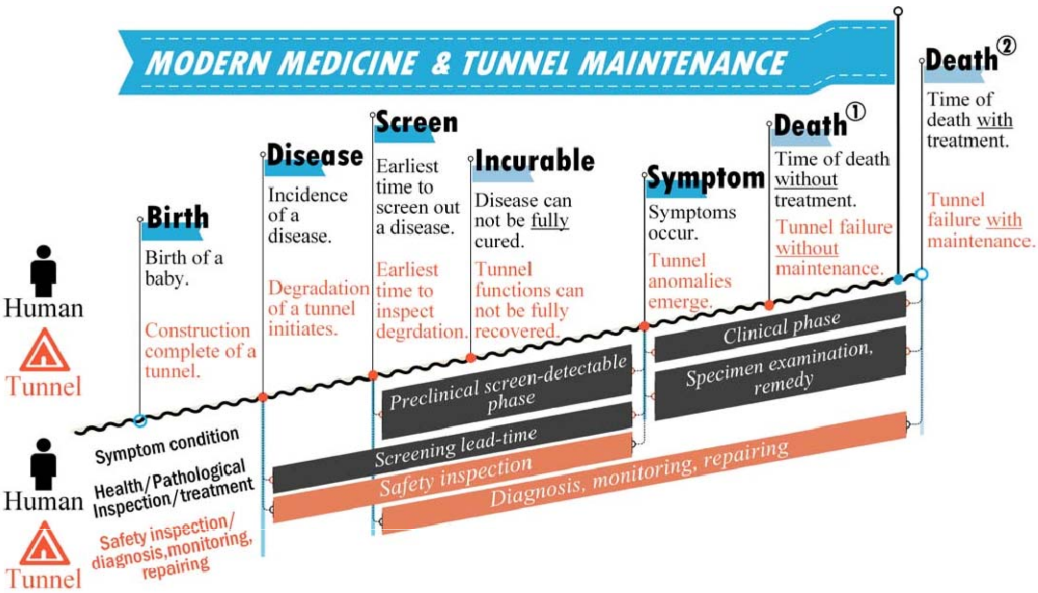

Figure 7 Relationship between modern medicine and tunnel maintenance

6. CONCLUSIONS

Unlike countries where modern tunneling methods originated, Taiwan has tough geologic conditions for the engineering of tunnels, causing many difficulties in construction. Therefore, the Rock Mass Classification of the Public Construction Commission (PCCR-system) (Public Construction Commission, Executive Yuan, 2000), which is a rock mass rating system that is tailored for Taiwan was established after about 30 years of use of the NATM for. However, the geological environment raises challenges not only in tunnel excavation, but also in tunnel maintenance. Tunnel lining cracks because it undergoes stresses that exceeds its material strength, whereas modern tunneling methods are intended for situations in which lining bears minute stresses. In Taiwan, a revolution in the concept, theory and technology of tunnel engineering is happening, promising a future of longer and better service lifetimes of tunnels. The most important lesson is that effective infrastructure maintenance strategies should
always adapt to local needs.

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