Analysis on The Causation and Classification of Common Damages of Highway Tunnel

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ABSTRACT: Highway tunnels involves various types of lining and various geological conditions. It is difficult to obtain sufficiently accurate information on geological conditions, and the existing tunnel design theories and the methods are not mature either. At the same time, the stresses of the tunnels during the stage of design, construction, operation and maintenance are also different. So it is difficult to determine the causes of the damages of tunnels because of the joint influence of the above factors. Through the overall investigations of various damages of highway tunnel and the analysis of the causes and patterns of the damages, tunnel damages have been classified. The causes of damages have been studied in respect of external forces, design, construction and the crack of materials for different types of highway tunnel problems. The experience can be used for reference and the similar damages an be avoided through precaution to improve the quality of design and construction. Additionally, the conditions of the structure can be evaluated scientifically on a theoretical basis. Effective measures can be taken to delay the process of damages and extend the lives of tunnels.

1 INTRODUCTION

With the fast development of tunnelling in China, many highway tunnel damages have appeared. In order to identify the causes of these damages and find out some solutions solving these problems through investigation of tunnel conditions, it needs to classify the damages of tunnel and analyze their causes. Nowadays, most researches focuses on the analysis of the causes of the tunnel damages and do not cover all the problems. Therefore, there are no solutions which can be used to all the situations. The paper attempts to analyze the reasons of these tunnel damages caused by external forces, design, construction and deterioration of materials for different types of highway tunnel damages.

2 CLASSIFICATION OF TUNNEL DAMAGES AND ANALYSIS OF CAUSES

2.1 Damages caused by the external force

Highway tunnel suffers from unpredictable external force in the process of construction and operation. External force comes from the changes of surrounding rock and supporting system. Under the influence of external force, the tunnel lining will be subject to active confinement which is pushed and passive confinement is pushed outwards. If there are gaps behind the lining under passive confinement, the surrounding rock behind the lining cannot provide the reaction to the lining. Therefore, the lining will be easily become a deformed structure. In addition, if uneven gaps are present, the loose contact between the lining and surrounding rock under active confinement and passive confinement will produce even stronger stress (Zheng , 2005).

The damages caused by external force include earth pressure relaxation, sudden collapse, bias voltage and creeping slide, landslide, expansibility of soil pressure, inadequacy of bearing capacity, water pressure, freezing pressure and so on.

2.1.1 Earth pressure relaxation

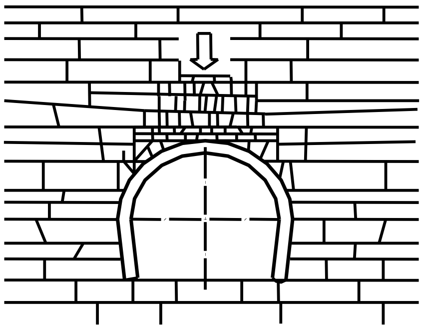


Fig. 1. Earth pressure relaxation on the crown of arch (after Guan, 2004)

When surrounding rock is flabby under natural conditions, it cannot withstand its own weight, so the lining will produce vertical resisting force. The crown of arch will probably have open crack in the vertical direction alongside the tunnel. It is shown in Fig. 1.

Earth pressure relaxation on the tunnel in vertical direction will lead to the arch of tunnel having to withstand the weight of surrounding rock. Therefore, the crown of arch will be the area under active pressure. Under this circumstance, open crack will be formed at the crown of tunnel in vertical direction. Meanwhile, there will be inclined crack and testudinate crack on both side of the arch (area under passive pressure).

2.1.2 Expansible earth pressure

Expansibility of earth pressure refers to surrounding rock of tunnel producing inward movement as a result of geological conditions; this extrusion will reduce the internal space of tunnel and lead to increase in pressure on the lining. From a narrow point of view, expansible pressure of soil is caused by expansion of weathered formation and formation with clay and mineral substance. Other people also think that expansible pressure is partly due to pressure of surrounding rock caused by the plastic deformation of formation. Yet the pressure of surrounding rock is difficult to be distinguished. Expansible pressure is likely to occur in geological conditions such as mud rock, shale and serpentine rock. As far as construction factors are concerned, tunnel damages easily happen when there is no inverted arch, lining is not thick enough, or when there are gaps at the back of lining at the crown of arch. Meanwhile, if water inflow does not take place in the construction stage but in the operation stage, swelling phenomena may happen.

2.1.3 Sudden collapse

If there are large cavitations at the top of tunnel, rock over the gap might be separated from the surrounding rock and fall because of certain reasons. The lining will probably be impacted under various circumstances. If the lining is not thick enough, it will be damaged and result in the downfall of rock and debris. Thus, concentrated load may happen and lead to the sudden collapse of tunnel.

After completion of tunnel, it has been shown in Fig. 2(a) that the flow of groundwater might lead to the sand/rock running down and large cavitations being formed at the top of tunnel. The rock at the top of the hole may separate from the surrounding rock and drop suddenly. It will probably hit the lining. If lining is not strong enough, it will be broken and fall into tunnel together with rock. If lining is strong enough, there might be two possibilities. One possibility is that the cavitations will fall down to the top of the lining, as shown in Fig. 2(b). The other possibility is that it may break the lining and fall into the tunnel as shown in Fig. 2(c).

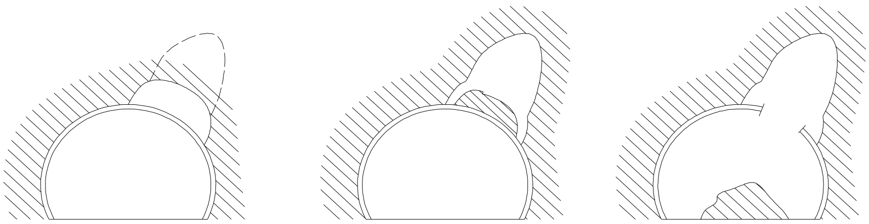
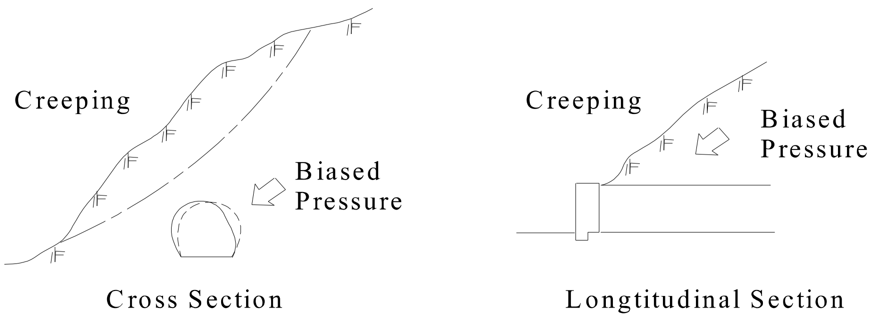

(a) (b) (c)

Fig. 2. Sudden collapse of surrounding rock (after Guan, 2004)

2.1.4 Biased pressure and creeping slide

Slope damage and slope instability induced lining and portal damages occur frequently. Biased pressure caused by slope creep directly act on tunnel lining. With the development of slope deformation, the pressure or the thrust from sliding slope may increase deformation and enlarge fractures on tunnel or even severe damage can happen. During sliding, greater deformation in slopes can occur, especially around the sliding zone. Shear stress and shear deformation will increase, which affect the tunnel severely.

As shown in Fig. 3a, ground pressures are different at both sides of a tunnel due to biased pressure. There is active pressure around one spandrel and passive pressure on the other. Longitudinal fracture can occur on the spandrel in the active zone. Compressed fractures can happen on the spandrel in the passive zone. Sometimes arch top can also be damaged by passive soil pressure. Such fractures can happen even under a very small biased pressure.



(a) (b)

Fig. 3.Ground creeping and effect caused by biased pressure (after Guan, 2004)

2.1.5 Landslide

With the development of creeping on slope surface, collapse and even landslides can occur in slopes. Cracks along longitudinal direction and ground deformation can occur. Especially when combined with rainfall, the damages can develop even further and landslide may happen (Xia & Zhao, 2006).

When sliding happens along the transverse direction of a tunnel, the sliding zone influences the tunnel most as shown in Fig. 4a. When the sliding zone and tunnel intersect, the part within the sliding block has a tendency to move while the other part will remain stable. The differential deformation can be large and complex damages can happen due to this difference. Major damages are fractures in lining. When the sliding zone is located above the tunnel as shown in Fig. 4b, damages are similar to that caused by biased pressure.

As shown in Fig. 4c, the sliding mass is the part that leaves a slope after sliding. When the tunnel is in a sliding mass, the deformations inside this mass are small. But at the position where the tunnel intersects the sliding mass, deformations are big. Damages are similar to that caused by biased pressure. With the growth of mass slope deformation, the tunnel may move outward and bend. Side walls may move differently along dilatation joints. Horizontal fractures are more likely to be found than vertical ones. Vertical fractures and deformation occur on sidewall near the mountain side. Cross section of the tunnel is raised upward in an inclined direction. The arch may be partly compressed.

Bending happens in the longitudinal direction and circumferential fractures will happen. Fractures also happen in the direction vertical to the fracture as mentioned. The portal may move outward.

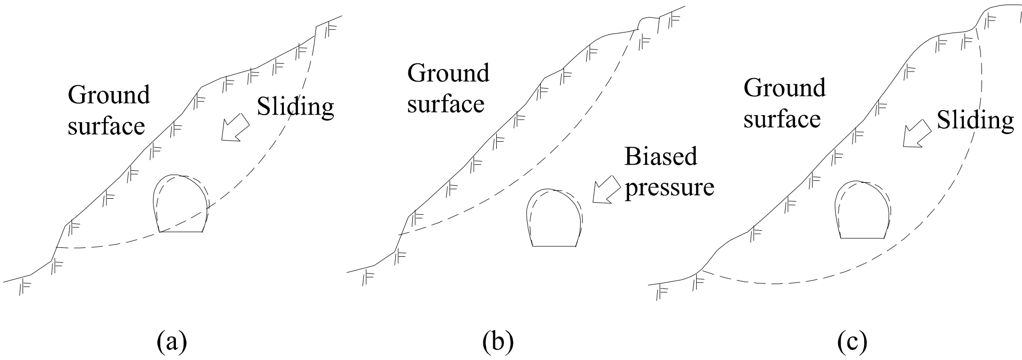


Fig. 4.Sliding happening in transverse direction (after Guan, 2004)

2.1.6 Deficiency in bearing capacity

Uneven settlements along and across tunnel lining may happen due to deficiency in bearing capacity(Liu & Zhu, 2004). Vertical fractures occur at intersection of tunnel sidewall and road surface when uneven vertical settlements expand to form circumferential fractures. Fractures at the top of arch are vertical and expand to circumferential fractures, which occurs at the intersection of settled and unsettled zone. Inclined fractures may happen due to uneven cross sectional settlements. Inclined fractures may happen on slope when bigger settlement happens at one side near valley (Fig. 5).

When uneven settlements happen at tunnel portal, the portal wall move forward and open fractures occur. This kind of damage will be more severe when foundations of tunnel at both side walls are inhomogeneous. When the tunnel portal is of gravity type or semi-gravity type, the front wall and tunnel lining often separates. In this situation, the front wall may rotate forward. Circumferential fractures may appear at the top of portal lining and open. Road surface also cracks or settle unevenly.

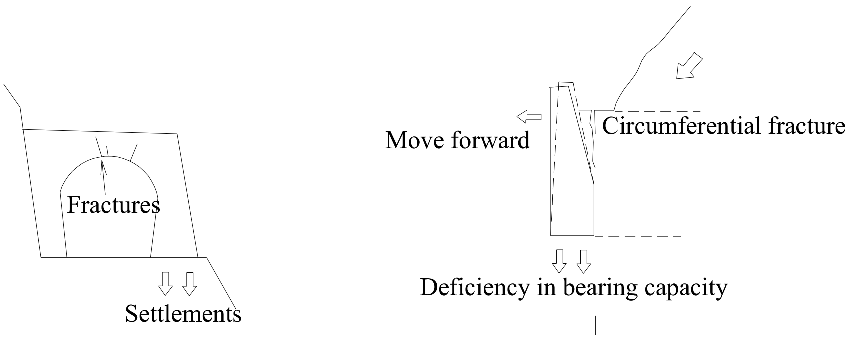


Fig. 5. Damages and fractures induced by deficiency in bearing capacity (after Guan, 2004)

2.2 Damages caused by design

In current construction practice of highway tunnel, the adjustment or changes of design parameter is merely based on the type of surrounding rock. In only a few cases, the parameters are founded to have been adjusted according to the available data in an interactive manner (Chen, 2004). Generally speaking, changes on the design are more likely to happen where there are landslide, deformation, fault, water inflow, cave, coal series stratum and so on. Therefore, it might be said that they are not real interactive design. It will be difficult to avoid the possibility of damages caused by the design deficiency.

2.2.1 Large deviation between inferred and actual geologic conditions

Geological and environmental conditions through which a tunnel passes are very complicated. If the location of tunnel is decided without reliable geological information, damages will occur in the process of construction or gradually happen after the tunnel is put into operation when tunnel passes complex construction or poor district such as ancient faulted rock mass, sliding zone, karsts area, underground river and so on.

Geological problems in the construction of tunnel include soft or broken surrounding rock, karsts, underground river, shifting sand, landslide, expansive surrounding rock, water inflow, rock accumulation, high stress, bias voltage, high water level, coal seam, gas, high ground temperature, uneven settlement of foundation, strong earthquake, rockburst, acidic water erosion, debris flow, etc. all these problems probably will lead to deformation, damage, leakage water or collapse of the supporting structure, especially the construction of tunnels is in deeply buried area, high water level, and karsts area.

2.2.2 Inappropriate choice of structural shape and cross-section shape

Straight wall cross section and inverted arch of the three/four/five class surrounding rock should not be used for highway tunnels. If surrounding rock of tunnel has a swelling layered structure or is easy to soften when it encounters water, especially when this kind of rock stratum is located in the side wall, a straight wall shape is not suitable because the top of the side wall of tunnel is likely to topple. The distance among side walls will shorten, side wall will crack horizontally and slide. If surrounding rocks easily soften when it encounters water, the bearing capacity of the foundation of side wall may be insufficient. Uneven settlement probably will happen and crack will occur in the side wall.

2.2.3 Supporting structure is not strong enough

If supporting structure is not strong enough, the secondary lining can suffer deformation, collapse or has to withstand a greater pressure from the surrounding rock. If the secondary lining is not safe enough, (for example, the secondary lining is still made of plain concrete although there are serious collapses in the construction of tunnel), plain concrete may crack after tunnels is in operation.

2.2.4 No inverted arch

There is no inverted arch in the process of construction. However, the pressure of soil might amplify for various reasons after completion of tunnels. Hence, some damages will occur in the area without inverted arch. These damages include: surface of highway is rough; the bottom of side wall squeezes out, ditch cracks; sand and clay flow into the tunnel, stratum settles.

2.2.5 Insufficiency of waterproof and drainage system

If waterproof and drainage systems are not well designed, water could not be well drained and if there is no heat insulation system, the bottom of side wall is likely to squeeze out. In addition, sand and clay may flow into the tunnel and stratum probably will settle. As far as surrounding rock with high expansion or softening characteristics is concerned, the foundation of tunnel might have such problems as water accumulating in the foundation of tunnel, poor drainage and mud pumping.

2.3 Damages caused by the construction

The problems occurs during the construction phase (Chen, 2004) such as unreasonable methods of excavation and support, inappropriate method for dealing with overbreak and underbreak, insufficient clearing up of the foundation surface of the tunnel, reinforcement of lining structure underprovided, concrete pouring and curing not following the standard, the strength of concrete and the thickness of lining not enough, severe honeycomb and scale, inadequate design and blockage of drainage system.

Damages caused during the construction phase are as follows:

(1) Local cavity caused by loose backfilling and holes at the arch or haunch forming the water logged space, which are the reasons for water leakage. It also prevents the surrounding rock from forming an integral part of the tunnel. Furthermore the holes behind the lining is the reason of surrounding rock flabby, increased soil pressure. This will lead to cracking of spandrel near arch springing line and side wall, crushing of arch roof, reduction in clear space of the tunnel.

(2) Cheating in carrying out the works and cutting down the quantities of materials, (like cheating on the quantity of anchors installed and quality of anchor bar not complying with design requirements). This makes initial supporting system inadequate and collapse may follows. If the method of dealing with landslip is not appropriate, damages such as voids will occur.

(3) Underbreak causing insufficient thickness of secondary lining. When the real thickness of lining is smaller than the design thickness of lining, damages like horizontal crack and peeling at the arch

roof may occur under the designed soil pressure.

(4) Substandard waterproof materials or displacement of the waterproof board causing leakage of water in tunnel.

(5) Substandard cement and aggregate or inappropriate mix proportion of concrete causing the strength of secondary lining concrete not reaching the design standard.

(6) For surrounding rock which softens easily when water is encountered, residue in the bottom of tunnel will not clear up when the inverted arch is poured. It will result in the mud pumping.

2.4 Damages caused by the deterioration of materials

Damages caused by the deterioration of materials can be divided into damages resulted from environmental and application conditions and damages caused by the type of materials used and construction conditions (Chen, 2004). Corresponding damages are described as follows:

2.4.1 Damages resulted from the environmental and application conditions

(1) Erosion of underground water. Under physical or chemical effect, the alkalinity of concrete is reduced, hydrated products will be decomposed or accumulated. Therefore, the integrity of concrete will be reduced, and the concrete may be become cracked or damaged.

(2) The influence of air mainly affects the carbonation of concrete. When carbon dioxide in the air interact with alkaline hydrated products such as calcium hydroxide, tricalcium silicate, dicalcium silicate and so on, carbonate will be formed and the alkalinity of concrete will be decreased. Thus, concrete probably can no longer protect the steel reinforcing bar. The erosion of steel reinforcing bar will be increased. Carbonation of concrete will also speed up the contractibility of concrete and lead to cracking and damage of concrete structure.

(3) The influence of frost damage. In the cold area, surrounding rock behind the lining may freeze and produce freezing force. In the freezing surrounding rocks, the volume of water will increase 20%-30%, and then damage in the form of crushing might happen around the top of arch.

(4) Alkali-aggregate reaction: there are damages caused by the alkali-aggregate reaction in the lining of tunnels.

(5) In a fire disaster resulted from the vehicle accident, concrete is likely to blow out and crack under high temperature. It will also reduce such mechanical behavior as intensity and coefficient of elasticity of concrete in the lining.

(6) Salt attack in tunnel results in salt water reacting with concrete of tunnel lining. This will cause erosion of steel reinforcing bar in the concrete and multi-aperture structure. Erosion of steel reinforcing bar will result in the expansion and spalling of concrete. In addition, crack and fall-block of concrete along the steel reinforcing bar probably will reduce the cross-section and bearing capacity of structure.

(7) Others: Carbon monoxide and nitride in the gas exhausted from the vehicle passing the tunnel react with water and may produce the strongly acidic water.

2.4.2 Damages resulted from the materials and the methods of construction

This kind of damage more occurs in the early stage of construction. If the material is not properly chosen, it will lead to the abnormal accumulation of cement. Main damage caused by the condition of construction is crack which is likely to occur when temperature stress and volume stress resulted from the hydration heat of cement are restricted by the surrounding rock.

3 CONCLUSION

When the tunnel has undergone long-term effects of the natural and operational environments, it will gradually be damaged. The functionality is reduced and the service life of tunnel will be shortened as well. Two benefits can be gained through the overall investigation on the various damages of highway tunnel and the research on the causes for the damages. The first one is that experience can be obtained and lessons learnt for design and construction of new tunnels. Some measures can be taken to prevent these damages and quality and design of the construction can be improved. Another benefit is that through systematic and overall diagnosis and scientific analyses of the tunnel conditions, an important and valuable theoretic basis can be established for the later repair and enhancement of tunnels. Some useful measures could be taken in advance to slow down the process of existing damages and prolong the service life of tunnel. Thus, great economic benefit will be gained.

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