Research into the characteristics of the Jin Jiguan Tunnel's geohazards and their control

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Abstract: The Jin Jiguan Tunnels on the Chuan-Zang Highway at Ya-an town were opened to traffic in January 1995. However, in 2001 the twin tunnels were found to be suffering from water penetration and deformation phenomena to varying degrees with heave and rock fracturing evident at several places within the tunnels. This had some detrimental effects on the normal use of the tunnels. Based on field investigation and other studies by the authors, it was concluded that three main factors contributed to the geohazards appearing in the tunnels. The first involved expansive soils present in the Guan-kou lithostratigraphical unit that expanded when they came into contact with water and caused arching and deformation of the road surface. The second factor stemmed from a combination of poor practice, inadequate equipment and uncontrolled working conditions during construction that caused fractures and construction crevices within the tunnel linings. Gypsum in the Guan-kou formation was dissolved by groundwater that seeped towards the tunnels and then recrystallized along the fractures and crevices caused by the construction. The third factor involved excessive groundwater flows associated with surface water infiltration. Surface water has penetrated along zones of faulted and fractured rocks and also bands of siltstones of higher permeability than the predominant mudstones. Based on the findings of this study, the authors proposed a series of remedial measures to deal with the geohazards and protect the Jin Jiguan Tunnels. These included blocking up in certain places and also drainage measures to control both the surface water and groundwater at the tunnels.

Résumé: Les deux tunnels de route Jinjiguan de la ville Yaan sur la route de Sichuan-Tibet ont été ouvert à la circulation en Janvier 1995. Mais à partir de 2001, le tunnel droit surgissait des différents niveaux de déformation et d'infiltration. Et il paraissait la fissure et la convexité locale. Par l'étude et l'analyse du prélevement sur place, unissant l'expérience de l'ancetre, on estime que la cause du tunnel est la raison géologique. C'est à dire que l'argile en gonflement dans la strate de l'équipe de Guankou rencontrant de l'eau surgissait le gonflement qui faisait la déformation. L'inféroflux qui a dissolu le platre dans la strate s'infiltrait au long des fissures circulaires de l'exécution des travaux la recristallisation. Le facteur induit est l'inféroflux. Sur la base de la caractère de la déformation de l'infiltration, on a proposé la mesure de traitement relative à la surface et au inféroflux autour du tunnel.

Keywords: deformation, fractures, geological hazards, highways, permeability, tunnels

INTRODUCTION

Known as the first gate opened to Tibet, the Jin Jiguan Tunnels on the Chuan-Zang Highway lie to the east of Ya-an town. The twin tunnels provide separate carriageways for each direction of traffic flow and each tunnel measures 7.0 m high by 9.5 m wide. The tunnel axes and inside walls are 40 m and 31 m apart respectively. The No 1 Tunnel carries traffic in the direction from Ya-an to Chengtu and measures 511m in length whereas the No 2 Tunnel for traffic in the opposite direction is 500m long. Construction of the tunnels comprises two layers of waterproof concrete separated by a water-repellent layer of concrete designated S4. The outer layer is 500 mm thick and provides the main bearing layer whereas the inner layer is 300 mm thick.

The groundwater drainage system consists of open spring channels and non-woven fabric channels. Groundwater flows through the drainage pipes along the side-walls of the tunnels and then enters the side channels within the tunnels. Conventional barrel drains are installed above the tunnel portals and interceptor drainage channels are provided on the slopes at the ground surface.

Although the tunnels were opened to traffic in January 1995, over the last 4 years several types of geological hazard have become evident in both tunnels with severe cracking of the concrete lining causing greatest concern. The majority of the cracks have formed transverse to the tunnel axes but several longitudinal cracks also exist. The cracks provide pathways for seepage of groundwater and have given rise to bulging and swelling of the tunnel walls. Accordingly, investigations were carried out to determine the cause of the cracking and to identify appropriate remedial treatments to deal with the problems which exist (see Figures 1 & 2).

DESCRIPTION OF THE WATER PENETRATION AND DEFORMATION

Crystallization caused by water penetration

Crystallization caused by water penetration occurs when groundwater dissolves gypsum from the surrounding strata and then precipitates it within the cracks in the concrete lining of the tunnels. This recrystallization problem exists to a limited extent at the portal area and external sections of the No 1 Tunnel and between chainages 2558 m and 2636 m at the No 2 Tunnel. Elsewhere in the No 2 Tunnel and on the surface of the second concrete lining of the No 1 Tunnel, crystallization of gypsum erodes the concrete surface. The depth of concrete lining affected by this erosion ranges up to 70 mm at No 1 Tunnel and up to 40 mm at No 2 Tunnel.

Tunnel deformation, cracking and bulging

Geological surveys of the tunnels identified the principal sections where the current height of 3 ground baselines deviates from the original design height. These are from chainages 2310 m to 2650 m along No 1 Tunnel and from 2285 m to 2485 m at No 2 Tunnel (see Figures 3 (a) & 4(a)). The deviation increases from the ends towards the middle of the tunnels with the maximum deviations from 2440 m to 2450 m at No 1 Tunnel and from 2385 m to 2465 m at No 2 Tunnel.

The surveys also identified the sections where the current height of 4 ground baselines on the top of ditches deviates from the design height. These are from chainages 2230 m to 2530 m along No 1 Tunnel and from 2265 m to 2465 m at No 2 Tunnel (see Figures 3(b) and 4(b)). Once again, the deviation increases from the ends towards the middle of the tunnels with the maximum deviations from 2440 m to 2450 m at No 1 Tunnel and from 2385 m to 2465 m at No 2 Tunnel.

In addition, severe deformation and stress cracking up to 100 mm wide is evident on several stretches of the surface of the road at No 1 Tunnel. The surface of the road at the No 2 Tunnel reveals a distinct bulging in the central section and a minor subsidence of the pavement in the vicinity of the portal.

The majority of the cracks appear transverse to the axes of the tunnel and appear more pronounced at levels higher than 3 m above the drain cover. Also, a noteworthy longitudinal stress crack with a slight twist occurs between chainages 2263 m and 2280 m of the left side-wall at No 2 Tunnel.

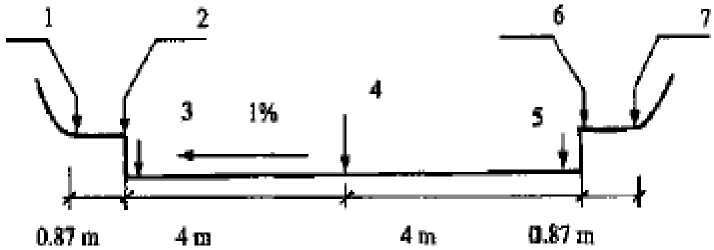


Figure 1. The layout of the measurement baseline of Jin Jiguan No 1 Tunnel.

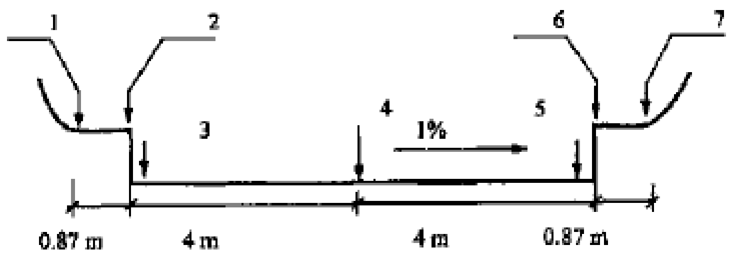
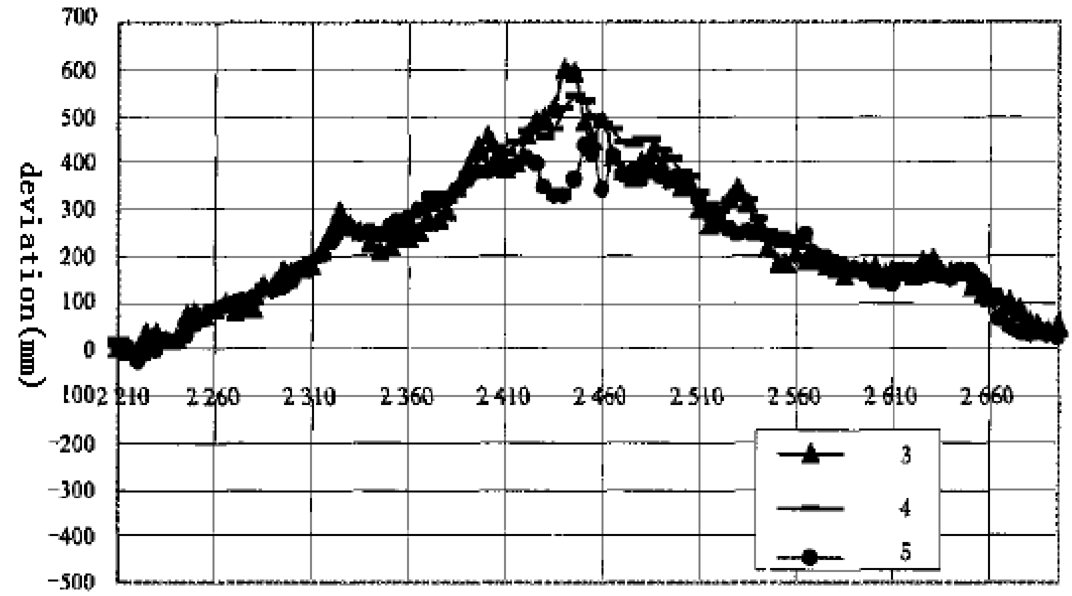
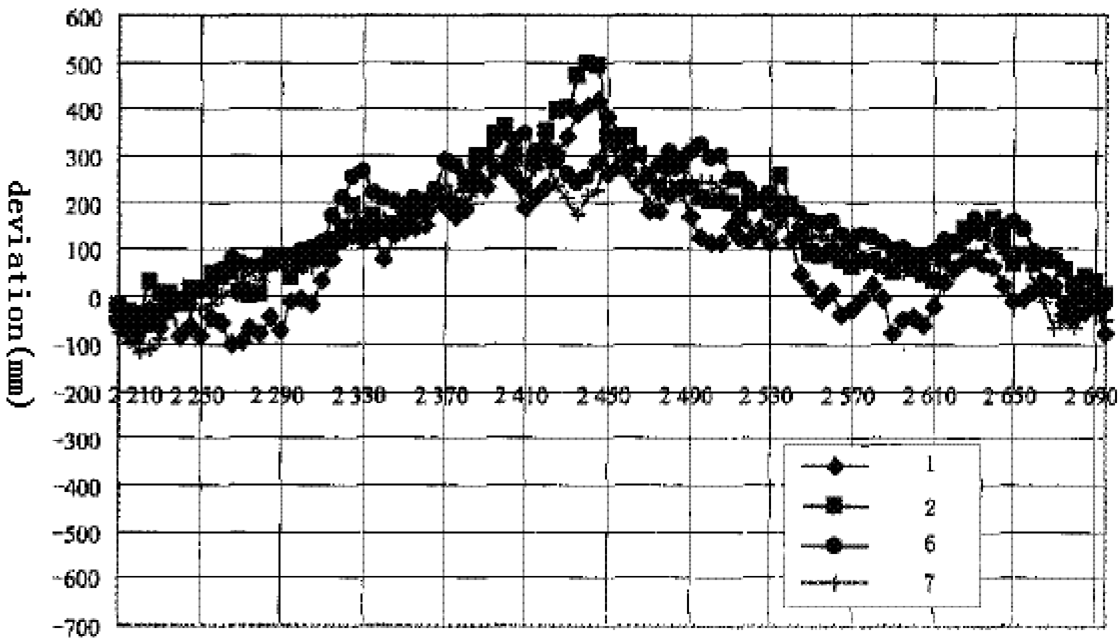


Figure 2. The layout of the measurement baseline of Jin Jiguan No 2 Tunnel.



Chainage of the tunnel (m)

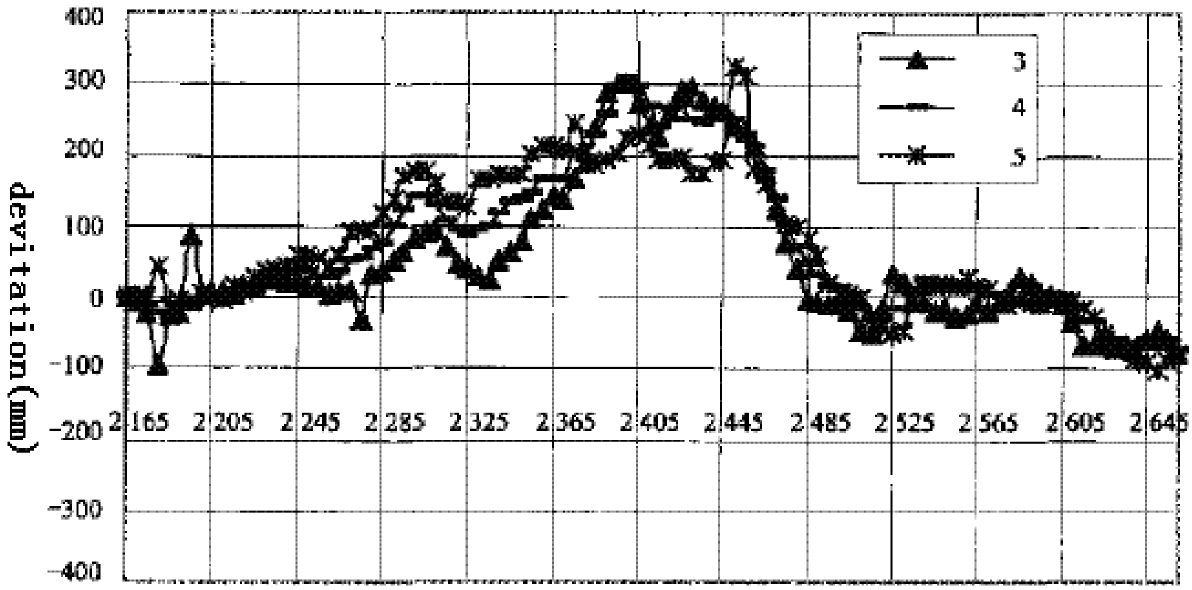
(a) The deviation of road surface between the current height and the design height (from 2210 m to 2695 m).



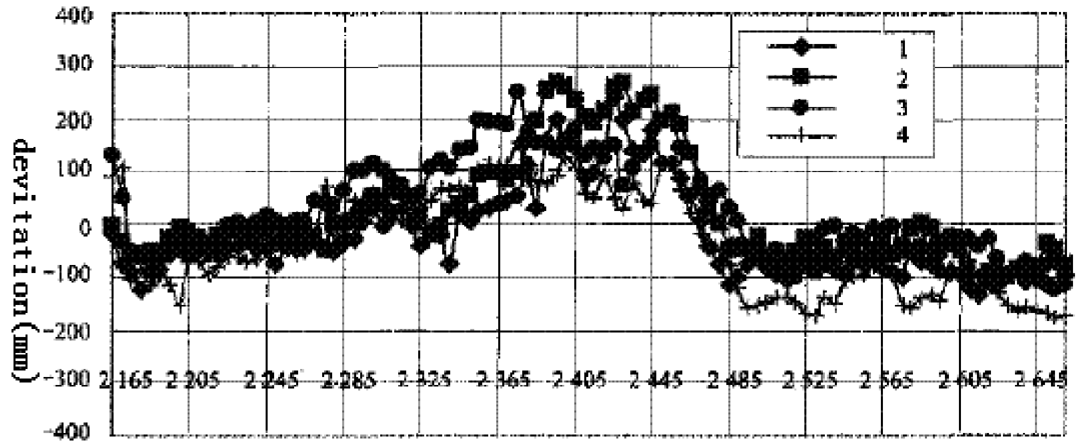
Chainage of the tunnel (m)

(b) The deviation of ditch top between the current height and the design height (from 2210 m to 2695 m).

Figure 3. The deviation between the current and designed heights at Jin Jiguan No 1 Tunnel.



Chainage of the tunnel (m)
(a) The deviation of road surface between the current height and design height (from 2165 m to 2662 m).



Chainage of the tunnel (m)
(b) The deviation of ditch top between current height and the design height (from 2165 m to 2662 m).

Figure 4. The deviation between the current and designed heights at Jin Jiguan No 2 Tunnel.

ANALYSIS OF GEOLOGICAL HAZARDS

Geological factors

The geological hazards are influenced by two geological factors. One is the geological structure and the other is the lithology.

First, the portal sections of the tunnels are composed of soil-rock whereas the tunnel body sections are of mud-limestone and mud-sandstone. The penetrability of the soil-rock is poor and forms a water insulation layer. The beds of mud-sandstone are relatively permeable and they allow the groundwater to penetrate through the rock mass to the tunnels. The external sections are composed of mixed lithologies but mainly mud-rock and mud-sandstone with occasional mud-limestone. Bedding varies between about 0.10 m and 0.50 m thick. Typically, all of the lithologies are soft and contain patches and veins of gypsum. The gypsum is prone to dissolution in the groundwater.

A significant fault cuts across the central part of the tunnels area with an associated zone of fractured rock ranging up to 25 m wide. The fault line intersects a prominent ridge at the ground surface above the tunnels and provides another pathway for groundwater to penetrate through the rock mass to the tunnels.

Secondly, the dominant clay mineral present in the mud-rock is montmorillonite. When in contact with water it expands until saturation. In addition, the gypsum dissolution and re-crystallization strongly influences the concrete integrity.

We concluded that the reason for the rounded appearance of the cracks in the side-walls may be due to the unbalanced floor load-bearing capacity of side-walls which has led to unbalanced sedimentation and the varying degree of bulging at the floor base-walls and created expansion cracks. Alternatively, the reason for the longitudinal cracking is that the groundwater penetrating the wall rock weakens the physical and mechanical character of the material leading to softened surfaces, higher wall-rock stress and concentrated stress to the secondary concrete lining.

Contrived factors

There are many round cracks that grow on top of the surface and pass through three walls. They range from 4 m to 12 m apart. Crack width varies from 0.5 mm to 5.0 mm and averages 4 mm. Because of certain restrictions on the size of the tunnel certain limitation applied to the level of investment and the type of equipment available during construction. In addition, much of the steel structure in the tunnels was built with pre-used steel and this has led to deformation in several places. Furthermore, the quality of the concrete influences the integrity and reliability of the tunnel construction.

Groundwater factor

Groundwater type and information

The main groundwater type of the tunnels is weathering crevice water and an analysis is presented in Table 1. It permeates through the rock mass along the mud-sandstone bands and fault-fractured zone. The pH is typically 8.4 and the style is alkaline with SO_4^{2-} - Na^+ Ca^{2+}. The main ions are derived from gypsum in the surrounding rock formations together with a lesser contribution from the mud-rock due to replacement of Na^+ by Ca^{2+} in the montmorillonite.

$$C_aSO_4 \bullet 2H_2O \rightarrow C_a^{2+} + SO_4^{2-} + 2H_2O \tag{1}$$

$$C_a^{2+} + 2N_a \rightarrow 2N_a^{+} + C_a \tag{2}$$

Both reactions produce water containing SO_4^{2-} - Na^+ Ca^{2+}, that can lead to alkaline expansion of concrete and influence the wear of the concrete lining and cause cracking. In order to protect the concrete the installation of an impermeable grout and water-repellent is required.

Table 1. The hydro-chemical composition of groundwater at the Jin Jiguan Tunnels.

ion	Ca^{2+}	$Na^{+}+K^{+}$	Mg^{2+}	SO_4^{2-}	Cl^{-1}	HCO_3^{-1}	CO_3^{2-}	CO^2
Content(mg. L^{-1})	436.87	346	85.12	1844.35	113.44	58.58	2.4	0

Concrete and sulfate

When calcium hydroxide in cement reacts with the calcium aluminium hydrate to form ettringite, the solid-volume increases by 94% causing the concrete to expand, crack and disjoint. This type of attack on the concrete can give rise to cracks of considerable size. Furthermore, while the ettringite grows, the interior's stress change also increases the expansion. So, one efficient way of controlling the expansion hazard is by controlling the solution alkalinity.

If the sulphate concentration of the liquor is too high, gypsum can also form as well as the ettringite. This formation of gypsum gives an increase in solid-volume of 124 %, and also causes the concrete to expand and craze. Additionally, the waste of C-H that is the steady existent base for the hydrate minerals can reduce the mechanical integrity and weaken the concrete.

3.3 Groundwater and montmorillonite

Montmorillonite is a clay mineral perhaps better known as bentonite that can expand when in contact with water. During the course of hydrating, the distance of the crystal lattice will extend, montmorillonite will expand and produce the small grains that can cause the system fabric change, the volume increases 20 fold and the largest reserve volume to water increases 15 times. The montmorillonite exists as a colloid and suspension solid and can changes its ion with others.

If more water penetrates into the distinct where a little water has penetrated and the expansive mud is not saturated the volume can expand ulteriorly and makes the road-bed plump up. While the distinct where much water has penetrated and the mud is saturation already, the loss of gypsum and mud-rock and mud sandstone will be greater.

CONCLUSIONS

Based on the analytical results, we conclude that the main reason for the geological hazards is lack of familiarity with the geological condition during construction of the tunnels. In relation to the hazards, remedial treatments are required otherwise the persistent effects of the groundwater and expansive mud will exacerbate the current situation.

Considering the characteristics and formation causes of the hazards, we consider that the key is rational control of groundwater. The following measures should apply:

(1) Installation of water-drains to intercept the surface-water and prevent it from penetrating through the weathering crevices and sandstone bands into underground.

(2) Installation of waterproof measures to prevent the groundwater penetrating and pooling in fault fractured zone and seeping towards the tunnels.

(3) Introduction of blocking and jamming measures to prevent groundwater seeping towards the roadbed and wall-base.
(4) Removal and replacement of expansive soils in areas where the road surface has plumped up.

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