ELSEVIER

Journal of Hazardous Materials 142 (2007) 381–388

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Environmental hazard analysis and effective remediation of highway seepage

Renmao Yuan[a,b], Y.S. Yang[c,*], X. Qiu[d], F.S. Ma[b]

[a] *Institute of Geology, State Seismology Bureau, Beijing 100029, China*
[b] *Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, CAS, Beijing 100029, PR China*
[c] *Cardiff University, School of Earth Ocean & Planetary Sciences, Cardiff CF10 3YE, UK*
[d] *South Engineering Geophysical Technology Exploration General Company of Guangdong Province, Guangzhou 510080, PR China*

Received 9 May 2006; received in revised form 10 August 2006; accepted 14 August 2006
Available online 18 August 2006

Abstract

Risk assessment and minimisation of environmental hazards are critical issues to consider in the geotechnical engineering projects. A case of highway pavement seepage induced by groundwater, at a locality along the section of Hua-Qing Highway of Guangdong Province, China, is presented for environmental hazard analysis and effective remediation. The environmental hazard analyses were based on in situ hydrogeologic investigation, rock–soil testing and integrated environmental understanding. The analyses indicate that the highway seepage was caused by elevation of groundwater hydraulic pressure in low permeable strata near the highway pavement, which was controlled by landform, hydrology, weather and road structure. The risk source of groundwater 'flooding' was the groundwater and surface water in the ring-like valley around Fenshui Village. A blind-ditch system for effective remediation of the pavement seepage hazard was proposed and successfully implemented by declining groundwater table near the highway based on the comprehensive assessment of various conditions. This geotechnical accident shows that the role of groundwater is an essential factor to consider in the geotechnical and environmental engineering studies and multidisciplinary effort for risk assessment of environmental hazards is important under current global climate change condition.

Keywords: Pavement seepage; Environmental hazard; Remediation; Groundwater; Highway

1. Introduction

Groundwater is always a problem for geotechnical engineers and comprehensive analyses and appropriate treatments related to water–soil–rock system are often required. Whilst the risk assessment for geotechnical hazards with little groundwater involvement is common [1–3], majority of the geotechnical engineering issues is frequently influenced by groundwater [4–11]. However, groundwater is often overlooked by geotechnical engineers as it is not directly exposed. Hydrogeology and related environmental issues are important to consider in such researches. The role of groundwater in geotechnical aspects has been well elaborated in some case studies [4–8]. Some advanced techniques, e.g. numerical modelling and GIS, were employed to quantitatively assess the risk of environmental hazards induced by groundwater in the landslides [9], spatial strata characterisation [10] and underground remediation scheme [11]. In the design and construction of highways, geotechnical engineers must consider water related issues, e.g. permeability, seepage and flow. Although there are many factors affecting the service life of highway, including quality of construction, ambient environmental factors and so on, there is no doubt that water is a major concern, especially in the rainy areas. Some researches have shown that moisture within the asphalt layer and the underlying soil can cause the bond between the asphalt cement and pavement aggregates to fail, resulting in asphalt 'stripping', which greatly decreases the service life of the asphalt layer, e.g. the work reported by Scullion et al. [12] and Maser [13]. Increase in the water content of the sub-asphalt soils can decrease the soil stiffness and cause greater pavement deflections [14]. There has been a great progress in road construction in recent years in China, due to the social and economic development. However, the service life of highway is always lower than designed life because of pavement failure mainly induced by seepage in

---

[*] Corresponding author. Tel.: +44 29 2087 0232; fax: +44 29 2087 4326.
E-mail address: YangY6@cardiff.ac.uk (Y.S. Yang).

0304-3894/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2006.08.025

this country. The service life of concrete pavement is about 8–10 years and asphalt pavement about 5–6 years [15]. There has been so much being spent to remedy the failure that the development of highway in China was affected seriously.

Many studies provided insight into the seepage mechanism and helped identify key parameters affecting seepage. For example, research of Snaith and Bell [16], Hoare [17] and Dawson [18] suggested possible mechanisms for the occurrence of pumping. Alobaidi and Hoare [19] tried to analyse the factors affecting the pumping at the subgrade–subbase interface of highway pavements by laboratory method. Zhou [20] and Gu and Liu [21] studied influence and prevent technology for water damage of the asphalt pavement. Some remedial methods have been proposed for pavement seepage problem [20–22]. However, much attention was paid to the design of pavement structure and drainage used for surface water, little to the hydrogeology features, which can be the major problem for seepage.

This paper presents a study on environmental hazard risk analysis of the highway pavement seepage and proposes an effective remediation methodology for sustainable engineering quality based on the insight of hydrogeologic and environmental characteristics at a highway area. It was in a locality along the section from K40 + 600 to K41 + 1000 of Huadu-Qingyuan (Hua-Qing) highway of Guangdong Province, China. Hua-Qing highway spans 23.5 km and lies in the north of Zhujiang Delta, Guangdong Province (Fig. 1), which was reconstructed as 107# high standard road. The highway is in the south subtropics with coastal monsoon climate, where heavy rainfalls and high temperature prevail.

Hua-Qing highway began to be constructed in July 1997, finished and opened to traffic in 2 years. During the design and construction, engineers considered the conditions of heavy traffic, high temperature and great rain capacity, high standard materials, such as the asphalt concrete (AC) and stone mastic asphalt (SMA), were used. The highway pavement structure was designed and constructed by AC subbases and SMA layer. The pavement drainage system was constructed for surface water drainage requirement [23,24]. The highway pavement seepage from groundwater was not expected because of good surface drain design. The overall engineering design and construction was lack of hydrogeological and other environmental considerations.

After few months' operation of the highway, problem of water seepage occurred. It was thought as a minor drainage incident; however, it persisted for some time afterwards. A preliminary investigation came into force then and in situ drilling tests were carried out as well in September 2004. The borehole cores, obtained during the investigation, revealed the quality of asphalt pavement along the section from K40 + 600 to K41 + 1000 of Hua-Qing highway, and the seepage phenomenon was found in the boreholes. Groundwater slowly percolated out from the cement stable layer, and the accumulated water thickness reached about 5 cm in 3 h during the drilling. It just coincided with continuous rainfalls during later stage of the in situ drilling test, and the seepage phenomena and gush mud were found in the pavements of this section at the same time. The seepage increased with the rainfalls; it resulted in completely muddy pavement. Several days after the rains, the seepage and

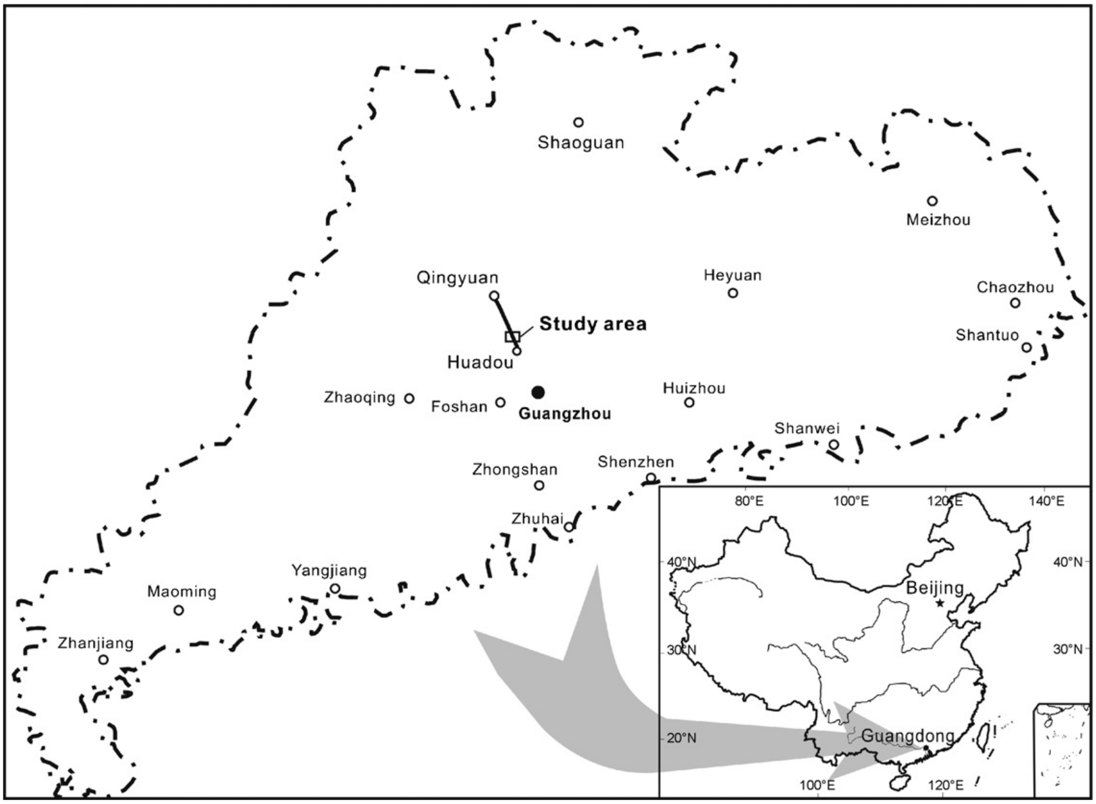

Fig. 1. Map showing location of the study area.

gush mud still exist. Due to the seepage and gush mud for a long time, the structure of the pavement was destructed. The normal operation of the highway was seriously affected; therefore, it was necessary and timely to research the origin of seepage and gush mud and propose an effective remediation method for such an environmental hazard.

Based on the in situ investigation and field observation, a series of systematic analyses for the environmental hazard of the highway pavement seepage on geomorphic, geologic and hydrogeologic conditions was carried out and an effective remediation was implemented for better engineering quality of the highway. It turned out to be a successful and timely treatment of the environmental hazard.

2. Geomorphic and hydrogeological settings

2.1. Landform and hydrogeology

The study area is located in Fenshui Village, Huadu City, Guangdong Province (Fig. 2). The hills around the village with elevation of between 200 and 300 m, belongs to the hilly landform. The hilly hypsography varies in elevation of 50–100 m in this area.

Fenshui Village, surrounded by hills with luxuriant vegetations, is evergreen in the year around. Groundwater is well recharged with good storage in the study area. The incident road section, in the west of the Village, is situated at the bottom of the "ring-like" valley. To the east of the highway, the topography is flat and open and steep to the West. From a hydrogeological point of view, the area to the west of the highway (upper gradient) possesses a large catchment area; groundwater and surface water are captured into the bottom of valley, where the highway is located.

According to the survey, the mountain stream at the east of Fenshui Village keeps a steady flow all year around, even in the dry season (October–March). A well in the village is in depth of some 7.5 m below ground level (mbgl) and the aquifer is gravelly clay and sands. The static water level is about 3.25 mbgl and water depth about 4.25 m.

2.2. Geology

In order to observe the subsoil conditions and obtain representative samples, six investigation boreholes were drilled along the seepage section of the highway (Fig. 2). The geotechnical profile was divided into four layers from the top to bottom of the boreholes (Fig. 3). Details are described as below:

(1) Made ground layer (Q^{ml}): the thickness of the made ground is about 1.4–2.8 m, not available in the borehole ZK4. This layer is slightly compact and wet, with yellowish brown colour, consisting of gravel clay.

(2) Alluvium layer (Q^{al}): it is only distributed in ZK1, ZK2, ZK3, not seen in other boreholes. The alluvium layer consists of silty clay with some gravel and humus matter with putrefactive odour and grayish black colour, saturated and in elastic and mucose state, with fine texture. In borehole ZK3, this layer consists of silty soil with colour of light grayish

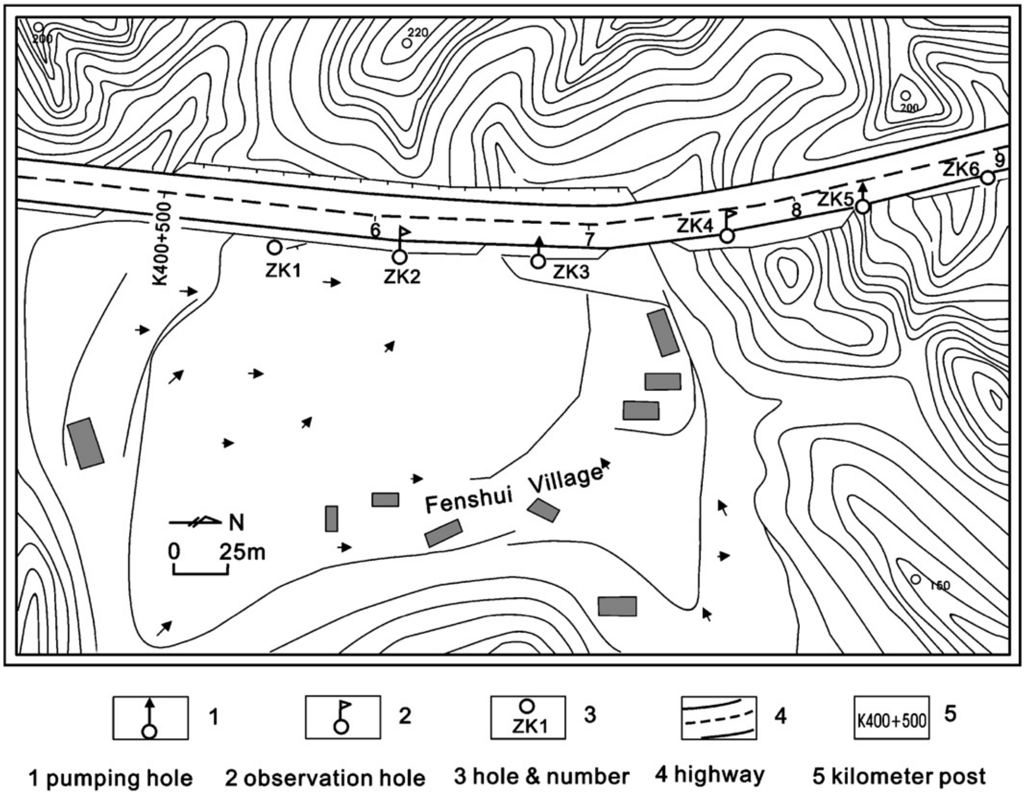

Fig. 2. The landform, locality and investigation of the highway seepage.

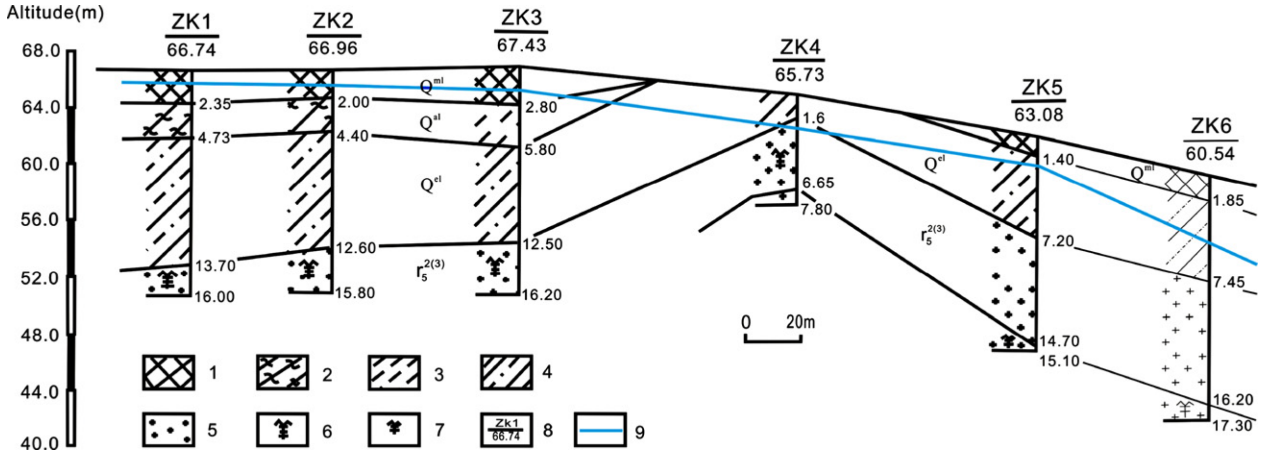

Fig. 3. Cross-section of the engineering geology obtained from the field investigation: 1, made ground; 2, mucky clay; 3, silty soil; 4, gravel clay; 5, granite; 6, well-weathered; 7, medium-weathered; 8, no. of borehole and height; 9, groundwater table.

yellow, very wet, slightly compact. It can be pinched into powder by fingers if dry.

(3) Eluvium (Q^{el}): it is widely distributed, with thickness of 1.6–9.0 m. It is mainly composed of yellowish brown gravel clay with rough texture. The eluvium is humid and plastic materials consist of weathering residual of the coarse-grained granite and approximately 25–45% fine quartz gravels. The feldspar and black mineral in it were weathered into clay.

(4) Bedrock ($r_5^{2(3)}$): this layer is widely spread, with depth of 1.6–13.7 mbgl. The penetrated thickness is 2.3–9.85 m in the boreholes. According to the degree of weathering, this bedrock layer can be sub-divided into the well-weathered zone and medium weathered zone. The samples of the well-weathered zone with colour of yellowish brown were transformed into soil and local rock fragments in them were fragile. The samples of the medium weathered zone with grayish red have many joints and fissures; the joint planes with a little secondary mineral have been contaminated by iron composition.

2.3. Groundwater

The depth of water table was measured carefully during drilling the boreholes. The results are listed in Table 1. ZK1, ZK2 and ZK3 have not been sunk to the medium weathered zone of granite. From the depth (mbgl) of water table (Fig. 4) and corresponding elevations in meter above datum (mAD) (Table 1), it is known that the initial water strikes are lower than those of the rested water strikes, which indicates that there is no perched water body in this area and the water is not confined in the soil and well-weathered granite layers. The other boreholes (ZK4–ZK6) were drilled to the medium weathered granite. The rested water strikes in these bores are same as initial water strikes, and are higher than the upper bound of the weathered rock, which therefore is confined in the weathered granite. The conclusion can be drawn that there are two types of groundwater: the phreatic pore water in the soil and well-weathered granite layers, and the confined water in the cracks and fissures of the medium weathered granite.

The permeability test (Table 2) and pumping test (Table 3) were carried out in the investigation, the permeability of the soil layer and the well-weathered granite are very small, which can be described as aquitard layers. The water content in these layers is very small with average specific outflow of $q = 1.37\ \mathrm{m^3/d\,m}$ for the boreholes. The monitored groundwater table is shallow (Table 4 and Fig. 5), about 0.9–2.07 mbgl. Moreover, the water table intends to decline gradually during dry seasons. The elevation of the phreatic groundwater table declines from ZK1 to ZK2 and then to ZK3, which indicates the direction of the phreatic

Table 1
The groundwater level revealed during drilling (mAD)

	Boreholes no.					
	ZK1	ZK2	ZK3	ZK4	ZK5	ZK6
Initial water strike	65.74	65.73	65.48	63.86	61.19	58.56
Final water strike	64.54	64.21	64.27	63.34	60.96	55.82
Rested water table	65.87	65.86	65.65	63.33	60.97	55.78

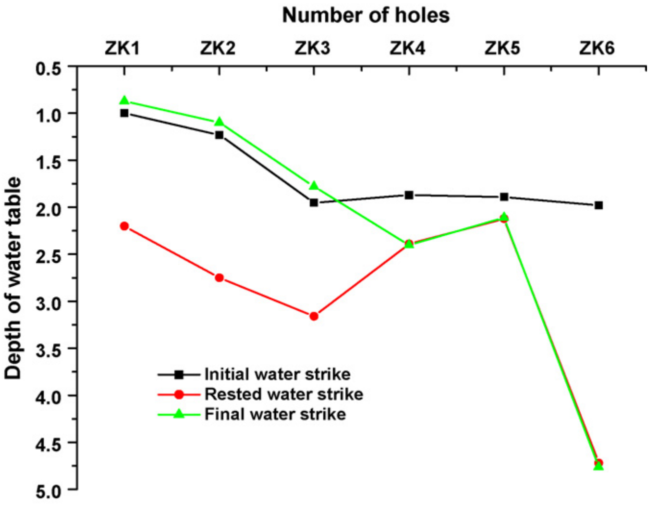

Fig. 4. Diagram showing the profiles of groundwater level (mbgl).

Table 2
The permeability results of the penetrative experiments in laboratory

Soil layers	Sample depth (m)	Permeability/K_{20}		Classification of permeability
		m/s	m/d	
Made ground	0.65–0.85	1.66×10^{-7}	0.143	Low permeable (aquitard)
Silty clay	2.50–2.70	1.43×10^{-9}	0.0012	Extremely low permeable (aquiclude)
Gravel clay	3.20–3.40	4.78×10^{-8}	0.041	Low permeable
	5.50–5.70	5.69×10^{-8}	0.049	Low permeable
	6.90–7.10	5.93×10^{-7}	0.512	Low permeable

Table 3
The results of the small-scale pumping tests in the field

Boreholes	Aquifer thickness (m)	Drawdown (m)	Discharge[a] (m^3/d)	Permeability (m/d)	Observation well		
					Boreholes	Distance to pumping borehole (m)	Drawdown (m)
ZK3	14.15	3.89	19.36	0.473	ZK2	66.65	0.16
ZK5	0.40	3.43	82.50	20.24	ZK4	85.20	0.04

[a] The screening section of ZK3 is gravel clay and well-weathered granite and that of ZK5 is medium weathered granite.

groundwater flow. By incorporating these into the geomorphology characteristics and the testing results, it is found that the “ring-like” valley around Fenshui Village is the recharge area of phreatic groundwater in the study region and the direction of phreatic groundwater flow is north-oriented along the highway. The drainage condition of phreatic groundwater is very poor because of the low permeability of the soil and weathered bedrock layers.

The permeability of the well-weathered granite is relatively large in the study area (Table 3). It is a water rich layer with specific flow of $q = 206.25\ m^3/d\,m$. The monitored groundwater head in this layer is about 2.1–4.8 m with some fluctuation (Table 4 and Fig. 5), which is lower than the phreatic ground water level. The groundwater pressure of the confined water in the fissured granite is 43.0–125.8 kN. The groundwater recharge comes from percolation of rainfall through upper soil and lateral flow of the aquifer.

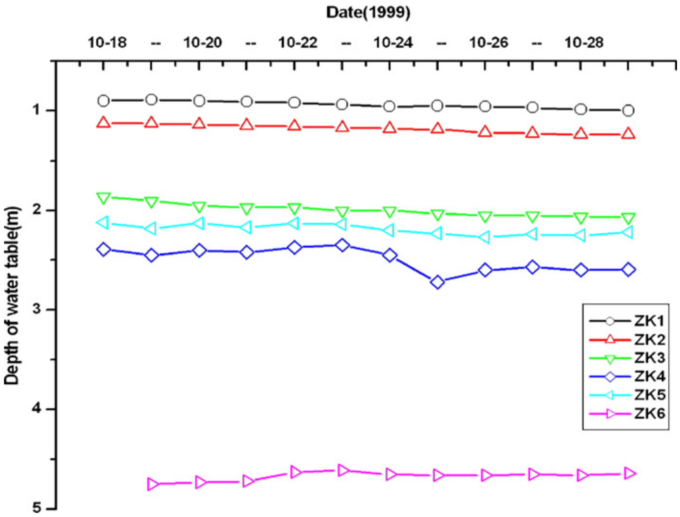

Fig. 5. Groundwater hydrographs of the investigation boreholes (mbgl).

3. Environmental hazard analyses of seepage

In order to investigate the origin of the pavement seepage, the environmental hazard analysis method was introduced in this project. The geoenvironmental conditions and the highway structure were considered as an integrated system.

3.1. Geotechnical conditions

As discussed previously, the well-weathered granite and the overlying soil layer are low permeable aquitard in the study area. The medium weathered granite is fissured, confined and groundwater-rich strata. The monitored head of the groundwater is 2.12 m in this thick but low-permeable confined layer. The impact of the confined water on the highway looks relatively limited. Therefore, if the geotechnical condition is considered alone, groundwater cannot cause problem in terms of hydrogeology, directly to the highway pavement.

3.2. Geomorphology conditions

The section of highway seepage is situated at the bottom of the ring-like valley. The catchment area of the valley is very big; groundwater and surface water with abundant recharge are captured to the bottom of the valley. The hills and valleys with the luxuriant vegetation are green in the whole year. All these conditions are favourable to accumulating and holding ground and surface water. The mountain stream at the east of Fenshui Village thus flows in whole year; though the wells in the village were drilled to the low permeable layer (gravel-clay), there is good amount of water in them.

Table 4
The elevations of groundwater level observation (mAD) in the monitoring boreholes in 1999

Boreholes	Date											
	18 October	19 October	20 October	21 October	22 October	23 October	24 October	25 October	26 October	27 October	28 October	29 October
ZK1[a]	65.84	65.85	65.84	65.83	65.82	65.80	65.78	65.79	65.78	65.77	65.75	65.74
ZK2[a]	65.83	65.83	65.82	65.81	65.80	65.79	65.78	65.77	65.74	65.73	65.72	65.72
ZK3[a]	65.57	65.53	65.48	65.46	65.46	65.43	65.43	65.40	65.38	65.38	65.37	65.36
ZK4[b]	63.34	63.28	63.33	63.31	63.36	63.38	63.28	63.01	63.13	63.16	63.13	63.14
ZK5[b]	60.96	60.90	60.95	60.91	60.95	60.94	60.88	60.85	60.81	60.84	60.83	60.86
ZK6[b]		55.79	55.81	55.82	55.91	55.93	55.89	55.88	55.88	55.89	55.88	55.90

[a] Phreatic groundwater level.
[b] Confined head.

Another feature of the ring-like valley is drainage difficulty. Groundwater and surface water are accumulated at bottom of the ring-like valley for long time but hard to find their way to be discharged. Some muddy clay found in the boreholes ZK1 and ZK2 also indicates that much surface water was accumulated at the bottom of the valley with drainage difficulty. All these topographical characteristics are prone to the highway seepage from the ring-like valley in the study area.

3.3. Climate and hydrogeology

The study area is situated in the subtropics climate region, with abundant rainfall. The precipitation is 1800–2200 mm/a with the majority in April–September, which is greater than evaporation of 1629 mm/a.

As confined groundwater in the fissured intermediate-weathered granite system was considered having little influence on the highway and the drainage system was designed mainly to drain surface water. It is inferred that the seepage of highway came from the phreatic groundwater in the soil layers. During the dry seasons, the depth of water table is approximately 0.9–2.1 mbgl. Considering the shallowest section of water table (0.9 m), the water table also is under the cement stabilised base of the highway nearby. The cement stabilised base is composed of detritus with 4–6% cement, with very coarse granularity. In general, the capillary height of groundwater is not likely over 30 cm under such condition, so the influence of the phreatic groundwater on the highway pavement should be minor even with capillarity. However, due to excessive rainfall in this area and drainage difficulty of the ring-like valley in rainy season, surface water and groundwater are collected and accumulated in the valley. Groundwater table rises nearly to ground level with abundant surface water infiltrating into ground. Because the bottom elevation of the valley and the highway is almost at same level, the phreatic groundwater level reaches the highway pavement. Therefore, the seepage phenomena happened in the sections where the pitch layer is not uniform and/or with fissures available. As the soil and well-weathered granite are aquitard, they are not saturated during short-term rainfalls; groundwater table will not be high enough to the highway and the seepage will not happen. Hence the prerequisite for pavement seepage is continuous raining climate.

Because of low permeability of the soil and drainage difficulty of the ring-like valley, the groundwater table declines slowly. Once the groundwater table rises to the height of pavement, the soil will keep saturated and the water table will remain for a long time even after rainfalls. The pavement seepage can continue.

3.4. Highway structure

The structure of the highway pavement was designed into three layers being composed of 6 cm AC-25II subbase, 6 cm AC-25I medium layer and 4 cm SMA-16 road crust according to the heavy traffic condition, high temperature and heavy rain capacity. According to the engineering studies of the characteristics and mechanism of SMA, a good mixture design of the SMA surface for this local environmental condition was made

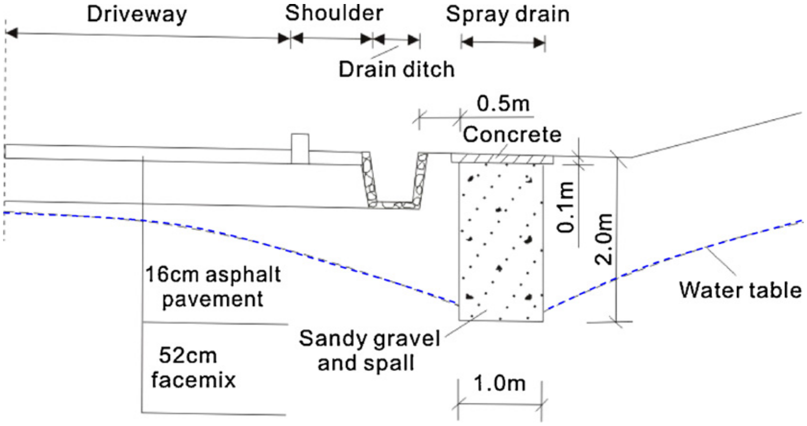

Fig. 6. Design of the blind-ditch system for the effective remediation.

[24]. The asphalt pavement is waterproof in structure, but it is not absolutely waterproof. Under adverse environmental conditions, surface water still can infiltrate into the pavement and groundwater still can seepage out pavement under water pressure via cracks or other paths.

The water-proof drains were constructed with concrete and slabstone along either sides of highway, which can only capture the surface water runoff. As a matter of fact, the groundwater table was elevated continuously with recharge, the pavement and drains formed a confined bed for groundwater, which led to groundwater seepage out from the highway pavement under water pressure.

4. Effective remediation

The close pavement elevation to that of the valley bottom, the cracks and fractures of the highway pavement and abundant recharge from rainfall provided essential environmental conditions for the seepage problem in this case. When groundwater table or confined head rises to or over the pavement, seepage will occur under hydraulic pressure. As such seepage is directly connected with groundwater and characteristics of subbase soil, it is key point in remediation to cut off the hydraulic connection between groundwater and the subsoil of near and underneath the highway. For surface water, the drainage system has been constructed in either sides of the highway and can be drained properly. Therefore, the main aim of remediation method was to effectively decline groundwater table at the site.

There are two ways to achieve this: to raise the elevation of the highway base, or to directly decline the groundwater table. It was not a feasible and economic solution to raise the highway height by raising the base in this study area, because many constructions have been there for many years and cost too much for relocation.

Therefore, drawdown of groundwater table was adopted as the best remediation option to solve this environmental hazard in this project. With consideration of all factors above, a blind-ditch system was proposed in this highway section for remediation of the pavement seepage by draining groundwater away. Detailed design of the system is illustrated in Fig. 6. Along the K40 + 500–K41 + 100 section, the blind ditches were designed and constructed at the outsides of the highway drain, 0.5 m apart. The dimension is 2.0 m deep, 1.0 m wide, and the longitudinal gradient of the ditches is greater than 2% to secure the proper drainage. The blind ditches were filled by scree and gravels and covered by 10 cm thick concrete pre-constructed boards on the top, which can prevent surface water flows in directly. These designed blind ditches can discharge groundwater straight away to the lower gradient areas and change original hydraulic regime so that the drain system can effectively prevent the highway seepage. As a result, an artificial depression of water table was formed near the highway permanently. Therefore, even in the raining seasons, groundwater table in the upper gradient side cannot rise to the elevation to produce highway seepage. The blind-ditch system keeps the subgrade of highway dry by drawdown of groundwater table and cut-off the water flowing from the fissures of hillslope in the upper catchments to the highway subgrade. As the open drains have been designed and constructed outside of the road shoulders, there was no influence on road operation for normal traffics during the remedial construction. The geotechnical problem was solved by such a simple and practical engineering action with small workload and low cost on the basis of investigation and understanding of the hydrological, hydrogeological and other conditions. The environmental hazard caused by the highway seepage was hence diminished.

5. Conclusions

The problems in engineering constructions caused by groundwater are not rare, such as the case presented here. It is a good and practical lesson to learn from the environmental hazard caused by the highway seepage and its effective remediation. It is significant to pay more attention to some situations looking-like simple and straightforward. Some conclusions can be drawn for further environmental and geotechnical engineering researches.

(1) The role of hydrogeology and groundwater is sometimes a key factor in the geotechnical and environmental engineering studies. The hydrogeological characteristics, e.g. groundwater movement, storativity and its interrelationships with precipitation and surface water, need to be better understood for the cases like this highway seepage.

(2) Multidisciplinary effort for geotechnical engineering research is important with the development of modern engineering concept; it is particularly the case for current environmental situation, e.g. global climate change.
(3) In situ investigation, risk assessment and remediation strategy of environmental hazards and engineering design should aim at sustainable development of the social, environmental and economical aspects, particularly in the developing countries.

Acknowledgement

This study was supported by the "973" Special Funds for Major State Research Projects under grant no. 2002CB412702. We also acknowledge the support of the Royal Society International Joint Project.

References

[1] A.G. Benardos, D.C. Kaliampakos, A methodology for assessing geotechnical hazards for TBM tunnelling—illustrated by the Athens Metro, Greece, Int. J. Rock Mech. Mining Sci. 41 (2004) 987–999.

[2] M.L. Lin, C.C. Tung, A GIS-based potential analysis of the landslides induced by the Chi-Chi earthquake, Eng. Geol. 71 (2004) 63–77.

[3] M. Floyd, M.A. Czerewko, J.C. Cripps, D.A. Spears, Pyrite oxidation in Lower Lias Clay at concrete highway structures affected by thaumasite, Gloucestershire, UK, Cement Concrete Compos. Vol. 25 (2003) 1015–1024.

[4] B. D'Acunto, G. Urciuoli, Groundwater regime in a slope stabilized by drain trenches, Math. Comp. Model. 43 (2006) 754–765.

[5] N.S. Isik, V. Doyuran, R. Ulusay, Assessment of a coastal landslide subjected to building loads at Sinop, Black Sea region, Turkey, and stabilization measures, Eng. Geol. 75 (2004) 69–88.

[6] R.A. Forth, Groundwater and geotechnical aspects of deep excavations in Hong Kong, Eng. Geol. 72 (2004) 253–260.

[7] I. Yilmazer, O. Yilmazer, C. Saraç, Case history of controlling a major landslide at Karandu, Turkey, Eng. Geol. 70 (2003) 47–53.

[8] M.S. Rosenbaum, A.A. McMillan, J.H. Powell, A.H. Cooper, M.G. Culshaw, K.J. Northmore, Classification of artificial (man-made) ground, Eng. Geol. 69 (2003) 99–409.

[9] P.L. Wilkinson, M.G. Anderson, D.M. Lloyd, J.P. Renaud, Landslide hazard and bioengineering: towards providing improved decision support through integrated numerical model development, Environ. Model. Software 17 (2002) 333–344.

[10] K. Koike, S. Matsuda, Spatial modeling of discontinuous geologic attributes with geotechnical applications, Eng. Geol. 78 (2005) 143–161.

[11] Y. Yang, K. McGough, R. Kalin, K. Dickson, Numerical modelling for remediation of contaminated land & groundwater, J. Environ. Contam. Toxicol. 71 (2003) 729–736.

[12] T. Scullion, C.L. Lau, Y. Chen, Pavement evaluations using ground penetrating radar in Texas, in: Proceedings of the 5th International Conference on GPR, vol. 1 of 3, June 12–16, Kitchener, Ontario, 1994, pp. 449–463.

[13] K.R. Maser, Condition assessment of transportation infrastructure using ground-penetrating radar, J. Infrastruct. Syst. 2 (1996) 94–101.

[14] Kelley, E.J., Soil moisture effects in pavement systems, M.S. thesis, Ohio University, Athens, 1999.

[15] W. Yuan, Function of pavement drainage design in highway engineering, Shanxi Architec. 19 (2004) 132–133 (in Chinese).

[16] M.S. Snaith, A.L. Bell, The filtration behaviour of construction fabrics under conditions of dynamic loading, Geotechnique 28 (1978) 466–468.

[17] D.J. Hoare, A laboratory study into pumping of clay through geotextiles under dynamic loading, in: Proceedings of the 2nd International Conference on Geotextiles, vol. 2, Las Vegas, 1992, pp. 423–428.

[18] N.A. Dawson, The role of geotextiles in controlling subbase contamination, in: Proceedings of the 3rd International Conference on Geotextiles, vol. 1, 1986, pp. 593–598.

[19] I.M. Alobaidi, D.J. Hoare, Factors affecting the pumping of fines at the subgrade subbase interface of highway pavements: a laboratory study, Geosynth. Int. 1 (1994) 221–259.

[20] Q.S. Zhou, Influence and prevent technology for water damage of the asphalt pavement, Transport. Sci. Technol. 6 (2004) 57–59 (in Chinese).

[21] Q. Gu, M. Liu, Analyses of asphalt pavement seepage, Hunan Commun. Sci. Technol. 4 (2004) 8–9 (in Chinese).

[22] Wang Lianzhng, Study on the factors of asphalt pavement seepage, China Road 4 (2005) 92 (in Chinese).

[23] X. Liu, J. Li, H. Zhang, R. Miao, Construction and quality control of SMA pavement of Hua-Qing highway, Guangdong Road Commun. 6 (2000) 1–8 (in Chinese).

[24] H. Zhang, R. Liao, The mix design of Huaqing expressway SMA surfacing, J. Chongqing Jiaotong Univ. 22 (2003) 46–54 (in Chinese).