Time-dependent Performance of Dublin Port Tunnel

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ABSTRACT: It is widely observed that existing tunnels deform and deteriorate over time due to various factors. Among them, tunnel lining permeability plays a significant role. In practice, the development of lining cracks and adjustment of drainage system may gradually alter the permeability of tunnel lining and water drainage path around a tunnel with time. Nevertheless, past investigations usually assume unchanged lining permeability during the whole life of a tunnel but fail to take time-dependent aging process into consideration. In this study, a set of hydro-mechanical coupled analyses is conducted to evaluate the effect of time-dependent crack development on the behaviour of a cross passage twin-tunnel section in Dublin Port Tunnel. The numerical results compare the transverse and longitudinal settlement profiles above the twin-tunnel with and without cross passage. The deformational characteristics of tunnel lining subject to the influence of the time-dependent permeability change are also analysed, which brings more insights into the understanding of aging tunnel structures.

KEY WORDS: Time-dependent lining permeability; Cross passage; Tunnel performance; Hydro-mechanical coupled analysis.

1 INTRODUCTION

Tunnel structure inevitably deforms and deteriorates over time due to the influence of various factors, such as tunnel geometric profiles, mechanical characteristics, soil geological properties, etc. Among them, the permeability of both tunnel lining and surrounding soil is of great importance [1]: the permeability of soil governs how groundwater flows inside the soil, whilst the permeability of lining controls tunnel's hydraulic performance (e.g. water seepage) and subsequently has an impact on its mechanical and deformational responses [2].

To assess the effect of lining permeability on tunnel performance, field measurements from Gourvenec et al. [3] showed that in London Clay, permeable linings caused a reduction of pore water pressure around the tunnel whilst this reduction was barely observed around impermeable linings. Based upon numerical analyses, Wongsaroj et al. [4] noted ground heave for impermeable tunnels excavated in London Clay and continuous surface settlement for permeable ones in the long term. As a further study, Li et al. [5] evaluated the effect of lining permeability on the long-term tunnel performance around a cross-passage section in London Clay, and found that the increase of lining permeability led to the build-up of long-term consolidation settlement at the ground surface. Nevertheless, recent studies addressed the effect of ageing lining permeability on tunnel structural performance in the long term. Wu et al. [6] conducted a numerical analysis on the impact of localised groundwater leakage on ground and tunnel performance and predicted that a localised leakage at the joints of a segmented tunnel led to inclined oval-shaped tunnel deformation. Likewise, Shin et al. [7] pointed out that the hydraulic deterioration of joints (i.e. the blockage of segment joints) of a segmented tunnel resulted in changes in the bending moment, hoop thrust and deformation of the segments. Li et al. [8] reported that due to the influence of a temperature-related lining permeability deterioration on a seasonal basis, the widening and shrinkage of the ring joint opening of an aged segmented tunnel repeated annually.

Many of the previous studies primarily assumed the permeability of tunnel linings to be constant throughout the whole life of tunnels. In practice, however, tunnel lining permeability gradually changes over time due to structural and hydraulic deterioration. Moreover, the hydraulic deterioration mentioned in many past investigations [7, 9, 10] mainly considered the degradation as a result of drainage system blockage (deduction of permeability coefficient) rather than the increase of lining permeability due to factors such as concrete crack development which forms water leakage channels. Furthermore, limited research has been conducted to investigate the ground and tunnel behaviour around cross passage sections which, theoretically, are more structurally critical, compared with other non-cross passage sections.

In this study, a set of hydro-mechanical coupled numerical analyses was conducted to evaluate the effect of time-dependent permeability increase caused by lining crack development on the long-term performance of a twin-tunnel cross passage section in Dublin Port Tunnel (DPT). The influence of cross passage and tunnel lining permeability on surface settlement was examined, and the numerical results on tunnel deformational performance were evaluated against onsite observations.

2 PROJECT BACKGROUND

As a project built to channel heavy goods vehicles travelling between Dublin Port and Dublin City, DPT has been in operation for more than a decade since its opening in 2006. According to historical inspection and maintenance records, it was found that the twin-tunnel structures have developed some deformation and deterioration, such as lining cracks, water seepage, concrete spalling, etc., of which water leakage and lining cracks have been two serious issues for engineering maintenance. Along the whole tunnel alignment, the sections with obvious water seepage and concrete cracks were found around four enlarged layby sections joined by vehicle cross passages (VCP). However, the degree of tunnel deformation and deterioration around these four sections varies, with the most serious lining cracks and water ingress concentrating around VCP16 which was located at the lowest elevation along the alignment, as illustrated in Figure 1 (red dot). Based on maintenance records and previous site visits, the deterioration around this section has been developing for several years after construction with no evidence of stabilisation, which may pose a challenge to tunnel serviceability in the long run. Besides, some later-added drainage ditches were also found around layby tunnel circumference at VCP16 to flow water into the main drainage pump buried underneath the tunnel invert. The two types of degradation practically influence the water flow regime around tunnels, indicating the change of water boundary conditions or lining permeability. The linings around section VCP16 are composed of both primary and secondary linings, with the details listed as follows: (1) VCP: 200mm shotcrete primary lining and 500mm in-situ concrete secondary lining; (2) layby tunnel: 200mm shotcrete primary lining and 500mm in-situ concrete secondary lining; (3) bored tunnel: 115mm nominal annular grout, 350mm concrete segmental lining and 275mm nominal in-situ concrete inner lining.

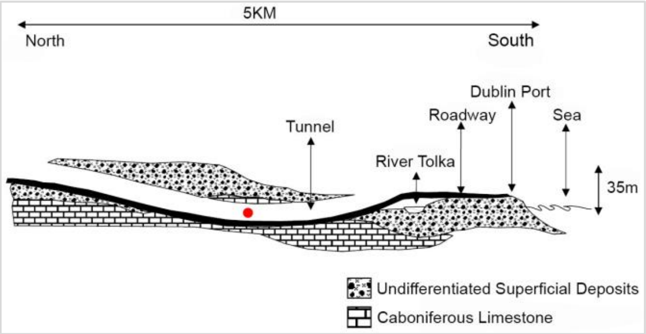


Figure 1. Location of target tunnel section [11]

3 FINITE ELEMENT SIMULATION

3.1 Ground condition and model profile

Dublin Port Tunnel, mainly consisting of northern and southern cut-and-cover sections, in-between bored section, and surface road, goes through different geological stratigraphy along its alignment [12]. Of particular interest in this study is VCP16 section in bored section buried 19.5m beneath ground surface where the most severe structural and hydraulic deterioration occurs, including lining cracks, tunnel leakage, concrete spalling, etc. The target section features a twin layby tunnel in irregular oval shape, with a spacing of around 40m, transversely connected by a horseshoe-shaped VCP for emergency evacuation and longitudinally linked by a headwall structure to the circular bored tunnel with an outer diameter of 11.77m, as shown in Figure 2.

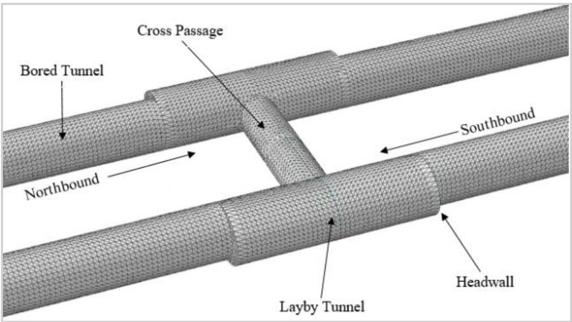


Figure 2. Numerical model of DPT

Considering symmetrical tunnel configuration in both transverse and longitudinal directions, a quarter finite element model of the twin-tunnel cross passage was developed. To minimise boundary effect, the dimension of the model is 100m (length) ×100m (width) ×80m (depth), which is as much as eight times greater than the tunnel diameter. Vertical displacement at bottom of the model was fixed while the top was free. The back and right boundaries were allowed moving vertically but not moving perpendicularly to boundary faces, whereas the front and left sides were assumed as symmetrical planes.

According to DPT geotechnical investigation report [13] and previous studies [14], the general geological profile along the depth at this section is given as follows: (1) sandy clayey gravel (SCG) (0-4.8m); (2) sandy gravelly clay (SGC) (4.8-8.3m); (3) argillaceous calcisiltite (AC) (i.e. limestone) (8.3-80.0m). The physical and mechanical parameters, such as permeability, elastic modulus, cohesion, etc., are listed in Table 1. The initial pore water pressure was considered as hydrostatic with the groundwater table at 2.0m below ground surface.

The model was discretised by finite element analysis software ABAQUS [15] using 4-node linear coupled displacement-pore pressure tetrahedron element (C3D4P), with finer mesh at and around tunnel structures and coarser mesh at the further boundaries as to minimise computational cost without compromising accuracy [8]. The tunnel linings were all modelled using 3D continuous solid elements, which are the same as soil units. No interface was considered as the tunnel

Table 1. Soil and concrete properties

Material	γ(kN/m³)	e	k (m/s)	E (MPa)	v	C (kPa)	φ (°)	K_0
SCG	20.00	0.400	6.40×10^{-8}	60.0	0.30	47.8	30.0	0.50
SGC	22.00	0.300	4.80×10^{-6}	100.0	0.30	120.0	35.0	0.50
AC	26.64	0.233	6.10×10^{-8}	38.2	0.15	30.0	48.0	1.00
LC	25.00	/	/	30.0	0.30	/	/	/

Note: γ is the dry density, e is the void ratio, k is the permeability coefficient, E is the elastic modulus, v is the Poisson's ratio, C is the cohesion, φ is the internal angle of friction and K_0 is the horizontal earth pressure coefficient at rest.

lining is very unlikely to slip away from the surrounding ground during soil consolidation [8]. The whole 3D model was comprised of 465,529 elements and 75,723 nodes. A Mohr-Coulomb constitutive model was adopted for all soils and a linear elastic model was assigned to concrete. The physical and mechanical properties of lining concrete are given in Table 1.

3.2 Tunnel construction and long-term consolidation

On the basis of construction history, the excavation of VCP followed shortly after the construction of main tunnels (MT, i.e. bored tunnel, headwall and layby tunnel). In general, there are four main stages in this numerical modelling: initial geostatic equilibrium state, MT construction, VCP construction and long-term consolidation, as detailed in Table 2.

Table 2. General stages considered in FE analyses

Stages	Stage description
1	1. Initial geostatic equilibrium state
2	2.1. Excavation of MT and MT nodal force reduction to 50%
	2.2. Activation of MT linings and further MT nodal force reduction to 0%
3	3.1. Excavation of VCP and VCP nodal force reduction to 50%
	3.2. Activation of VCP linings and further VCP nodal force reduction to 0%
4	4. Long-term soil consolidation

After initial geostatic equilibrium state, the soil elements of MT were removed first, followed by the application of nodal force around MT external circumference. To simulate the stress redistribution after MT excavation and the time lag before the installation of tunnel linings, the equivalent nodal forces were relaxed to 50% of its original magnitude, with subsequent placement of linings and another nodal force reduction of 50%. The same process was also adopted for VCP excavation before long-term consolidation begins.

3.3 Lining permeability change with time

After tunnel construction, the presence of lining structures may create different types of new drainage boundaries within the soil mass depending on the permeability difference between soil and lining. During ground consolidation with time, two basic scenarios may occur:

(1) The blockage of water drainage system around tunnel lining potentially caused by limestone concretion due to calcite precipitation on tunnel drainage paths [10];

(2) The cracking/construction joints-induced water seepage or infiltration into tunnels which may lead to the change of tunnel lining permeability [1].

To model these two time-dependent effects on tunnel performance, the clogged drainage system was simulated by decreasing the coefficient of tunnel lining permeability whilst cracking-induced water leakage was considered by the increase of lining permeability [1]. Due to limited space, only cracking-induced water infiltration modelled by increasing lining permeability was considered in this study. The details of cases considered in this study are listed in Table 3. As DPT has been in operation for over 14 years, the lining permeability was assumed to change linearly during this period.

Table 3. Cracking-induced lining permeability change

Cases	k_l at the start of the 14-year period	k_l at the end of the 14-year period
A1	2.0×10^{-10} m/s	2.0×10^{-9} m/s
A2	2.0×10^{-10} m/s	0.5×10^{-8} m/s
A3	2.0×10^{-10} m/s	2.0×10^{-8} m/s
A4	2.0×10^{-10} m/s	0.5×10^{-7} m/s
A5	2.0×10^{-10} m/s	2.0×10^{-7} m/s
A6	2.0×10^{-10} m/s	2.0×10^{-6} m/s

4 RESULTS AND DISCUSSION

4.1 Ground response

Transverse consolidation settlement

Previous efforts have investigated the long-term hydraulic-mechanical coupled performance of tunnels with different relative permeability between tunnel lining and surrounding soil layers [1, 4, 16]. In this section, the effect of cross passage on long-term ground settlement above twin tunnels is specifically examined subject to different relative ground-lining permeability.

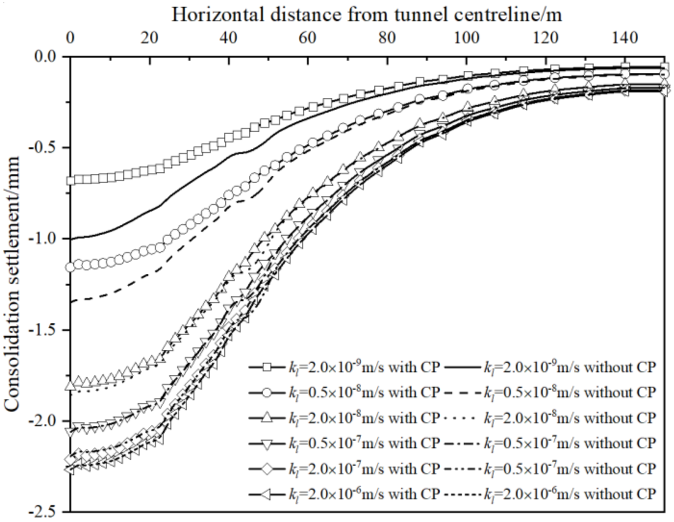


Figure 3. Transverse consolidation settlement in the long term

Figure 3 shows the effect of lining permeability on the long-term surface consolidation settlement in the transverse direction for twin-tunnels with and without cross passage. For both types of twin tunnels, the maximum consolidation settlement in the long term occurs at the centreline of VCP16, indicating that the existence of VCP has no impact on the location of maximum surface settlement in the long term. The lower the tunnel lining permeability is, the smaller ground surface subsidence would be. When the tunnel lining is relatively impermeable compared with the surrounding soil (e.g. lining permeability k_l=2.0×10^{-9} m/s < soil permeability k_s=6.1×10^{-8} m/s), the existence of cross passage leads to smaller consolidation settlement above the twin tunnel with cross passage than that for one without cross passage. This is due to the buoyancy effect of watertight tunnel with the increasing water pressure around the tunnel during ground consolidation [8]. However, the difference of maximum consolidation settlement for twin tunnels with and without cross passage becomes less significant for higher lining permeability cases, from 0.32mm for impermeable lining (k_l=2.0×10^{-9}m/s) to approximately 0.0mm for permeable lining (k_l=2.0×10^{-6}m/s). The findings show agreement with the conclusion by Li et al. [8] that for permeable cast-iron twin tunnels excavated in lower-permeability stiff London Clay, the effect of cross passage on the long-term surface ground settlement is negligible. That is, the soil consolidation due to drainage into cross passage barely changes the drainage characteristics around fully permeable twin tunnels.

Longitudinal consolidation settlement

Figure 4 shows how the existence of cross passage affects the long-term consolidation settlement of surface ground above cross passage along the longitudinal direction for tunnels with different permeability change. When tunnel lining is relatively impermeable, the existence of cross passage in twin tunnels leads to smaller longitudinal settlement than that for one without cross passage, as noted in the transverse consolidation settlement. When the tunnel becomes more permeable (i.e. $k_l \geq$ 0.5×10^{-7}m/s), the cross-passage effect becomes negligible. This is because the lining permeability of a twin-tunnel without cross passage is sufficiently high to enable the complete dissipation of negative excess pore water pressure generated during tunnel construction, while the contribution from cross passage drainage barely changes the water flow regime. Generally, the effect of cross passage on longitudinal consolidation settlement in the long term may not be significant from the engineering assessment point of view. Along the longitudinal direction, it can be seen that generally, the surface settlement almost remains constant at further sections from cross passage, and even, the maximum settlement is less than 2.5mm for fully permeable linings. The deflection ratio *DR* which is usually adopted to assess the risk of potential damage to surface structures caused by tunnelling activities is defined in equation (1) [17]:

$$DR = \Delta / L \tag{1}$$

where Δ is the relative vertical deflection and L is the length of sagging zone.

It can be calculated that the *DR* of 0.02‰ in this case is far smaller than the recommended threshold 0.67% at which structural damage may occur [18]. This indicates that the permeability change of tunnel linings in this analysis, big or small, barely can cause any damage to ground buildings or structures.

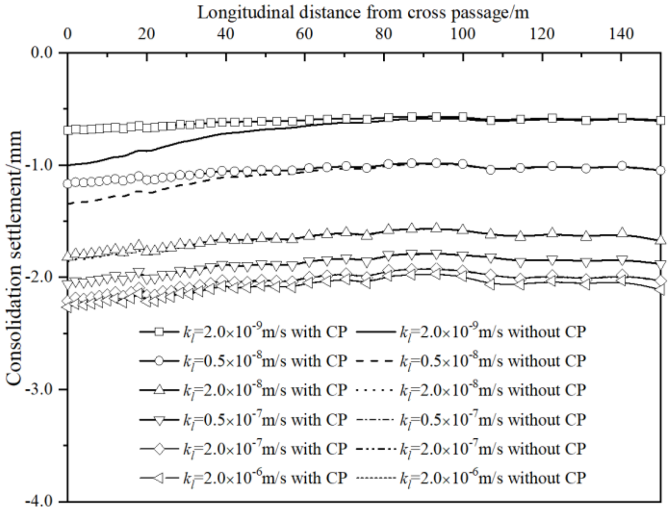
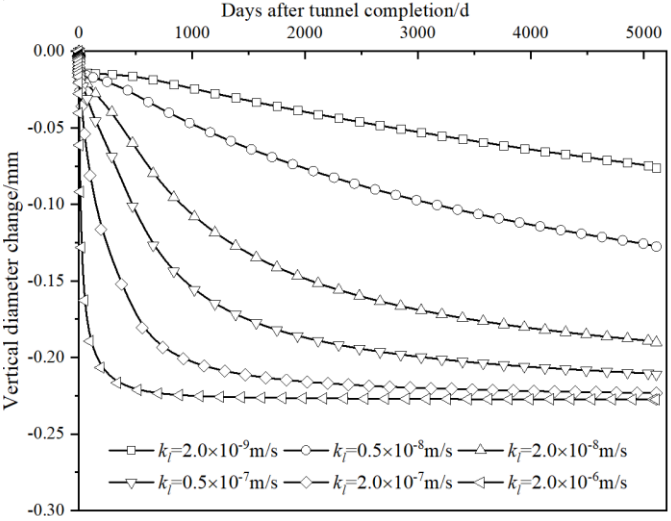


Figure 4. Longitudinal surface settlement in the long-term

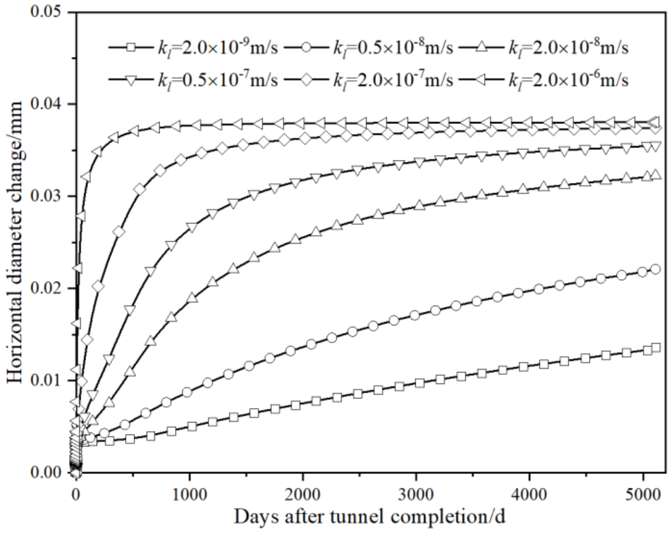
4.2 Tunnel deformation

Tunnel deformation at cross passage opening

Figure 5(*a*) shows the change of vertical diameter with time for layby tunnel along the cross-passage section. For tunnels with a permeability increase from 2.0×10^{-10} m/s to 2.0×10^{-9} m/s, the tunnel lining deforms linearly during the 14-year period with no sign of stabilisation, which is in line with continuous development of deformation observed in DPT. This is because the negative pore water pressure generated during tunnel construction has not fully dissipated by the end of this period, indicating that the consolidation process may continue before a steady-state flow condition within surrounding soil is reached. As the degree of permeability increase becomes higher, tunnel vertical deformation builds up faster. The time it needs to reach stabilisation lessens while the magnitude of final vertical



(*a*). Layby tunnel vertical deformation at CP opening



(*b*). Layby tunnel horizontal deformation at CP opening

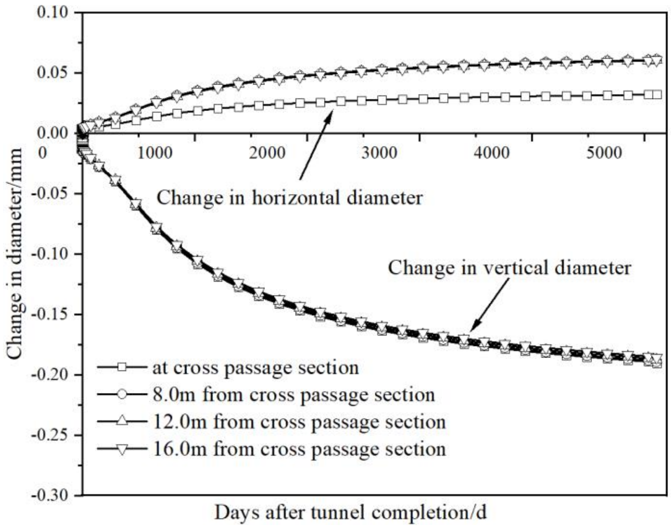
Figure 5. Tunnel deformation at CP opening

diameter change increases. When the tunnel lining permeability degrades from 2.0×10^{-10} m/s to 2.0×10^{-6}m/s, the development of tunnel vertical deformation stabilises shortly after tunnel completion (approximately 300 days). This can be attributed to the accelerating dissipation of negative pore water pressure induced by the significant permeability increase, thus leading to rapid tunnel deformation. The results show that during the 14 years, a gradual increase of lining permeability causes gradual build-up of tunnel deformation while a substantial increase leads to rapid development and stabilisation

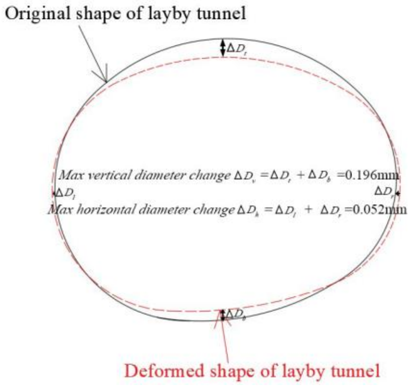
Similarly, as shown in Fig 5(*b*), the pattern of tunnel horizontal deformation is consistent with that of vertical deformation. The less permeable tunnel lining is (e.g. $k_l\leq2.0\times10^{-8}$m/s), the slower tunnel horizontal deformation is in the long term. The increase of lining permeability contributes to fast development of horizontal diameter change. When tunnel linings become fully permeable (e.g. $k_l\geq0.5\times10^{-7}$m/s), the horizontal deformation reaches stabilisation within less than 1000 days. The reason for this is the same as that for vertical diameter change.

Tunnel deformation at further sections

Due to limited space in this paper, the tunnel deformation at father sections is presented for case A3 with a permeability change from 2.0×10^{-10} m/s to 2.0×10^{-8} m/s only.



(*a*) Tunnel deformation at further sections



(*b*) Squatting deformation of layby tunnel

Figure 6. Tunnel deformation at farther sections

Figure 6(*a*) illustrates the development of layby tunnel deformation at four different sections (i.e. 0m, 8m, 12m and 16m away from cross passage) over time in both horizontal and vertical directions. In general, the tunnel deformation profile of gradual development at further sections remains consistent with that at cross passage section, with the maximum vertical and horizontal deformation at 0.20mm and 0.06mm, respectively. The change of horizontal diameter at the incomplete cross passage section is smaller than that of further sections because only right spring-line point is recorded at that section. The results indicate that the layby tunnel exhibits a consistent deformation mode of squatting along the traffic direction, as represented in Figure 6(*b*). Besides, most of the layby tunnel squatting experiences a gradual build-up during the 14-year period and predictably it may take some more time for tunnel deformation to stabilise. As for other cases listed in Table 3, it can be forecasted that the tunnel deformation at further sections follows that significant increase of lining permeability leads to faster stabilisation of tunnel squatting whilst slight increase means a relatively longer period of deformation before it can level off.

4.3 *Effect of cross passage and time-dependent hydraulic deterioration*

In general, the effect of cross passage on the long-term surface settlement is dependent on relative permeability between tunnel lining and adjacent soil. Table 4 summarises the settlement difference caused by soil consolidation for tunnels with and without cross passage in the long. If the tunnel lining is relatively impermeable, compared to surrounding soil stratum (e.g. case A1), the existence of cross passage reduces surface settlement and leads to a settlement difference of 0.32 in the long term. With the tunnel lining becoming more permeable (e.g. case A6), the effect becomes negligible.

Table 4. Difference of long-term surface settlement (mm)

Cases	A1	A2	A3	A4	A5	A6
Transverse	0.32	0.18	0.04	0.02	0.02	0.02
Longitudinal	0.32	0.18	0.04	0.02	0.02	0.02

The time-dependent increase of lining permeability reflects the realistic tunnel deformational performance. If the tunnel deteriorates slightly, a gradual development of tunnel deformation is observed, indicating the time-dependent development of tunnel structural defects. However, for tunnels that degrade significantly, the tunnel deformation shows a substantial build-up shortly after tunnel completion and then stabilises within a short period of time.

5 CONCLUSION

This paper conducted numerical analyses on the effect of cross passage and time-dependent hydraulic deterioration on ground response and tunnel performance in the long term. The main conclusions derived from the results are as follows:

1. For the permeable lining, the presence of cross passage may create a new drainage channel between twin tunnels. The additional cross passage drainage, however, is unable to substantially alter the surrounding water pressure, which has already dissipated into the permeable twin tunnels. Hence, the presence of cross passage makes little change on the long-term surface

settlement of permeable twin tunnels in both transverse and longitudinal directions.

2. If the lining is impermeable, the twin tunnel with a cross passage leads to smaller consolidation settlement than that without a cross passage, due to buoyancy effect by water pressure below the watertight cross passage.
3. The less permeable the tunnel is, the slower tunnel deformation development is in the long term. If tunnel permeability increases gradually with time (e.g. from 2.0×10^{-10} m/s to 2.0×10^{-9} m/s), the tunnel deformation also builds up gradually, generally in line with observed continuous tunnel deformation years after construction. If tunnel permeability increases substantially at a significantly fast rate (e.g. from 2.0×10^{-10} m/s to 2.0×10^{-6} m/s), the tunnel deformation builds up rapidly and then stabilises within a short period of time.
4. After 14 years of soil consolidation, the layby tunnel shows a general squatting deformation mode along the longitudinal direction, regardless of the distance away from cross passage.

In this study, only time-dependent hydraulic tunnel deterioration was considered and the permeability of lining was assumed to increase linearly with time. In practice, however, hydraulic deterioration may not follow a linear relationship, whilst tunnel mechanical degradation (e.g. lining stiffness reduction) also develop with time. Further studies can be performed to examine such time-dependent effects on ground response and tunnel behaviour

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