Research on the Causes and Prevention of Airport Pavement Diseases

Xinpu Feng$^{1,2}$, Lei Guo$^{1,2}$, Geng Ren$^{1,2}$ and Shaoning Liu$^3$
$^1$China Airport Construction Group Co., Ltd., Beijing, China
$^2$Beijing Super-Creative Technology Co., Ltd, Beijing, China
$^3$Beijing New Airport Construction Headquarters, Beijing, China
Corresponding author: Xinpu Feng  e-mail: fengxinpu@163.com

Abstract. The structure of airport runway has changed the balance of water movement between the original surface and the atmosphere, resulting in the accumulation of water under the base of airport runway surface, forming a "pot-cover effect", aggravating the uneven settlement of the foundation under aircraft load, resulting in the destruction of the structure of the runway surface, frequent diseases, and seriously affecting the airworthiness of the runway. In order to solve the problem of water enrichment under the base of the runway surface, this paper proposes a specific layout scheme of diversion canals. In the runway overhaul project of Shenyang Taoxian International Airport, the water diversion canal was excavated on the spot, and it was found that the water level at the site was comparatively consistent with the water level at the scheme analysis. The layout scheme of the water diversion canal was reasonable and effective, and could well solve the problem of "pot-cover effect".

1. Introduction

Some experts and scholars found that the water content of the surface soil of the lower part of the pavement is obviously higher than that of the deep soil or the shoulder soil in the earlier research on the pavement diseases of the airport. They analyzed that this is due to the existence of a large area of impermeable pavement structure, which hinders the migration of porous water in the soil and results in the enrichment of the lower part of the pavement. They call this phenomenon of increasing water content in the lower part of the pavement "pot-cover effect".[1] The "pot-cover effect" is easy to occur in dry areas with large seasonal temperature variations. Once it occurs, it will reduce the bearing capacity of roadbed and seriously affect the pavement service life.[2]

Shenyang Taoxian International Airport is latitude 41.6 degrees north, temperate continental climate, cold and dry in winter, belongs to the typical dry and cold region, which provides conditions for the formation of "pot-cover effect". At the end of 2017, the runway surface inspection report of Shenyang Airport showed that the comprehensive evaluation of runway surface damage condition was "good". The main types of diseases were longitudinal and transverse cracks, irregular cracks, reflective cracks and surface loose spalling, among which irregular cracks, reflective cracks and surface loose spalling mainly existed in the runway non-wheel belt area.[3] In 2018, the Shenyang Airport Administration decided to overhaul the runway and set up vertical and horizontal diversion canals. Longitudinal diversion canals are located 5 m away from the shoulder of the runway, parallel to the runway. The transverse diversion canals are set up every 60 meters to connect the runway vertically. During the excavation of the diversion canal, the effluent effect of several diversion canals is obvious,
and the effluent level is consistent with the analysis of the scheme in this paper. The layout scheme of diversion canal proposed in this paper aims at solving the problem of runway surface diseases caused by "pot-cover effect" and prolonging runway service life.

2. Formation mechanism of "pot-cover effect"

2.1. Overview of "Pot-Cover Effect"
In dry areas with large seasonal temperature variations, "pot-cover effect" is liable to cause runway surface diseases. The "pot-cover effect" refers to the phenomenon that the water content of the upper soil under the runway structure layer increases due to the sealing of the pavement structure layer, which results in the isolation of water and air from the outside atmosphere and can not diffuse outward. The groundwater level in dry area is deep, and the capillary action of groundwater is limited to convey water upward.[4] It can not directly supplement the soil moisture under the pavement structure layer. The water in shallow soil generally comes from condensation or frozen water formed by the water migration caused by temperature difference effect. With the decrease of pavement temperature, the temperature of shallow soil decreases, while that of deep soil is less affected by pavement temperature, and the temperature is relatively stable. Under the action of this temperature gradient, water in soil moves from bottom to top, resulting in the continuous increase of water content in upper soil. This phenomenon will cause the occurrence of runway surface diseases [5].

![Formation mechanism of "pot-cover effect"](image)

Figure 1. Formation mechanism of "pot-cover effect"

2.2. Analysis of Moisture Transport in Soil Foundation Caused by Temperature Change
According to the law of conservation of energy and mass, it is assumed that the soil skeleton is not deformed, the liquid in the pore is water and the pore water is incompressible. For two-phase flow, the following expressions are used:

\[
\frac{\partial}{\partial t} (n S^g \rho_k^g + n S^l \rho_k^l) + \nabla (J_k^g + J_k^l) = Q_k
\]

(1)

\[
J_k^g = J_{Ak}^g + J_{Dk}^g
\]

(2)

In the formula, \(k\) represents the composition of the fluid, including water and air. \(w\) and \(a\) represent the composition of the fluid, respectively. \(t\) is time, \(n\) is porosity, \(S^l\) is pore liquid saturation, \(S^g\) is pore gas saturation, and it conforms \(S^g + S^l = 1\). \(\rho_k^g\) and \(\rho_k^l\) are gas phase and liquid phase densities, \(\rho_k^g\) and \(\rho_k^l\) are liquid water density and gaseous water density, \(\rho_k^a\) is dry air mass density; \(\nabla\) is Laplace operator, \(Q_k\) is source term, \(\lambda_g\) is gas phase and liquid phase, expressed by \(\lambda_g = g\) and \(\lambda_l = l\); total flow \(J\) includes convective \(J_{Ak}^g\) and diffusion \(J_{Dk}^g\).

According to Darcy’s law, the convective part can be expressed as:
In the formula, $K$ is the intrinsic permeability, $k_{rel}^\iota$ is the relative permeability coefficient, $\mu^\iota$ is the viscosity of the fluid phase, $p^\iota$ is the fluid pressure, $g$ is the gravitational acceleration.

According to Fick's law, the fluid diffusion part can be expressed as:

$$J_{de}^\iota = -nS^{\iota} \rho^\iota D^\iota \nabla \left( \frac{p^\iota}{\rho^\iota} \right)$$

(4)

In the formula, $D^\iota$ is the diffusion coefficient tensor. In practice, the gas phase in the soil pore includes water and dry air, while the liquid phase only has liquid water.

The equation of coupled action of temperature and seepage fields is:

$$n(\rho_a^p - \rho_w^p)(\frac{\partial S^l}{\partial t} + \frac{\partial S^l}{\partial T} + \frac{\partial p^c}{\partial T} + \frac{\partial p^c}{\partial t}) + (1 - S^l)n(\frac{\partial p^a_s}{\partial t} + \frac{\partial p^s_e}{\partial p^s} + \frac{\partial p^s_e}{\partial p^c} - \frac{\partial p^s_e}{\partial \partial p^c}) - \frac{\partial}{\partial z} \left[ k^g \left( \frac{\partial}{\partial z} (p^g - p^c) \right) - \frac{\partial}{\partial z} \left( k^g \left( \frac{\partial p^g}{\partial z} - \rho^g g \right) \right) \right]
$$

$$\frac{\partial}{\partial z} \left( \frac{\rho^g M_a M_w}{M_g^2} D^g \frac{\partial}{\partial z} \left( \frac{p^a_e}{\partial \partial p^c} \right) \right) = Q_a$$

(5)

$$-n\rho_a^p (\frac{\partial S^l}{\partial T} + \frac{\partial S^l}{\partial t} + \frac{\partial p^c}{\partial T} + \frac{\partial p^c}{\partial t}) + (1 - S^l)n(\frac{\partial p^a_s}{\partial t} + \frac{\partial p^s_e}{\partial p^s} + \frac{\partial p^s_e}{\partial p^c} - \frac{\partial p^s_e}{\partial \partial p^c}) - \frac{\partial}{\partial z} \left[ k^g \left( \frac{\partial p^g}{\partial z} - \rho^g g \right) \right] - \frac{\partial}{\partial z} \left( \frac{\rho^g M_a M_w}{M_g^2} D^g \frac{\partial}{\partial z} \left( \frac{p^a_e}{\partial \partial p^c} \right) \right) = Q_a$$

(6)

$$\left( \rho c_p^a \right)_{eff} \frac{\partial T}{\partial t} + \frac{c_p^a k^l}{g} \left( \frac{\partial p^a_s}{\partial z} + \frac{\partial p^c}{\partial z} + \rho^c g \right) \frac{\partial T}{\partial z} + \frac{c_p^a k^g}{g} \left( -\frac{\partial p^g}{\partial z} + \rho^g g \right) \frac{\partial T}{\partial z} - \frac{\partial}{\partial t} (K_{eff} \frac{\partial T}{\partial z}) + Q_i = 0$$

(7)

In the formula, $p^g = p^p$ is pore pressure, $p^a_s$ and $p^g$ are dry air and water vapor partial pressure, $T$ is soil temperature, assuming that the temperature of pore water and pore gas is equal to that of the soil at a certain time, $z$ is space coordinate, $\rho^c$ and $\rho^a = \rho^s + \rho^g$ are pore liquid and pore gas mass density, $M_g$ is average molecular mass of gas, $M_a$ and $M_w$ are dry air and water fraction. Submass, $R$ is gas constant, $Q_a$ and $Q_w$ are source terms.In this paper, $Q_a = Q_w = 0 \ K_{eff} = K^l + K^s + K^g$ is effective thermal...
conductivity, \( K^s \), \( K^l \) and \( K^g \) are solid, liquid and gas phase thermal conductivity, 
\[
\left( \rho c_p \right)_{eff} = (1 - n)\rho^s c_p^s + n(S^l \rho^l c_p^l + S^g \rho^g c_p^g)
\]
is equivalent specific heat capacity at constant pressure, \( c_p^s \), \( c_p^l \) and \( c_p^g \) are solid, liquid and gas phase specific heat capacity at constant pressure respectively.

Since pore fluid is water, \( S^w \) can be replaced by \( S^l \) and \( k^w \) can be replaced by \( k^l \). We obtained \( S^w = S^w(p^l, T) \). According to the gas equation, the vapor pressure in equilibrium state is given by

\[
p_{w}^{l} = p_{w}^{g} \exp\left(-\frac{p^l M_{w}}{\rho_n RT}\right).
\]

Kelvin-Laplace equation:

3. Example of Shenyang Airport Project

3.1. Runway Diseases of Shenyang Airport

Shenyang Taoxian International Airport is located in Taoxian Street in the southern suburb of Shenyang, China. The current airfield area level is 4E, which can guarantee the use of 747-400 and below. The cement concrete pavement of the airport flight area was built in 1986. The length of the runway is 3200m and the length of the parallel taxiway is 970 m. In 2009, Shenyang Airport carried out asphalt overlay on runway pavement.

| Runway area (North-South) | 0 ~ 500m | 500 ~ 600m | 600 ~ 2600m | 2700 ~ 3200m |
|----------------------------|----------|------------|-------------|-------------|
| Pavement structure         | 17cm asphalt overlay | 17cm asphalt overlay | 35cm Original cement concrete pavement | 3cm lime powder screed-coat |
|                            | 12cm asphalt overlay | 32cm Original cement concrete pavement | 20cm three-kinds ash upper-base | 20cm lime-ash soil sub-base |
|                            |                      | 32cm Original cement concrete pavement | 30cm cinder limestone soil cushion |                          |
|                            |                      |                            |                          | Compacted Soil Foundation |

Shenyang airport disease-prone areas are mostly concentrated in the runway center line within 12 meters, and the junction of high speed taxiway and runway. The main damages of pavement surface are longitudinal and transverse cracks, irregular cracks, reflection cracks and surface loose spalling. Among them, irregular cracks, reflective cracks and surface loose spalling mainly exist in the runway non-wheel track zone area (9 m away from the center line).

Figure 2. Runway surface disease zone (south)

Figure 3. Runway surface disease zone (north)

In order to further investigate the condition of runway diseases, core sampling was carried out along the east and west sides of the middle line of the runway. In the end area (0-600 m from the south end of the runway and 2600-3200 m from the south end of the runway), core samples were taken.
alternately at about 65 m intervals along the East and west sides of the central line. A total of 18 core samples were drilled (9 core samples at each end) and the thinning area in the middle part. (within the 600 m to 2600 section from the south end of the runway), 24 core samples were drilled alternately at intervals of about 85m along the East and west sides of the central line. Firstly, the appearance of the core sample was observed, and then the Cantabro test was carried out. There are 10 groups of surface layer separation or fragmentation in appearance.

Table 2. Test results of appearance of asphalt core samples

| Core sample number | Core position(North-South) | Core sample height/cm | Appearance description |
|--------------------|---------------------------|-----------------------|------------------------|
| 6#                 | West side/325m            | 16                    | Sub-layer separated    |
| 12#                | West side/770m            | 17                    | Both layers separated  |
| 13#                | East side/855m            | 19                    | Both layers separated  |
| 15#                | East side/1025m           | 5.5                   | Sub-layer separated    |
| 24#                | West side/1790m           | 13.5                  | Sub-layer separated    |
| 33#                | East side/2535m           | 12.5                  | Both layers separated  |
| 34#                | West side/2600m           | 5.5                   | Sub-layer separated    |
| 36#                | West side/2730m           | 18                    | Upper-layer separated  |
| 38#                | West side/2860m           | 14                    | Upper-layer separated  |
| 39#                | East side/2925m           | 19                    | Upper-layer separated  |

From Table 2, we can see that the separation of the northern runway (0 ~ 600m) surface is serious, and the cohesion between the upper-layer and the mid-layer is seriously insufficient. When core samples of 15#, 24# and 34# were taken, the aggregate fragmentation of the lower layer could not be removed, which indicated that the aggregate bonding strength of the lower layer of the middle (600 ~ 2600m) of the runway was poor.

Table 3. Cantabro test

| Test position       | Group/Position | Standard quality loss rate/% |
|--------------------|----------------|-----------------------------|
| End of the runway  | 4#/195m        | 11.8                        |
|                    | 10#/650m       | 19.4                        |
|                    | 38#/2600m      | 51.9 (Core sample fragmented) |
|                    | 41#/3055m      | 5.3                         |
|                    | 1#/0m          | (Core sample fragmented)    |
| Mid-layer(AC-20)   | 5#/260m        | 45.6                        |
|                    | 6#/325m        | 45.1                        |
|                    | 8#/455m        | 16.8                        |
|                    | 9#/520m        | 11.8                        |
|                    | 37#/2795m      | (Core sample fragmented)    |
|                    | 40#/2990m      | 33.7                        |
|                    | 14#/940m       | (Core sample fragmented)    |
|                    | 19#/1365m      | 16.5                        |
|                    | 24#/1790m      | 6.4                         |
| Middle of the runway | 31#/2385m   | 12.4                        |
|                    | 11#/685m       | 11.1                        |
|                    | 21#/1535m      | 19.1                        |
|                    | 25#/1875m      | 19.1                        |
|                    | 29#/2215m      | 15.6                        |

From the Cantabro test results in Table 3, it can be seen that:
The mass loss rate is less than 20% which of core samples’ upper-layer and sub-layer at both ends of the runway (0-600m, 2600-3200m). The resistance to external forces is in good condition, in which
the mass loss rate of the surface layer is obviously higher than 20%. Some core samples have been fragmented in the test. It shows that the aggregate bonding strength of the mid-layer of the north end pavement is poor, and the pavement resistance to external forces is poor. In the middle of the runway (600-2600m), except that the upper-layer of 14 # core sample has been fragmented, the standard mass loss rate of the upper-layer and sub-layers of the core sample is less than 20%. That is to say, the performance of aggregates on the middle and lower layers of the runway to resist external forces is in good condition as a whole.

Since the aircraft enters the runway through the end taxiway, the both ends of the taxiway are usually composed of small radius arcs. The landing gear wheels close to the inside of the arc are in the knob state when the aircraft is driving at low speed, which causes a greater torsional shear effect on the pavement[6]. Under such low-speed and torsional shear force, the end of the taxiway is in a disadvantageous stress state, and the time of internal load action increases significantly. Not only will the shear-tension crack occur, but also the displacement and rutting will occur. Therefore, the torsional force of aircraft turning will cause great damage to the end taxiway[7][8].

The joint of taxiway and runway will be damaged by torsion force. However, in the middle of the runway, there is no regular relationship between the action area of the aircraft wheel track and the disease area, and the disease mostly occurs outside the wheel track area. Therefore, it is assumed that the disease is caused by the "pot-cover effect".

3.2. Layout method and effect of diversion canal

The layout of diversion canals at Shenyang Airport can be divided into two categories: horizontal and vertical. The longitudinal diversion canals are parallel to the runway and has a distance of 5 m between the shoulder and the runway. Transverse diversion canals connect the water and gas under the runway structure layer with the outside atmosphere, exchanges water and gas, prevents the water and gas accumulation, and arranges a distance of 60 m, discharges the water and gas under the structure layer into the Longitudinal diversion canals.

There are 98 transverse diversion canals on both sides of the runway of Shenyang Airport, and there are 27 diversion canals with water. The location and situation of diversion canals with water are shown in the table below.

| Water outlet position | Water yield | Water outlet position | Water yield | Water outlet position | Water yield |
|----------------------|-------------|----------------------|-------------|----------------------|-------------|
| 60m/E                | Stream      | 320m/W               | Gush        | 1820m/W              | Gush        |
| 80m/W                | Stream      | 360m/E               | Gush        | 1880m/W              | Stream      |
| 120m/E               | Gush        | 380m/W               | Stream      | 2000m/W              | Stream      |
| 140m/W               | Gush        | 980m/W               | Gush        | 2300m/W              | Stream      |
| 180m/E               | Stream      | 980m/E               | Stream      | 2360m/W              | Seepage     |
| 200m/W               | Seepage     | 1220m/W              | Stream      | 2600m/W              | Stream      |
| 240m/W               | Seepage     | 1262m/E              | Gush        | 2840m/E              | Gush        |
| 260m/E               | Seepage     | 1280m/W              | Stream      | 2960m/W              | Gush        |
| 300m/E               | Gush        | 1820m/E              | Gush        | 3200m/W              | Seepage     |

Note: In Table 3, "E" means the diversion canals on the east side of the runway and "W" means the diversion canals on the west side of the runway.

The regional relationship between the diversion canals with water and the disease of runway is compared as follows.
From Fig. 4 and Fig. 5, it can be seen that the distribution of diversion canal with water is basically consistent with the actual detection of runway surface diseases. From this, it can be concluded that "pot-cover effect" is a major factor leading to runway diseases. In the area where aircraft loads are significant, pavement damage is more serious, and the distribution of outlet points of diversion canals is more intensive, and the amount of outlet water is larger. The existence of "pot-cover effect" will accelerate pavement damage. Therefore, the layout of diversion canals on airport runway surface in dry and cold regions can effectively solve the runway surface diseases caused by "pot-cover effect". In view of the above analysis, long-term diseases occur in areas outside the wheel action zone of aircraft. It is suggested that diversion canals should be laid in such areas to prolong the service life of the runway.

4. Conclusion

Based on the theory of "pot-cover effect" and Shenyang Airport Project, the following conclusions are drawn:

(1) The "pot-cover effect" is a main cause of pavement diseases, which is distributed in dry and seasonal areas with large temperature variations.

(2) Diversion canals are laid in areas where runway diseases occur repeatedly, which are divided into transverse and longitudinal diversion canals. The spacing of transverse diversion canals depends on the condition of pavement diseases. Both transverse and longitudinal diversion canals should be backfilled with plain soil and compacted by rolling. It is suggested that the structure of the diversion canal be as follows:

The cross section size of the diversion channel is 500mm * 500mm. It can be used sand-gravel or broken stone as filling material and be wrapped with 250g/m² permeable geotextile.
The bottom width of the longitudinal diversion canal is 600 mm, the upper width is 1100 mm, and the height is 800 mm. The slope is 1:0.3 on both sides, the material is 5-30 cm broken stone, the bottom of the ditch is paved with 200 mm soft permeable pipe and is wrapped with 250 g/m² permeable geotextile.

Appropriate layout scheme of diversion canal can effectively solve pavement diseases caused by water enrichment, which is of great significance to improve the service life of airport pavement.

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