Prediction model of runway thawing settlement in frozen soil region under aircraft dynamic load

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Abstract. To investigate the influence of different years and aircraft dynamic load parameters on the thawing settlement of airport runways in frozen soil region, a three-dimensional numerical model is applied to analyze the thawing settlement effect of the runway in frozen soil region under different aircraft quality, taxing speed, pavement evenness index and years. And the prediction model of runway thawing settlement in frozen soil region is established, which is affected by the multi-factor comprehensive influence of aircraft quality, taxing speed, pavement evenness index, and years. The goodness of fit of the prediction model is 0.988 under a 95% confidence level, which shows that the prediction model can objectively predict the thawing settlement of runway in frozen soil region. The study provides technical support for airport construction and development in frozen soil region.

Keywords: thawing settlement; aircraft quality; taxing speed; pavement evenness index; frozen soil.

1. Introduction

In China, the frozen soil region is about 22% of the country's land area [1]. According to the plan of the Civil Aviation Administration of China, China will build several feeder or general airports to meet the growing traffic demand in the frozen soil region by 2030. However, the subgrade in the frozen soil region is an isotropic non-homogeneous four-phase complex composed of gas, water, ice, and soil particles, which produces movement, diffusion, and phase change under the action of external conditions. The thawing settlement becomes one of the main diseases affecting the stability and safety of the subgrade in the frozen soil region.

In the last century, Stefan [2] derived the one-dimensional unsteady solution theory considering the phase transition in ice water without the experimental verification. Philip [3] comprehensively considered the interaction of gas, liquid, and solid in porous media as well as the difference of temperature gradient between void and soil. He established the coupled equation of moisture and heat of porous media under the combined action of temperature gradient and humidity gradient. Burkov et al. [4] predicted the temperature field of thawing settlement and studied the influence of temperature on the thawing settlement of the subgrade based on the stochastic analysis mathematical model. Yang et al. [5] studied the temperature field of thawing settlement in the frozen soil region of Qinghai-Tibet Plateau under climate warming. They obtained the influence law of climate warming on the temperature field of thawing settlement in the frozen soil region. Wang et al. [6] carried out random coupling analysis of water migration, ice water phase transformation, and heat conduction in the frozen soil region. They studied the variation law of unfrozen water content and temperature in the thawing settlement. Beskou et al. [7] analyzed the thawing settlement response of the subgrade in the frozen soil region using a three-dimensional numerical model. Meanwhile, they conducted field tests to verify the thawing settlement response of the subgrade in the frozen soil region. Chen et al. [8] used the gravel layer in the subgrade to increase heat absorption and reduce underground heat infiltration and evaluated thawing settlement with the help of numerical simulation. Yu et al. [9] applied hollow concrete bricks to cool the subgrade and reduce the thawing settlement. Liu et al. [10] calculated and compared the temperature field of the wide embankment and separated embankment of the Qinghai-Tibet expressway under different working conditions. Their results showed that the separation embankment had a wonderful effect on reducing subgrade thermal disturbance and thawing settlement. Hou [11] introduced the conservation law of energy, the conservation law of mass, and the determinism to derive the
expression of thawing settlement. They conducted comparative verification between numerical simulation and laboratory tests. Zhang et al. [12] analyzed the response pattern of asphalt concrete pavement and cement concrete pavement on the thawing settlement of subgrade based on the condition of multiple subgrade and pavement diseases in frozen soil region. Liu et al. [13] researched the temperature field of thawing settlement of block stone subgrade and soil subgrade in frozen soil region based on climatic conditions considering vehicle dynamic load comprehensively. Wang [14] studied the influence law of thawing settlement stability under ambient temperature change. Duan [15] discussed the change rule of the temperature field of the natural soil foundation and subgrade of the airport runway in the frozen soil region with temperature control measures. He analyzed the optimal cooling rate of gravel pavement under different average annual temperatures. Hao [16] analyzed the effect of the ventilation duct base on the temperature field of thawing and sinking of the road base in frozen soil region with the help of a numerical simulation and carried out an indoor test to verify it. Li [17] investigated the coupled hydrothermal effect of runway base thawing and sinking in the frozen soil zone using theoretical analysis, indoor tests, and numerical simulations.

Although the research on highway and railroad engineering in frozen soil region is mature and there are many achievements at home and abroad, the research on runway safety in frozen soil region is less. In addition, the wide pavement, large aircraft dynamic load, and high pavement evenness index of the airport runway in frozen soil region are not considered enough. Therefore, it is necessary to carry out the research on thawing settlement prediction model of the subgrade in frozen soil region based on the actual working condition of aircraft dynamic load under the influence of pavement evenness index. The study provides the theoretical support for the airport construction development and safe operation and maintenance in the frozen soil region.

2. Numerical model

The numerical model of the airport runway in the frozen soil region is established based on the subgrade section in the northeast Daxinganling region [17]. As shown in Fig. 1, there are clay soil (0.4m) in Zone II, silty clay soil (1.6m) in Zone III, a strongly weathered rock (18m) in Zone IV, and the structure of the pavement in zone I. According to the design specifications of asphalt pavements for civil airports, the structure of the pavement comprises an upper surface (0.15m) in Zone I-I, an under surface (0.15m) in Zone I-II, an upper base layer (0.3m) in Zone I-III, an under base layer (0.35m) in Zone I-IV, and subbase layer (0.5m) in Zone I-V. To eliminate the boundary effect, a 40 m wide natural surface is placed on both sides of the pavement structure. For the numerical model, the pavement structure is 45 m wide and 15 m long. The calculation time is 10 years. The thermal parameters of the clay soil, silty clay soil, and strongly weathered rock are presented in the literature [17]. The thermophysical parameters of the pavement layers are negligibly affected by temperature and presented in the literature [17].

Fig. 1 Runway schematic

The pavement structure layer adopts the linear elastic theory and the subgrade adopts the Mohr-Coulomb theory model, which mechanical and physical parameters presented in the literature [17]. The main landing gear configuration of B737-800 is shown in Fig. 2, which parameters are shown in Table 1 [18].
3. Prediction model

The maximum value of thawing settlement of the runway appears around August [14], so the maximum value of thawing settlement of the center of the pavement in August in the 1st, 5th, and 10th years for the 27 working conditions in Table 2 was selected and compiled in Table 3.

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The statistical analysis of the data in Table 3 is performed to obtain the relationship between aircraft mass, taxiing speed, IRI, and thawing settlement in the 10th year, as shown in equation (1). The prediction model of runway thawing settlement in different years are shown in equation (2).

\[
s = 3.79 \times 10^{-7} m + 1.68 \times 10^{-4} p + 3.48 \times 10^{-4} IRI \quad R^2 = 0.932 \quad (1)
\]

\[
s = 0.00044(k - 10) + s \quad R^2 = 0.988 \quad (2)
\]

Where \(s\) is the thawing settlement in the 10th year, \(m\) is the aircraft mass, \(p\) is the taxiing speed, and \(IRI\) is international, \(S\) is the thawing settlement in different years.

4. Conclusions

This paper establishes a three-dimensional numerical model of the runway in the frozen soil zone based on a three-dimensional unsteady heat conduction equation and thermal boundary conditions, and establishes a numerical model of the thaw settlement response of the runway in frozen soil zone under dynamic aircraft load by combining with aircraft dynamic load stochastic theory, and verifies the reliability and feasibility of the model by comparing with existing research results. Based on the validated numerical model, the influence of aircraft mass, taxiing speed, IRI, and year on the thawing of airport runways in frozen soil region is investigated, and the thawing prediction model for airport runways in frozen soil region under the combined effect of aircraft mass, taxiing speed, IRI and year is obtained through statistical analysis. The model has a goodness of fit of 0.988 at a 95% confidence level and can be used to predict the thaw settlement of runways in frozen soil region. This paper provides technical support for the development and safe operation and maintenance of airports in frozen soil region.

Acknowledgement

The authors gratefully acknowledge the Nation Natural Science Foundation of China (No. 52108333), Postgraduate Research Innovation Project in Tianjin (2022SKYZ366) and Tianjin Chengjian University Education and Teaching Reform and Research Projects (JG-YB-22071) for providing the funding that made this study possible.

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