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

Xiaolan Liu [1, a], Chuanwei Fu [1, b], Yixiang Chen [1, c], Chao Lv [1, d]

[1]College of Civil Engineering, Tianjin Chengjian University, Tianjin, 300384, China.

[a]1066323835@qq.com, [b]cwfu1992@126.com, [c]381827033@qq.com, [d]1317026669@qq.com.

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, taxiing 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, taxiing 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; taxiing 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].

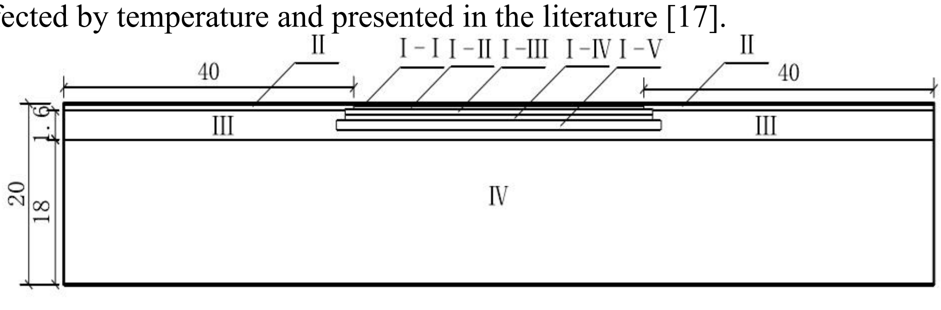

Fig. 1 Runway schematic

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].

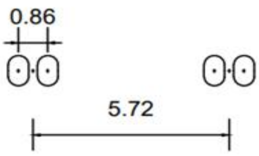

Fig. 2 Main landing gear configuration of B737-800

Table 1. Parameters of B737-800

Maximum take-off weight /kN	Number of main landing gears	Number of wheels	Main landing gear space /m	Wheel space /m	Load factor of main landing gear	Wheel load /kN	Tire pressure /MPa	Wheel print area /m^2	Wheel print length /m	Wheel print width /m
790.94	2	2	5.72	0.86	0.950	187.85	1.47	0.129	0.43	0.3

The main factors affecting the dynamic load of the aircraft are the aircraft mass, taxiing speed, and international roughness index (IRI). The aircraft masses includes 42275kg (0% aircraft load), 57878kg (60% aircraft load), and 73482kg (100% aircraft load). The taxiing speeds includes 10m/s, 30m/s, and 70m/s. The international roughness index includes IRI=1, IRI=3, and IRI=5. The working conditions are shown in Table 2.

Table 2. Working conditions

Number	Mass/kg,Speed/(m/s),IRI/1	Number	Mass/kg,Speed/(m/s),IRI/1
1	42275，10，IRI=1	15	57878，30，IRI=5
2	42275，10，IRI=3	16	57878，70，IRI=1
3	42275，10，IRI=5	17	57878，70，IRI=3
4	42275，30，IRI=1	18	57878，70，IRI=5
5	42275，30，IRI=3	19	73482，10，IRI=1
6	42275，30，IRI=5	20	73482，10，IRI=3
7	42275，70，IRI=1	21	73482，10，IRI=5
8	42275，70，IRI=3	22	73482，30，IRI=1
9	42275，70，IRI=5	23	73482，30，IRI=3
10	57878，10，IRI=1	24	73482，30，IRI=5
11	57878，10，IRI=3	25	73482，70，IRI=1
12	57878，10，IRI=5	26	73482，70，IRI=3
13	57878，30，IRI=1	27	73482，70，IRI=5

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.

Table 3. Maximum thawing settlement in pavement center under different working conditions

Number	1st year/m	5th year/m	10th year/m	Number	1st year/m	5th year/m	10th year/m
1	0.018458	0.021532	0.022575	15	0.019281	0.022353	0.023674
2	0.018543	0.021621	0.022663	16	0.019473	0.022536	0.023871
3	0.018608	0.021664	0.022739	17	0.019642	0.023006	0.024305
4	0.018617	0.021679	0.022778	18	0.019728	0.023114	0.024409
5	0.018636	0.021703	0.022801	19	0.020104	0.02358	0.024861

6	0.01867	0.021735	0.022879	20	0.023436	0.027725	0.028873
7	0.018781	0.021862	0.023128	21	0.023495	0.02777	0.028914
8	0.018804	0.021888	0.023179	22	0.023615	0.027863	0.028999
9	0.018814	0.0219	0.023191	23	0.027887	0.03202	0.033303
10	0.01882	0.021903	0.023194	24	0.030553	0.034703	0.035988
11	0.018829	0.021917	0.023208	25	0.045542	0.049792	0.051086
12	0.018856	0.021947	0.023238	26	0.053549	0.057852	0.059152
13	0.019115	0.022194	0.023504	27	0.061884	0.066243	0.067548
14	0.019144	0.022222	0.023534				

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).

$$s = 3.79 \times 10^{-7}\mathrm{m} + 1.68 \times 10^{-4}\mathrm{p} + 3.48 \times 10^{-4}\mathrm{IRI} \quad \mathrm{R}^2 = 0.932 \tag{1}$$

$$s = 0.00044(\mathrm{k} - 10) + s \quad \mathrm{R}^2 = 0.988 \tag{2}$$

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.

References

[1] Mao X S. Study on Coupling Model of the Moisture-Heat-Stress Fields in the Permafrost Subgrade [D]. Xi'an: Chang'an University, 2004.

[2] Stefan J. Uber die Theorie der Eisbildung[J]. Monatshefte für Mathematik und Physik, 1891, 278(2):269-286.

[3] Philip J R. Moisture movement in porous materials under temperature gradients [J]. Transactions of America Geophysics Union, 1957, 38(8): 222-231.

[4] Burkov P, Konan E C, Burkov V, et al. Stochastic analysis of temperature fields in frozen foundation soils[J]. AIP Conference Proceedings, 2017, 180(5): 1-6.

[5] Yang K, Yanhu M U, Wei M A, et al. The Evolution Law of Ground Temperature Field in Permafrost Roadbed of the Qinghai-Tibet Plateau under Climate Warming[J]. China Earthquake Engineering Journal, 2018, 40(4): 734- 744.

[6] Wang T, Zhou G Q, Wang J Z, et al. Stochastic coupling analysis of uncertain hydro-thermal properties for embank ment in cold regions[J]. Transportation Geotechnics, 2019, 21(2): 1-10.

[7] Beskou D N, Tsinopoulos S V, Theodorakopoulos D D. Dynamic elastic analysis of 3D flexible pavements under moving vehicles: a unified FEM treatment[J]. Soil Dynamics and Earthquake Engineering, 2016, 82(5): 63-72.

[8] Chen L, Yu W B, Yi X, et al. Numerical simulation of heat transfer of the crushed-rock layer embankment of Qinghai-Tibet Railway affected by aeolian sand clogging and climate change[J]. Cold Regions Science and Technology, 2018, 155(2): 1-10.

[9] Yu Q H, Mu Y H, Yuan C, et al. The cold accumulative effect of expressway embankment with a combined cooling measure in permafrost zones[J]. Cold Regions Science and Technology, 2019, 163(5): 59-67.

[10] Liu Z Y, Cui F Q, Chen J B, et al. Study on the permafrost heat transfer mechanism and reasonable interval of separate embankment for the Qinghai-Tibet expressway[J]. Cold Regions Science and Technology, 2020, 170(1): 1-9.

[11] Hou S G. Study on Mechanism of Subgrade Thawing and Countermeasrue Against Pavement Structure Distress in Permafrost Region [D]. Nanjing: Southeast University, 2006.

[12] Zhang J W, Li J P. Thermal stability analysis of different type embankments in permafrost regions[J]. Rock and Soil Mechanics, 2011, 32(S1): 532-537.

[13] Liu C, Che A L, Wu Z J, et al.Stability of embankments in permafrost regions considering temperature field coupled with dynamic field[J]. Chinese Journal of Geotechnical Engineering, 2011, 33(S1): 466-471.

[14] Wang S H. Study on Impact of Environmental Temperature Changes on Bearing Capacity of Airport Runway in Permafrost Regions[D]. Tianjin: Civil Aviation University of China, 2018.

[15] Duan S H.The Study of the Application of Gravel-filled Layer in the Construction of Runway in Permafrost Regions[D]. Tianjin: Civil Aviation University of China, 2019.

[16] Hao Y N. Study on Temperature Control Technology of Runway Foundation in Permafrost Area[D]. Tianjin: Civil Aviation University of China, 2019.

[17] Li Y. Study on Runway Subgrade Moisture-Heat-Stress Coupling Effect in Permafrost Regions[D]. Tianjin: Civil Aviation University of China, 2019.

[18] Liu X L,Zhang X M, Dong Q. Correlation analysis model of dynamic and static modulus for subgrade with taxiing aircraft[J]. Journal of Beijing University of Aeronautics and Astronautics, 2019, 43 (09): 1780-1789.