Moisture Content Distribution and Variation Law of Highway Subgrade in High-Latitude and Low-Altitude Deep Seasonal Frozen Ground Region

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Abstract. According to the tracking observation of the highway subgrade moisture content in the high-latitude and low-altitude seasonal frozen ground region in Heilongjiang province, the time-varying variation law of the subgrade moisture content and the distribution state of the subgrade moisture content at different depths are analysed to confirm that the distribution pattern of moisture content in fine-grained soil subgrade does not strictly conform to capillary ascent distribution law of groundwater (or surface water), which is related to the coverage and gap of the pavement, slope water seepage and water-holding capacity of the subgrade soil. In general, the distribution state can be roughly divided into B distribution, C distribution, D distribution and S distribution. As the distribution of subgrade moisture content is no longer the conventional pattern of “low up and high down”, the control of subgrade height should not be rigidly stuck to the subgrade height controlled by capillary ascent height, while multiple measures should be taken to ensure water temperature and strength stability of subgrade.

1. Introduction
To facilitate the continuous observation of subgrade moisture content, a section for test observation is selected from the highway connected to the Songhua River navigation-power junction. The section is located in the east of Songnen Plain, Heilongjiang Province, in the micro-hill plain. The overall strike of the section is from southwest to northeast. The mean annual precipitation of the region is about 583mm, and the rainy season is concentrated from June to September. The surface vegetation along the route is mainly dry farmland with a small number of paddy fields and forest lands.

The section for test observation is selected between K41+500 and K42+900 of the highway and located in the Bayan County, Heilongjiang Province, with temperate continental monsoon climate. Natural zoning of highway is II2 (heavy frozen region of piedmont plain in the central northeast). The region of the section for test observation has four distinctive seasons and a relatively large temperature difference: Spring is short with more wind and less rainfall. Summer is hot with plentiful rainfall. Autumn is cool and dry. Winter is long and cold. The local annual average temperature is 2.9℃. The historical highest temperature reached 37.9℃ and the lowest temperature reached -42.5℃. Annual frost-free season reaches 115-135 days.
2. Subgrade station layout scheme

2.1. Basic information of subgrade
The design height of the section subgrade is between 0.9m-3.7m and the technical grade of the highway is Grade II. The soil texture of foundation soil and subgrade filling is sandy silt of low liquid limit (MLS). To observe the distribution and variation law of subgrade moisture content along with the subgrade depth, four cross-sections (K41+605, K41+615, K42+780, K42+800) for observation are set at the corresponding design height of 2.51m, 2.40m, 2.11m, 2.03m. The underground water level is 1.60m.

2.2. Layout scheme of sensors
According to the needs of subgrade moisture content observation and analysis by comparing survey and consultation with indoor experiments, the soil temperature and humidity sensor sealed by resin is selected for the test observation section. The front end of the sensor is a metal temperature and humidity probe with a diameter of 1.4cm and a length of 25.5cm and the rear end is a resin-casted seal assembly with an engineering plastic shield and the dimension (length x width) of 5cm x 9cm and the thickness of 2.5cm. The matched DC-AC data acquisition instrument is rechargeable and portable. The diameter of the signal transmission line is 5mm. Data can be read when the signal line is connected with the portable data acquisition instrument during observation (as shown in Figure 1).

![Sensors and Line Concentration Holes Installed in Slope Toe](image1)

(a) Alternative Sensor  (b) Alternative Sensor

(c) Selected Sensor  (d) Line Concentration Holes Installed in Slope Toe and Portable Data Acquisition Instrument

Figure 1. Sensors and Line Concentration Holes Installed in Slope Toe for Highway Subgrade Moisture Content Test

To reduce the impact of horizontal subgrade positions on moisture content, three stations are simultaneously set on the left, central, right ends of horizontal subgrade along the cross-section of the subgrade at different depths. The average value of observation data on three stations at the same depth is regarded as the subgrade moisture content of the horizon. The placement horizons of subgrade stations are shown in Figure 2.
2.3. Technical parameters of sensors

Soil temperature and humidity sensors can be used to directly measure temperature and relative humidity\(^{[1,2]}\). To determine the subgrade moisture content, samples of subgrade filling are used for an indoor calibration test under the same compactness conditions to establish a relationship between the moisture content of the subgrade soil and the temperature and relative humidity measured by sensors\(^{[3]}\), so that relative humidity measured through the field tracking measurement can be converted into the subgrade moisture content.

Main technical parameters of the selected sensor are as follows:
- Temperature testing range: \(-50^\circ{}C\) to \(+60^\circ{}C\) at a precision of \(\pm1\%\);
- Humidity testing range: \(1\%\) to \(99\%\) at a precision of \(\pm3\%\) RH;
- Working voltage: AC220V\(\pm10\)V or DC12V (for portable data acquisition instrument);
- Standard length of sensor signal line: 5m-30m;
- Sensors are required to be permanently installed in the subgrade. Therefore, the service life of both embedded sensors and signal lines selected for this observation is more than three years.

3. Sensor construction and layout for subgrade moisture content

The setting position of and interval among temperature and humidity sensors selected for layered settings during subgrade filling are controlled by the slotting location and depth of the rolling surface of subgrade filling. The vertical interval between adjacent sensors is 20cm-25cm and the top sensor is about 15cm far away from the top subgrade surface (seal coat of the top subgrade surface is filled with weathered hilly sand and the sensor is installed in the seal coat).

Way to install sensors: Before the lower subgrade filling is paved, the current subgrade compaction surface is provided with shallow slots with a depth and a width of 5cm-10cm and a length of about 35cm to place sensors horizontally. Sensors and signal lines are covered by manually shoveling the soil with a certain thickness of filled soil (of 15cm-20cm). The signal line is buried along the subgrade surface to the slope. Then, the subgrade is normally paved, filled and compacted (as shown in Figure 3). Three sensors are installed on each filling layer of the same cross-section. For the depth range, sensors are mainly installed from the roadbed closely to the surface.

Figure 2. Schematic Diagram of Pre-embedded Sensor Position

Figure 3. Sensor Layout and Rolling Compaction of Subgrade Filling
4. Time-varying observation of subgrade moisture content

4.1. Observation time of moisture content

As the measurement reading of the sensor is the relative humidity of the subgrade soil, it is required to convert the data through field observation according to the calibration results of indoor tests. Tests and calibrations have been carried out in advance under various temperature and humidity conditions during sensor selection. Results show that the impact of temperature can be ignored in the conversion of moisture content at a general environmental temperature of 5℃-27℃. Besides, indoor tests and field verification show that this type of sensor only can measure temperature and cannot normally measure the relative humidity when the soil is frozen. The reading of the sensor will return to be normal when the temperature of the station reaches over 5℃ in the spring thawing period. Therefore, two field observations should be carried out in September and October of the same year when the capping of subgrade filling is completed (The subgrade is capped in June. The base course of pavement is completed in September. The pavement is completed in October.). In the same month of each spring, summer and autumn of the second, third and fourth year, an observation should be carried out respectively.

4.2. Time-varying observation result of subgrade moisture content at different depths

Figure 4. Time-varying Moisture Contents of K41+605 Section at Different Depths

Figure 5. Time-varying Moisture Contents of K41+615 Section at Different Depths
Figure 4 and 5 show observed results of subgrade moisture content at different depths for three years on two cross-sections for test observation sections of K41+605 and K41+615. The time-varying fluctuation law of subgrade moisture content for the other two cross-sections for test observation is basically the same.

The observation results in Figure 4 and 5 show that the moisture content of subgrade (roadbed) is relatively low in a period after the capping of subgrade filling. As the compaction of subgrade filling is controlled by the optimal moisture content, the total moisture content of the roadbed is low in a short time after formation. But as time extends, roadbed humidity is gradually balanced with the surrounding environment due to the changing environmental humidity and temperature. There are several regular variations to a certain extent: The moisture content of the roadbed is higher in the spring and rainy seasons and is lower in the autumn. As the sealing material is weathered hilly sand with relatively weak water-holding capacity, the measured moisture content in the layer (at the 15cm position) is relatively small.

Figure 6 and 7 show observed results of depth-varying subgrade moisture content for three years on two cross-sections for test observation sections of K41+605 and K41+615. The time-varying fluctuation law of subgrade moisture content for the other two cross-sections for test observation is basically the same.

The observation results in Figure 6 and 7 show that the vertical distribution of the subgrade moisture content is not the distribution pattern of “low up and high down” affected by capillary water.
In the initial stage of the completion, the distribution of “low up and high down” occurred indeed, but it is because of the time difference of filling and the rainfall in the construction period, that is, early-compacted filling soil on the lower part of the subgrade is affected by rainfall and environmental humidity and the moisture content gradually rise from the best moisture content controlled by the compaction. After the subgrade is capped and the pavement is completed, the humidity of the soil matrix is inclined to be the balanced humidity in a natural environment. The moisture content of later-compacted filling soil on the upper part of the subgrade increases gradually so that the phenomenon of “low up and high down” no longer exists.

Besides, the coverage of the pavement plays a “moisturized” role in the subgrade and offset the impact of capillary water ascent changing in height to a certain extent [4-6]. On the other hand, the underground water level of the section is not very high (at a depth of about 1.6m from the earth’s surface). The impounded surface water only exists a week after rainfall in the rainy season, which is the temporary transitional surface water. Therefore, there is no sufficiently significant influence of underground water and long-term surface water.

5. Distribution law of subgrade moisture content along depth

According to the previous analysis and the tracing observation result of the moisture content of subgrade, there is no “distribution law of the moisture content along subgrade depth impacted by underground (surface) water” during the investigation, namely “low up and high down” in a general sense. It is because the distribution law of “low up and high down” in a general sense is based on the premise of the coverage of subgrade homogeneity, asphalt-free or cement pavement, as well as very little impact by the surface water [7, 8]. That state only exists in the process of subgrade construction in practical engineering and changes gradually after the subgrade is capped.

From the moisture content observation result of four subgrade sections, it can be seen that the distribution laws of subgrade (roadbed) moisture contents differ from each other. In general, it could be approximately divided into Type B distribution, Type C distribution, and Type S distribution, as shown in Figure 8.

![Figure 8. Distribution Type Diagram of Roadbed Moisture Content](image-url)
Because the distribution of subgrade moisture content and the volume of moisture content are related to the road surface condition, underground water level, subgrade soil texture, subgrade soil construction, as well as air temperature, rainfall, wind direction & wind speed and sunlight, etc., the water distribution type in the roadbed (subgrade) is not fixed. In Figure 5 and Figure 6, the moisture content of the same section differs at different times, indicating that the subgrade moisture distribution along depth is in a dynamic change process.

Besides, according to the comprehensive investigation report in Anda, Binxian County, Yanshou County, Mudanjiang City and Fujin by the “preparation team of revising Specifications for Design of Highway Pavement in Heilongjiang province” in the 1970s [3], even though it is the sand-gravel pavement in the early period, as for the moisture content at 80cm of the upper subgrade in the spring thawing period, there are also diversified types including Type A (approximately the ideal type of “low up and high down”), Type B, Type C and Type D, etc. Namely, there are diversified signs of distribution law along subgrade depth of moisture content.

6. Conclusions

(1) As for the moisture content of the fine-grained soil subgrade of the observed highway section, it does not follow the capillary rise distribution law of underground water (or surface water) strictly. To some extent, the cause is related to the pavement coverage, pavement cracks, water seepage of the slope, and water holding capacity of the subgrade soil. In summary, it can be approximately divided into Type B distribution, Type C distribution, Type D distribution and Type S distribution.

(2) As for the new highway with good pavement appearance, due to the weak impact by the surface water, there is a regular change in the moisture content of the roadbed to some extent: In spring and rainy season, the roadbed moisture content is high, while it decreases to a certain extent in autumn. Besides, the same section could have different moisture distribution types in different periods, showing that the subgrade moisture distribution along depth is in a dynamic change process.

(3) In different years, there are certain differences in the subgrade moisture content in unfavorable seasons and the moisture content fluctuation range is within 0.3%-6.0%. The fluctuation range of average roadbed moisture content is about 2.3%-4.6%. It is possible that the dry & wet type of subgrade changes because of the moisture content change.

(4) As for the impact on the design control height of the subgrade, relative to strength, stability is the key, i.e. the water and temperature stability of the subgrade play a major role. Because the distribution law of the subgrade moisture content no longer follows the ideal type of “low up and high down”[8-10], as for the control of subgrade height, it is not recommended to follow the subgrade height controlled by the capillary rise. Various measures should be taken to ensure the water temperature stability and strength stability of the subgrade.

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