GEOTECHNICAL ENGINEERING CHALLENGES TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

'Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society' includes the papers presented at the XVIII European Conference on Soil Mechanics and Geotechnical Engineering (Lisbon, Portugal, August 26 to 30th, 2024). The papers aim to contribute to a better understanding of problems and solutions of geotechnical nature, as well as to a more adequate management of natural resources. Case studies are included to better disseminate the success and failure of Geotechnical Engineering practice. The peer-reviewed articles of these proceedings address the six main topics:

- New developments on structural design
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- Environment, water, and energy
- Future city world vision

With contributions from academic researchers and industry practitioners from Europe and abroad, this collection of conference articles features an interesting and wide-ranging combination of innovation, emerging technologies and case histories, and will be of interest to academics and professionals in Soil Mechanics and Geotechnical Engineering.

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Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society

Les Défis de la Géotechnique pour Répondre aux Besoins Actuels et Émergents de la Société

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Evaluation of frost heaving in frozen foundation layers due to the transfer of water in a gaseous state

Évaluation du soulèvement par le gel des couches de fondation gelées dû au transfert d'eau à l'état gazeux

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ABSTRACT: The redistribution of moisture during uniaxial freezing of the soil at the base of roads in winter is of great importance for its bearing capacity during the spring thaw. In winter, an ice lens forms directly under the road due to the higher thermal conductivity of the pavement layers. And during the spring thaw, the base of the road may become oversaturated, leading to volume changes and damage to the road structure. This article presents a theoretical calculation of moisture accumulation in frozen layers due to water migration in a gaseous state based on monitoring data. A section of the highway near Kosshy town 20 km from the capital of Kazakhstan, was monitored in the winter period of 2021-22 and 2022-23. The water mass transfer in a form of vapour 1.41-1.44·10^{-4} g/h per 1 dm^3 of soil at with temperature fluctuations -5-8 °C based on monitoring data of the highway foundations in winter period. The rate of vapour transfer in the frozen soil was 0.467-0.472 m/h and caused the formation of 430-456 g of ice due to the accumulation of water in a gaseous state in every 1 m^3 of soil, which increased the humidity by 40% or more and significantly reduced the bearing road capacity during the spring thaw.

RÉSUMÉ: La redistribution de l'humidité lors du gel uniaxial du sol au pied des routes en hiver est d'une grande importance pour sa capacité portante lors du dégel printanier. En hiver, une lentille de glace se forme directement sous la route en raison de la conductivité thermique plus élevée des couches de chaussée. Et lors du dégel printanier, la base de la route peut devenir sursaturée, entraînant des changements de volume et des dommages à la structure de la route. Cet article présente un calcul théorique de l'accumulation d'humidité dans les couches gelées en raison de la migration de l'eau à l'état gazeux, basé sur des données de surveillance. Un tronçon de l'autoroute près de la ville de Kosshy, à 20 km de la capitale du Kazakhstan, a été surveillé au cours de la période hivernale 2021-22 et 2022-23. Le transfert de masse d'eau sous forme de vapeur est de 1,41-1,44·10^{-4} g/h pour 1 dm^3 de sol avec des variations de température de -5-8 °C, d'après les données de surveillance des fondations routières en période hivernale. Le taux de transfert de vapeur dans le sol gelé était de 0,467 à 0,472 m/h et a provoqué la formation de 430 à 456 g de glace en raison de l'accumulation d'eau à l'état gazeux dans chaque m^3 de sol, ce qui a augmenté l'humidité de 40% ou plus et a considérablement réduit la capacité portante de la route lors du dégel printanier.

Keywords: Highway construction; temperature-moisture monitoring; freezing of soils; bearing capacity; ice lens formation.

1 INTRODUCTION

Temperature effects and especially moisture content have a huge impact on the strength characteristics of road bases (Teltayev et al., 2022). Due to the continental climate, the impact of temperature changes and transitions through 0°C have a more pronounced impact on the durability of the road structure (Teltayev and Suppes, 2019). The increased thermal conductivity of pavement materials distorts the temperature field under the road, contributing to the accumulation of moisture under the influence of cryosuction forces. The gradual freezing of layers of a road structure in winter initiates the transfer of water in a gaseous state from warm layers to colder ones and, as it freezes, it captures a large suction zone (Sarsembayeva and Zhussupbekov, 2021). The formation of an ice lens under roads leads to a significant decrease in bearing capacity when melting in the spring.

This study examined temperature and humidity monitoring data during the winter period for 2021-22 and 2022-23 at a section of the highway near Kosshy town, 20 km from the capital of Kazakhstan, Astana. The transfer of water in frozen soils in a gaseous state was considered as the main source of ice lenses formed in the foundation soils of highways in winter.

2 METHOD

The cross-section design of the highway at the experimental site is presented in Figure 1. The temperature and humidity of the highway structure was monitored at a depth of up to 3 m using sensors embedded in metal capsules and recorded by a data logger every hour.

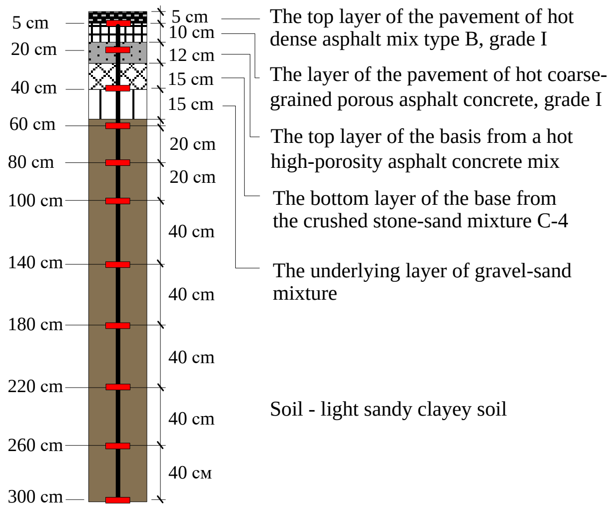

Figure 1. Design of highway structure.

Table 1. Physical and mechanical characteristics of road base soils.

Soil property	Unit	Value
Moisture content	%	20.2
Liquid Limit	%	26.5
Plastic Limit	%	15.1
Plasticity Index	%	11.6
Consistency index		0.5
Bulk density	g/cm³	2.0
Particle density	g/cm³	2.7
Void ratio		0.7
Degree of saturation		0.8
Deformation modulus	MPa	6.5
Cohesion	kPa	23.5
Angle of internal friction	degree	22

The base soil is light sandy clay loams, light brown in colour, hard, with layers of clay at a depth of 2.4 m with a thickness of up to 0.2 m. Soil samples taken from the construction site are water-bearing sediments. The amplitude of groundwater level fluctuations is 1.0-2.0 m from the ground surface, the minimum level is observed in February, the maximum at the end of May. Physical and mechanical characteristics of road base soils are presented in Table 1.

The amount of water transported in a vapour state directly depends on the type of soil and the volume of pores in the soil, the temperature gradient or temperature difference across the depth of the soil, as well as humidity at the transition through 0°C. Calculation of vapour mass using the saturated vapour pressure P_{si} over ice surface is:

$$m_{vapour,t_i} = \frac{\mu \cdot P_{si} \cdot V_{air}}{R \cdot T} \qquad (1)$$

where μ - molar mass of vapour, g/mol; P_{si} - saturated vapour pressure over ice surface corresponding to the current temperature, Pa; V_{air} – volume of air in the soil, cm³; R - Universal gas constant, J/(mol·K); T – temperature; Kelvin.

The mass of ice built from the vapour passing over time period t with speed v over the cumulative air channel cross section A_{air} is calculated:

$$m_{ice} = \rho_{vapour} \cdot V_{air\ voids} = \rho_{vapour} \cdot v \cdot t \cdot A_{air} \qquad (2)$$

where, m_{ice} - mass of built ice in grams; ρ_{vapour} - is taken as an average density value of the vapour densities at the start and end time point, g/cm³. The detailed calculation method was described in Sarsembayeva et al, 2022a.

3 RESULTS AND DISCUSSION

Figures 2 and 4 present temperature monitoring data in the above layers of the road structure in January 2022 and 2023. And in Figures 3 and 5 the measured moisture content of the pore space in the soil base is presented at a level of 60 cm from the surface of the road surface and below. More detailed results on monitoring temperature and humidity can be found in Sarsembayeva et al. (2022b).

The average air temperature in the winter of January 2022 was –8.12 °C, with maximum air temperatures reaching up to +6.0 °C and minimum values reaching -20.9 °C. In general, this period was characterized by higher average values compared to data from previous years. The greatest temperature fluctuations were confirmed for the upper layers of road pavement with the densest structure. There were 11 short-term transitions through 0°C in air temperature, but the layers of the road base remained in a frozen state and never crossed the 0°C, apparently due to compensation for the heat transfer of the underlying layers with a lower temperature. Relative stabilization of the foundation soils reached a depth of -180 cm at negative temperatures ranging from -4 - 6°C. The freezing front in January 2022 occurred at a depth of -140 cm and -180 cm, as evidenced by a drop in humidity from 21 and 23%, respectively, to 17% in a frozen state.

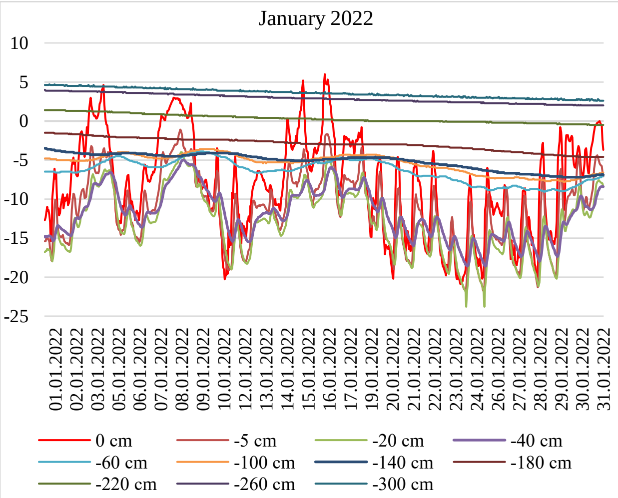

Figure 2. Temperature monitoring in January 2022.

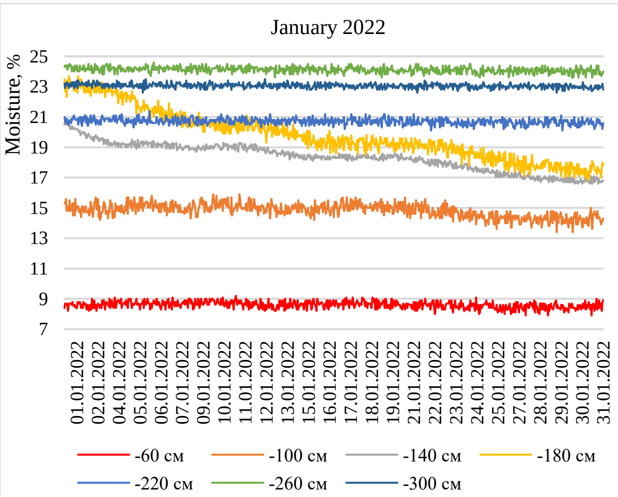

Figure 3. Monitoring of soil humidity in January 2022.

Base soil located at a depth of -60 cm consisting of light sandy clayey soil is a frost susceptible and is in a stably frozen state at a temperature of -5-8 °C. This layer acts as a moisture accumulator during the winter period, and it is there that an ice lens is formed, leading to a weakening of the bearing capacity of the road base during the spring melting period. Therefore, as an example of calculating vapor mass transfer, a soil layer at a level of -60 cm was considered. The water mass transfer in a form of vapor $1.44 \cdot 10^{-4}$ g/h per 1 dm^3 of soil. The rate of passage of vapor towards the freezing front in the soil was 0.467 m/h.

The freezing of the ground base continued for 132 days in the winter period of 2021-22 in Astana with the formation of 456.72 g of ice due to the migration of water in a gaseous state in every 1 m^3 of soil, which increases the moisture content by 40% or more comparing to the pre-freezing period and significantly reduces the bearing road capacity during the spring thaw.

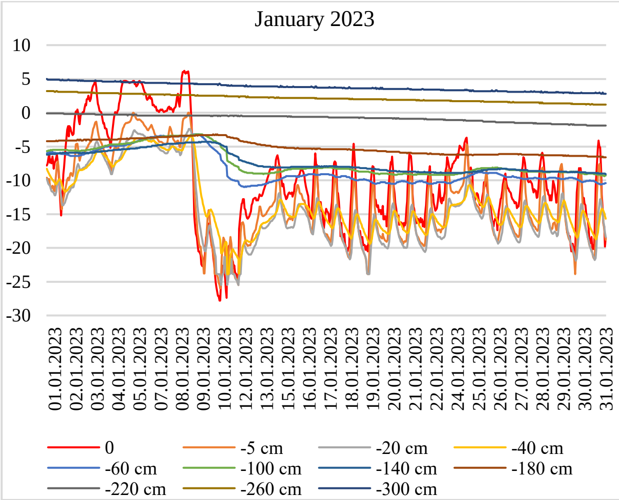

Figure 4. Temperature monitoring in January 2023.

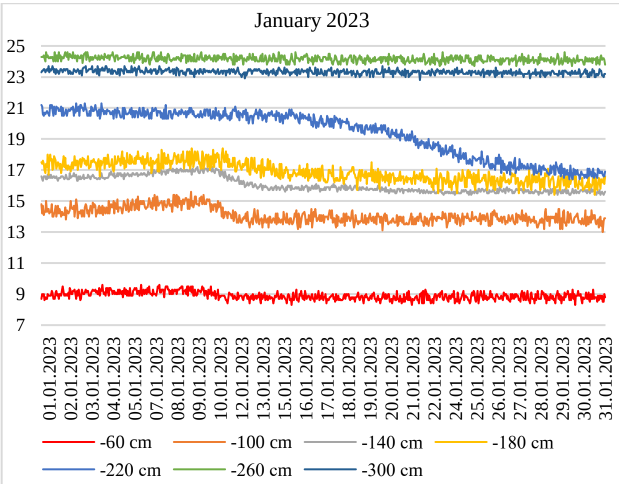

Figure 5. Monitoring of soil humidity in January 2023.

The average temperature for the month of January 2023 was -9.8 °C, with a minimum value of -27.8 °C and a maximum of +6.2 °C. The freezing front against the backdrop of a colder 2023 was deeper than in 2022, at -220 cm from the road surface. In this layer, a drop in humidity was also observed from 21% to 17% as the phase transition of water from liquid to solid state.

The duration of the frozen state of the soil under the highway was 126 days in the winter of 2022-23. The average temperature of the layer -60 cm was -9.49 °C and at a vapor transfer rate of 0.467 m/h, which led to the formation of $1.41 \cdot 10^{-4}$ g/h per 1 dm^3 of soil per day in January 2023. According to the calculations obtained, during the period of frozen state, 426.38 g of ice per 1 m^3 of base soil were accumulated in this soil layer only due to the migration and condensation of water in a gaseous state from warmer layers. An increase in humidity of up to 40% in the event of rapid melting can lead to collapse of the road structure during the spring thaw. In this area there is a restriction on cargo transportation with a large axial load, however, to prevent such risks, it is recommended to lay an additional layer of vapor barrier at a depth of -60 cm, which will also serve as thermal insulation by maintaining low humidity in the pore space of the soil.

4 CONCLUSIONS

1. Soil bases of highways, as well as layers of road pavement, remain in a stably frozen state during short-term temperature of air increases up to +6.0 °C due to sub compensation of heat (heat transfer) of the underlying layers and have a sufficient margin of safety.

2. With short-term increases in air temperature, only 25 cm from the top of the pavement are affected, which corresponds to the top layer of the base made of a hot, highly porous asphalt concrete mixture.

3. Daily temperature fluctuations in the top covering of hot dense asphalt concrete mixture average 2-5 °C with air temperature fluctuations of 6-12 °C.

4. The freezing of the layers is accompanied by a sharp drop in the humidity of the pore space from 21-23 to 11-14%, when part of the water in the gaseous state sublimates and forms a negative cryosuction pressure in these layers.

5. The base soil, located at a depth of -60 cm, consisting of light sandy clayey soil, is a frost susceptible layer and is in a stably frozen state at a temperature of -5-8 °C.

6. The water mass transfer in a form of vapour 1.41-$1.44 \cdot 10^{-4}$ g/h per 1 dm^3 of soil at with temperature fluctuations -5-8 °C based on monitoring of the highway foundations in winter period over the past 2 years. The rate of passage of vapour towards the freezing front in the soil was 0.467-0.472 m/h.

7. The freezing of the ground base continued for 126-132 days in winter periods of 2021-2023 and 2022-2023 in Astana city with the formation of 430-456 g of ice due to the accumulation of water in a gaseous state in every 1 m^3 of soil, which increased the humidity by 40% or more and significantly reduced the bearing road capacity during the spring thaw.

6. As a solution to the problem of water migration in the form of vapour, it is proposed to lay an additional layer of vapour barrier over the soil base at a depth of -60 cm.

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