Estimation method of rigid pavement deformation caused by a frost heave of subgrade

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ABSTRACT

Rigid pavement has advantages of long life with durability and less maintenance cost, which can be justified the higher initial cost when we consider costs over the whole life of pavement. We have little information, however, about the displacement or deformation of rigid pavement laying on a frost susceptible subgrade in cold regions. This paper shows a simple analytical method to estimate a deformation of rigid pavement, supposing a frost heave and a frost depth of subgrade and using FEM. The results are compared with the surface deformation data of rigid pavement of the airport apron constructed on a local frost susceptible subgrade soil. This analytical method is shown to be useful for rigid pavement design in cold regions.

Keywords: rigid pavement, frost heave, design method, cold regions

1 INTRODUCTION

The replacement method has been generally used for the frost protection of pavements in cold regions, Japan. The design theory or method for rigid pavements, however, is not always definite, comparing to that of flexible pavements. The authors focused on the rigid pavements of Obihiro airport apron damaged due to the differential frost heave action, because of the different replacement thickness on the adjacent portions with and without the drainage layer. As results of comparative study of the field measurement data and calculated values by FEM analysis, the both agreed approximately.

This analytical method is found to be useful for rigid pavement design in cold regions.

2 FIELD MEASUREMENT DATA

Surface deformation of pavement of airport apron had been measured through two winter seasons to investigate the uneven displacement of concrete slabs. Significant uneven deformations were observed on the slabs with the drainage layer in the center of subgrade. The measurement results were estimated due to the difference of frost susceptible properties of subgrade and drainage layer because the frost depth had reached into the frost susceptible subgrade soil. Pavement profile of the airport apron is shown in Figure 1, which has drainage layer with drain pipe in the center of subgrade layer along the long side direction of the slab. The field measurement data of reference points are shown in Table 1. The two points are located away about 23 m with same pavement profile.
3 FROST HEAVE OF SUBGRADE

It is necessary to calculate the amount of frost heave of subgrade to estimate surface deformation of rigid pavement. The displacement of subgrade due to frost heave is assumed to transmit elastically through the base course to the pavement surface.

3.1 Frost heave model

The frost heave rate of subgrade can be modeled by the following Equation 1 (Takashi et al. 1978).

\[
\xi = \xi_0 + \frac{\sigma_0}{\sigma} \left( 1 + \frac{\varphi_0}{\varphi} \right) \times 100
\]  

(1)

where \( \xi \) = frost heave ratio (%), \( \sigma \) = confining stress at freezing front (kN/m²), \( U \) = speed of freezing front (mm/hour), \( \xi_0 \) (%), \( \sigma_0 \) (kN/m²), \( U_0 \) (mm/hour) = soil constants on freezing.

Equation 1 is an experimentally obtained reliable relationship, which has been successfully predicting frost heave for more than 5,000,000 m³ of domestic artificially frozen ground in a number of construction cases. Soil constants can be determined from the literature or freezing test using samples from the site (JGS, 2009).

3.2 Soil constants

The soil constants in Equation 1 are determined from the literature (Ryokai et al., 1980) by referring to the frost heave test results carried out by the subgrade soil samples in the investigation report of the airport (City of Obihiro, 1984) because the tests results described in the report were indices of frost susceptibility, and are not able to use directly to determine the constants.

The constant \( \sigma_0 \) is related to an effect of confining stress at the freezing front, \( \xi_0 \) is to an intrinsic frost susceptibility, and \( U_0 \) is to an effect of freezing speed which controls the quantity of ice lens. \( U_0 \) can be zero in this investigation because the freezing speed is less effective under natural freezing.

4 FEM ANALYSIS

Surface deformation of rigid pavement due to frost heave of subgrade is obtained by two dimensional linear elastic FEM analysis, giving uniform displacement of frost heave to the nodes of upper boundary of subgrade layer. The amount of frost heave
is decreased gradually along the upper boundary of drainage layer until the bottom of the drainage layer comes to be flat. Finite elements, boundary conditions and displacement distribution are shown in Fig 2.

4.1 Physical properties
The subgrade material is frost susceptible natural volcanic soil. Pavement material is a concrete with tie-bars between slabs. The physical properties of all layers used for the FEM analysis are summarized in Table 2. The properties of concrete pavement and gravel layer are determined after the rigid pavement design code, and those of subgrade are determined based on the value of design CBR.

<table>
<thead>
<tr>
<th>Material</th>
<th>Concrete</th>
<th>Gravel</th>
<th>Gravel</th>
<th>Natural Volcanic soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (kN/m³)</td>
<td>24.5</td>
<td>20.9</td>
<td>20.9</td>
<td>14.0</td>
</tr>
<tr>
<td>Elastic modulus (kN/m²)</td>
<td>2.8×10⁷</td>
<td>3.5×10⁵</td>
<td>3.5×10⁵</td>
<td>2.0×10⁴</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.20</td>
<td>0.35</td>
<td>0.35</td>
<td>0.40</td>
</tr>
<tr>
<td>ξ (%)</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α(kN/m²)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>2.6</td>
</tr>
<tr>
<td>U₀ (mm/hour)</td>
<td>NS</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

NS : Non-frost susceptible material

4.2 Analytical results
The analytical result by FEM is shown in Fig.3. The concrete pavement is pushed up according to the deformation of the base course layer due to the frost heave of subgrade soil. Frost heave is obtained on the center of slab though non-frost susceptible materials are layered beneath it. The vertical surface displacement at the center of slab is calculated to be 31.4 mm, and at the edge of pavement surface is 62.7 mm.

The analytical results are compared to the measurement data of pavement surface in Fig. 4. The measurement data are available on the center and the edge of slab. The displacement at the center of the slab is observed a little larger than the calculated value and a little smaller at the edge of slab.

5 EVALUATION OF RESULTS
The calculated vertical displacement values of the pavement practically agree with the observed field data. The calculated value at the center of the slab could be increased when the base course and the drainage material are assumed to contain fine and frost susceptible fraction.

The displacement of the edge of the slab could be decreased when the tie-bars connected to the adjacent slab are assumed to be more constraint on the vertical movement of the slab end.

It is not considered the hardening of the base course layer caused by the freezing of water between particles, which may decrease the frost heave of the pavement.

6 SUMMARIES AND CONCLUSIONS
The displacement of rigid pavement due to the frost heave of subgrade can be calculated by means of FEM linear elastic analysis applying Takashi’s frost heave model.

Uneven deformation of the pavement is shown by the calculation and it agrees with the measurement data of surface displacement of the rigid pavement of the airport apron which has drainage layer in the center of
frost susceptible subgrade.

Frost susceptibility of base course and drainage material, confining condition of tie-bars at the end of slab and hardening of base course layer due to freezing are possible influencing factors to the calculation results.

The estimation method mentioned above is useful for the design of rigid pavement on the potential frost susceptible ground in cold regions.

REFERENCES