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Mechanistic Analysis of Frost Action under Pavements

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Introduction

In cold regions frost may penetrate to large depths below the surface of pavements, resulting in the formation and growth of subsurface ice lenses. Such frost action is accompanied by volume expansion that forcefully and unevenly displaces lower pavement boundaries [***1***]. Ultimately, the subterranean deformations result in added distortion at the ride surface - both longitudinally and transversely [***2***]. From a design and construction viewpoint, the adverse effects of frost action can be limited by considering remedial measures such as [***3***]: (i) increasing the thickness of non-frost-susceptible layers, (ii) introducing an insulation layer, (iii) lowering the water table level, and (iv) chemically treating the underlying soil. In essence, these measures aim at deepening the problem source.

In the current work a mechanistic model originally developed for the evaluation of pavements on expansive clays is offered for analysing deformations due to frost action [***4***,***5***]. The model introduces a rational association between imposed subsurface deformations and consequent surface deformations. Conversely, when surface deformations are known, the model can be employed in an inverse analysis to infer on the magnitudes and spatial pattern of frost action under pavements. This framework can be useful for studying the effectiveness of different design alternatives and as an additional input to pavement management in cold regions. Herein, the model basics are reiterated, followed by a demonstrative application.

Modelling and Analysis

The proposed model for analysing frost action considers (see Figure 1) a weightless, isotropic, homogeneous, and linear elastic layer (infinite laterally) with thickness H and material properties E (Young's modulus) and ν (Poisson's ratio). This layer represents the sum of all non-active materials within a pavement system, e.g., asphalt concrete, granular base, aggregate subbase, capping, and treated subgrade soil. Initially, the layer is assumed stress-free and undeformed with both top and bottom boundaries completely flat - as indicated by the dash-dot lines in the Figure. An axisymmetric blister-like displacement field is forced at the bottom of the layer, deforming the lower boundary in the vertical direction without inducing shear stresses at the interface. This deformation, indicated in the Figure by a solid line, represents the effect of frost action.

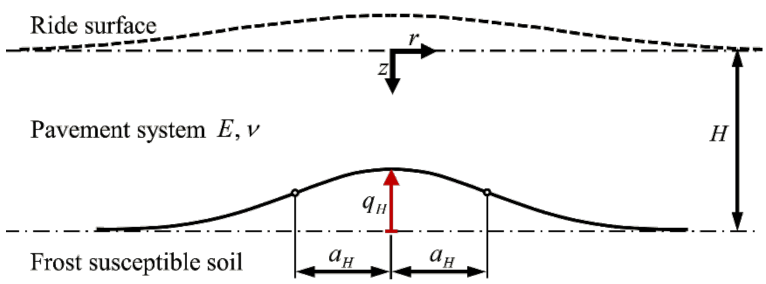

Figure 1: Illustration of basic model definitions with cylindrical coordinate system placed at the top of the undeformed layer.

The model permits calculation of all mechanical response types (i.e., stresses, strains, and displacements) inside the layer as well as at the top - corresponding to the ride surface level. The imposed displacement field at bottom is denoted by u_z^H, mathematically expressed as an axisymmetric Gaussian, i.e. $u_z^H(r) = q_H e^{-(r/a_H)^2/2}$, where r is the radial coordinate, q_H is the peak displacement occurring at $r=0$, and a_H represents the location of sign-change in the curvature of $u_z^H(r)$, i.e., the so-called Gaussian width. Both q_H and a_H have units of length; a_H must be positive, while q_H can be either positive or negative to indicate downward or upward deformation (respectively). The particular form of $u_z^H(r)$ was chosen because it can serve as a radial basis function for representing any other deformation shapes - not necessarily axisymmetric. This modeling flexibility is needed when simulating realistic situations. The vertical displacement at the top of the layer, denoted as u_z^0, is shown in Figure 1 by the dashed line. The mathematical formulation is given in [**5**]; it involves numerically evaluating a semi-infinite integral.

As a demonstration exercise, the model was applied to the analysis of settlements observed on the runway at the Kangerlussuaq Airport. Kangerlussuaq is the main airport hub in Greenland, and is situated in the continuous permafrost zone. The west end of the runway was constructed in 1957/58 on a thick embankment resting on ice-rich marine sediments. The thickness of the active layer is about 2 m, and the thickness of the non-active pavement structure (i.e. H) is approximately 1.5 m. This part of the runway has experienced severe differential settlements over the past decades. Surface elevation measurements were performed in 1973 (about 15 years after construction). After subtracting the original (as-built) elevations, these measurements are shown in Figure 2 for a certain longitudinal profile (dashed line). As can be seen, over a 400 m long strip, from station 2250 to 2650, the pavement settled unevenly by up to 0.4 m.

Model application to the problem commenced with spatially matching the measured elevation differences $MSE(x,y)$ with a function that is composed of a sum of $N=6$ radial Gaussians, each having a set of new parameters $q_{0,\mathrm{i}}$ and $a_{0,\mathrm{i}}$ in place of $q_{H,i}$ and $a_{H,i}$. This is carried out with a nonlinear optimization algorithm to determine the numerical values of the unknown Gaussian parameters. Next, the model was used to find the corresponding parameters for the subsurface Gaussians, see [**4**]. The resulting subsurface deformations are included in Figure 2 (solid line). It can be seen that the top of the active layer practically mirrors the surface shape and that the subsurface deformations are larger than the surface deformations.

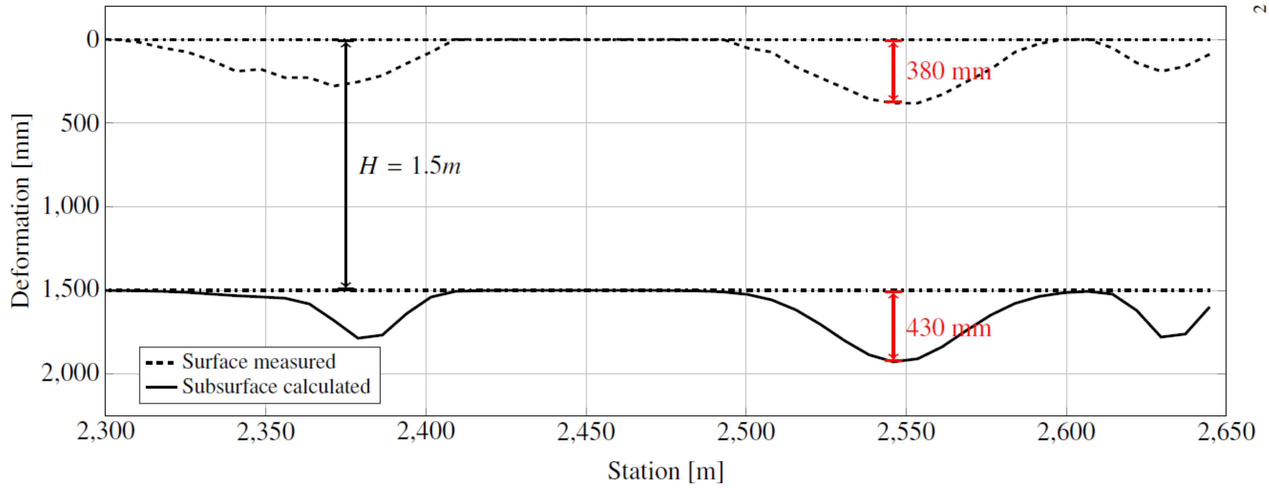

Figure 2: Measured and calculated surface and subsurface deformations.

Summary and Conclusions

In this study a mechanistic model is proposed and applied for simulating the coupled effect of a pavement with underground movements. A Gaussian function was used to represent the axisymmetric vertical deformation field of the runway surface in Kangerlussuaq Airport. The results obtained show that surface deformations can be approximated with a function that is composed of a sum of radial Gaussians. Calculated subsurface deformations were seen to be similar in shape to the observed surface deformations, and of larger in magnitude.

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