8.6 PARAMETERIZATION OF FROZEN SOIL PHYSICS AND FROST HEAVE FOR A NUMERICAL WEATHER PREDICTION MODEL

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1. INTRODUCTION

Much of the world's landmass is located in areas that experience prolonged winters. These areas include large parts of Asia, northern Europe, Alaska, Canada and the northern third of the USA. In these regions the land surface experiences cyclical freezing and thawing. Manmade structures are adversely affected by these freeze-thaw cycles. The spring thaw results in a weakened roadbed and reduced load bearing capacity. Trucks and other vehicles with large axel loads may drive over these pavements and cause permanent pavement deflection. To prevent the damage associated with high axel loads springtime road restrictions are placed. We anticipate a model-based solution to the road restriction dilemma. Roadbed thaw is reactive to the environmental conditions of the land surface and synoptic weather patterns while the roadbed strength is determined by the thermal and hydraulic state of the thawed portion of the frost susceptible subgrade. A numerical weather model that includes strong land surface dynamics can provide the backbone to drive a model solution of the springtime roadbed thaw depth. A shakedown analysis of the thawed roadbed, specifically the thermal and limits that will result in the critical load level required to reach the "shakedown load".
Consequently, a three-tiered approach of a numerical weather, land surface, and shakedown analysis program will provide useful decision support criteria to agencies responsible for road restriction placements.

2. FREEZE-THAW CYCLES – THEORY

Soil freezes from the top down along what is known as the "freezing front". As the soil freezes water is drawn upwards to the freezing front due to various mechanisms. These include water vapor pressure effects due to the soil temperature gradient, osmosis effects due to ion concentration variance, and tension at the ice-water interface that tends to pull water upwards. Under the right conditions as the soil freezes "ice lenses" of pure ice will form that heave the soil upwards. Conditions needed for frost heave include a frost susceptible soil, freezing temperatures, and a supply of water. As temperatures warm the soil will thaw from the top downwards.

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3. THAW WEAKENING OF PAYEMENTS – THEORY

The thaw weakening factors of pavements include soil type, permeability, drainage conditions and rate of thaw. As the thaw proceeds downwards areas that have high amounts of ice lenses begin to thaw. These thawing ice lenses create soils with a very high water content. Melt water flow is restricted latterly by the presence of frozen road shoulders while downward flow is restricted by the frozen soil and upwards flow is restricted by the road itself. Consequently, as a vehicle travels over roadbed the pavement the load is transferred to the water, creating a high pore water pressure. If the gravel directly below the pavement is frost susceptible then the gravel will become unstable and the pore water pressure will create an upward pressure that can crack and break up the asphalt. This effect happens early in a thaw. Similarly, when the thaw reaches a frost susceptible subgrade the excess water may cause a significant decrease in soil strength and result in pavement deformation. This type of damage occurs relatively late in the thaw.

4. LAND SURFACE MODEL – VIC

The Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model is an ideal land surface model to use for several reasons. It has been part of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) as well as the ongoing Land Data Assimilation Systems (LDAS) project. Meanwhile many of the cold season aspects of the model were refined in an upper Mississippi Valley study encompassing most of Minnesota, the eastern neighbor to the state of North Dakota. The inclusion of VIC in several model comparison studies as well as the cold season refinement in Minnesota provides the model with a basis for accuracy. Furthermore the routing aspects of VIC may lead towards better modeling of springtime streamflow in the Red River Basin. Considering the seasonal issues the Basin has with springtime flooding problems caused by snow melt and runoff an accurate routing model is itself of much benefit even without road restriction considerations. Cold season parameters included in the VIC model include such aspects as wind, vegetation, elevation and shortwave energy effects on snow depth, distribution and melt as well as a frozen soil algorithm that considers soil parameters that are applicable to the M_1 model (Nakano, 1999). The role of the VIC model will be to handle all land surface issues not set aside specifically for the M_1 model as well as provide part of the initialization data to run the M_1 model and shakedown analysis. Furthermore, VIC and M_1 can act as reliability checks on their comparative model runs to decrease model error. If thaw depth/frost depth estimates between VIC and M_1 start to differ significantly in a random or non-random manner it might indicate a variety of possible problems.

5. M_1 MODEL

The M_1 model is used to determine the freezing and thawing aspects of the roadbed itself. Since springtime load-bearing capacity is largely determined by the state of the frost susceptible subgrade it is essential to accurately model both the freezing process and ice lens formation in the fall to winter period as well as the subsequent springtime thaw and accompanied soil strength loss of the subgrade. While the frozen soil algorithm for VIC is itself similar to the M_1 model, it is not as computationally intensive nor accounts for a critical soil strength issue – pore water pressure. However, with no real need to model frost heave and springtime loss of soil strength for the general land surface the VIC frozen soil algorithm is used for land surface applications while the M_1 model is used exclusively for the roadbed freezing and thawing process.

6. SHAKEDOWN – THEORY

Classical shakedown theorem developed by Melan (1932) and modernized by Maier (1969) provides a mechanism to determine pavement structure characteristics. A pavement structure will undergo plastic and elastic deformation while developing stresses and strains as a result of loading. At "shakedown" after a certain number of loads the plastic deformation will become static, with no alteration in the plastic flow. Any subsequent deformation due to loading is purely elastic.

The shakedown load is defined as "the critical load level below which shakedown occurs, but above which permanent strains continue to occur" (BOULBIBANE, M and COLLINS, I.F. 1998). The shakedown load represents the maximum possible axel load that a pavement structure can support without permanent damage resulting.

However, if there is a reduction in subgrade soil strength then the bearing capacity of the pavement structure will be reduced below the previous shakedown limit and critical failure may occur as vehicles with high axel loads cause rapid and catastrophic plastic flow coupled with elastic stresses and strains leading to rutting or pavement breakup.

7. VIC- M_1-SHAKEDOWN COUPLING

While the VIC model handles the land surface parameters, generating a model forecast, the time step outputs are used to initialize certain M_1 data fields.

Subsequently, M_1 model outputs are used to in generating the shakedown analysis and resultant pavement load bearing capacities for the environmental and roadbed conditions.

8. DECISION SUPPORT

The final product of this model for road restriction use is axel load bearing capacity of the pavement structure. It is anticipated that Transportation personal will use the bearing capacity as a benchmark in setting appropriate road restrictions in regards to timing, location and degree of placement.

9. REFERENCES

VIC CODE REFERENCES – these 3 are requested to be cited when using vic model

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M1 MODEL

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