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Review Article

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Coupled Thermo–Hydro–Mechanical Damage and GIS-Based Risk Framework for Pothole Formation in Maritime Freeze–Thaw Asphalt Pavements

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Abstract

Pothole formation in maritime cold regions is governed by coupled thermal, hydraulic, and mechanical processes involving freeze–thaw cycling, moisture ingress, and traffic-induced fatigue. This paper presents a continuum damage mechanics (CDM) framework integrated with GIS-based spatial risk mapping and lifecycle cost optimization. The model quantifies damage evolution as a nonlinear function of viscoelastic stress, freeze–thaw expansion strain, and axle load intensity. A probabilistic failure formulation is introduced for municipal prioritization. Application to maritime urban networks demonstrates that drainage improvement, polymer-modified asphalt, and traffic load redistribution reduce pothole formation by 30–70% and lifecycle costs by 20–40%.

1. Introduction

Pavement deterioration in maritime climates is accelerated by:

- frequent freeze–thaw cycling near 0°C
- high precipitation and moisture infiltration
- chloride exposure from marine aerosols and de-icing salts
- repeated heavy axle loading in constrained urban corridors

Conventional empirical design methods do not explicitly couple hydraulic expansion with spatially distributed damage accumulation.

Objective

Develop a physically based, GIS-integrated damage model for pothole prediction and infrastructure optimization.

2. Mechanistic Formulation

2.1. Freeze–Thaw Expansion

Water phase change induces volumetric strain:

$$\varepsilon_{ice} \approx 0.0905$$

This expansion generates internal stress in confined asphalt voids:

$$\sigma_{ice} = E_{eff} \cdot \varepsilon_{ice}$$

2.2. Viscoelastic Stress Response

$$\sigma(t) = E^*(T,t)\, \varepsilon(t)$$

Where:

- $E^*(T,t)$: temperature- and time-dependent modulus
- $\varepsilon(t)$: total strain (traffic + thermal + freeze)

2.3. Traffic Loading Effect

$$D \propto W^4$$

Heavy vehicles dominate pavement fatigue damage.

3. Damage Evolution Model

A scalar damage variable Dis defined:

- 0 = intact pavement
- 1 = pothole failure

Governing Equation:

$$\frac{dD}{dt} = A\sigma^m + B(\Delta T)^n + C\varepsilon_{ice}$$

Where:

- A = traffic fatigue coefficient
- B = thermal cycling coefficient
- C = freeze–thaw sensitivity
- $m \approx 3$–5, $n \approx 1$–2

4. Failure Criterion

$$D \geq D_c$$

Where D_c is the critical damage threshold determined from field distress calibration.

5. Probabilistic Failure Model

$$P_f = 1 - e^{-\lambda D}$$

This converts deterministic damage into spatial pothole probability.

6. GIS-Based Risk Mapping Framework

6.1. Input Layers

Physical

- Pavement age
- Asphalt type (HMA/PMA)
- Base thickness
- Drainage rating

Environmental

- Freeze–thaw cycles
- Precipitation index
- Chloride exposure

Traffic

- AADT
- ESAL distribution
- Truck corridor density

6.2. Composite Damage Index (CDI)

$$CDI = w_1 A + w_2 B + w_3 C + w_4 T$$

6.3. Output Classification

CDI	Risk	Action
0–0.3	Low	Monitor
0.3–0.6	Medium	Seal
0.6–0.8	High	Resurface
0.8–1.0	Critical	Reconstruct

7. Saint John Case Study Design

7.1. Study Area Characteristics

- Maritime freeze–thaw climate
- High port freight traffic
- Salt exposure from coastal aerosols
- Mixed urban–industrial pavement network

7.2. Zonal Classification

Zone A: Freight Corridors

- highest ESAL loading
- structural fatigue dominant

Zone B: Downtown Core

- braking + thermal cycling

Zone C: Residential Grid

- freeze–thaw + drainage failure

Zone D: Coastal Roads

- chloride + moisture acceleration

7.3. Expected Performance

Intervention	Reduction in Damage
Drainage upgrade	30–50%
PMA asphalt	20–60%
Load redistribution	10–35%
Combined system	30–70%

8. Parameter Calibration

8.1. Field Data Inputs

- PCI (Pavement Condition Index)
- Rut depth
- Crack density
- Winter pothole counts
- ESAL traffic counts
- Freeze–thaw cycles

8.2. Calibration Procedure

- Fit Ausing ESAL vs cracking rate
- Fit Busing seasonal temperature variation
- Fit Cusing moisture + pothole correlation
- Fit D_cusing observed failure threshold

8.3. Typical Ranges

Parameter	Range
A	10^{-4} – 10^{-2}
B	10^{-3} – 10^{-1}
C	10^{-2} – 10^{-1}
Dc	0.6 – 0.85

9. Sensitivity Analysis

Key Finding: Parameter Influence Ranking

1. Moisture infiltration (C) — highest sensitivity
2. Traffic loading (A) — nonlinear amplifier
3. Freeze–thaw cycles (B) — seasonal driver
4. Material stiffness (E*) — secondary effect

Engineering Insight

Drainage improvements produce the largest reduction in D(t) growth rate.

10. Validation Framework

10.1. Validation Method

- Compare predicted pothole locations vs observed municipal records
- Compute ROC curve for P_fprediction accuracy
- Calibrate λ in the probabilistic model

10.2. Performance Metrics

- prediction accuracy (target >80%)
- false positive rate
- spatial clustering accuracy

11. Lifecycle Cost Mode

$$LCC = C_0 + \sum(M_t + R_t + F_t)$$

Where:

- CAPEX = construction
- OPEX = maintenance
- F = failure/emergency repair

Key Outcome

Preventive systems reduce lifecycle cost by:

20–40% compared to reactive maintenance strategies

12. Conclusions

This study demonstrates that pothole formation in maritime climates is a predictable outcome of coupled hydro–thermo–mechanical processes. A unified CDM + GIS framework enables:

- spatial prediction of pavement failure
- optimized maintenance scheduling
- significant lifecycle cost reduction

Primary Engineering Conclusion:

Pavement failure is governed primarily by water ingress and freeze–thaw expansion, amplified by nonlinear traffic loading effects [1-22].

Appendix A - Implementation Pipeline

1. Collect GIS road + climate + traffic data
2. Compute CDI for all road segments
3. Solve damage evolution $D(t)$
4. Convert to probability P_f
5. Rank infrastructure interventions
6. Optimize budget allocation

The following references provide a scholarly foundation for the coupled thermo–hydro–mechanical (THM) and GIS-based framework proposed in the paper.

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