

A coupled thermo-mechanical model for frost heave and mitigation design in cold-region pavements

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Abstract

Frost heave is a major cause of pavement damage in cold regions, where the growth of ice lenses in frost-susceptible subgrade produce differential ground movement, deformation, and cracking. This study presents a transient coupled temperature-displacement finite-element model for predicting frost heave and its structural effects in layered flexible pavements. Latent heat released during pore-water freezing is represented using the apparent heat-capacity method, and frost heave is simulated through a temperature-dependent expansion model based on the free-heave strain of the soil. Calibrated with a free-heave strain of 1% for a frost-susceptible silt, the model predicted a surface heave of 14.3 mm, within 3% of the literature value of 14.7 mm. The predicted heave and peak tensile stress (2.76 MPa) were correctly concentrated above the frost-susceptible zone, and a sensitivity analysis confirmed an almost perfectly linear relationship between free-heave strain and surface heave ($R^2 = 0.9998$). The validated model was then applied to evaluate three widely used frost-mitigation strategies. A 76 mm insulation board was the most effective, reducing surface heave by about 99% and almost eliminating frost-induced tensile stress, with negligible differences between polystyrene, polyurethane, and glass-fibre boards. Lime stabilisation of the upper 0.30 m of the subgrade reduced surface heave by 73% and peak tensile stress by 77%, while subgrade drainage, represented by a reduced degree of saturation, achieved heave reductions of 20% and 41% at 80% and 60% saturation, respectively. The proposed framework provides a practical and computationally efficient tool for evaluating frost-mitigation measures and supporting the design of durable flexible pavements in cold regions.

1. Introduction

Roads and airport runways constructed on frost-susceptible soils in cold regions often experience repeated damage due to frost heave. Frost heave occurs only when three conditions exist at the same time, namely freezing temperature that remain below 0°C, frost-susceptible fine-grained soil, and a continuous supply of water to the freezing zone [1]. Under these conditions, water moves toward the freezing front, where it freezes and forms layers of ice called ice lenses [2]. As these ice lenses grow, and push the pavement upward. Since soil properties and moisture content are not uniform throughout the ground, the amount of uplift varies from one location to another. This uneven movement causes the pavement to bend, creating tensile stresses that can lead to cracks. During spring, the ice lenses melt, leaving empty spaces in the soil and reducing its ability to support the pavement. As a result, the pavement settles and becomes further damaged. This repeated cycle of frost heave in winter and settlement during thawing makes road maintenance expensive and continuous and frost action is widely recognised as one of the most severe environmental factors affecting pavement performance in cold regions [3]. Recent unidirectional freezing experiments on subgrade soils from the Kashmir region confirmed that fine-grained soils become strongly frost-susceptible at moisture contents above about 45%, while frost heave in coarse-grained soils peaks near 20% fines content [4]

The mechanisms of frost heave have been investigated for almost a century. Early studies showed that frost heave is mainly caused by the formation and growth of ice lenses, which develop as water moves

toward the freezing front, rather than by the expansion of pore water during freezing alone [2]. Later research improved the understanding of this process by explaining the role of capillary forces, frozen fringe development, and ice-lens formation [5–7]. Further studies introduced engineering concepts such as segregation potential, which relates the rate of water movement to the temperature gradient, and developed models to describe ice-lens growth more realistically [1, 8, 9]. More recent studies have explained ice segregation from a thermodynamic perspective and have confirmed through field investigations that water availability, soil type, and freezing conditions are the main factors controlling frost heave in transport infrastructure [10, 11].

Since, frost heave involves the interaction of temperature, water movement, and soil deformation, it is generally treated as a coupled thermo-hydro-mechanical (THM) process. Over the years, several THM models have been developed to describe these coupled processes. Early studies established the theoretical framework for coupled heat and moisture transport in freezing soils and introduced finite-element formulations that considered thermal, hydraulic, and mechanical interactions [12–14]. Later models included additional processes such as ice-lens growth, porosity changes, thaw settlement, cryosuction, and air-water capillary effects, leading to more realistic simulations of freezing soils under different field conditions [15–22]. Although these models improve the understanding of frost-heave behaviour, a large number of soil and hydraulic properties are required, which are not always available in routine pavement design and high computational cost also makes quick comparison of different design alternatives difficult.

For pavement engineering, several numerical studies have investigated the influence of frost heave on pavement performance. Dong et al.[23] developed a random finite-element model to simulate frost heave and the resulting pavement stresses, and showed that thermal insulation, thicker base layers, and improved drainage can significantly reduce frost-related damage. Huang et al.[24] used Abaqus to study the influence of different frost-heave patterns on airport pavements and proposed structural tolerance limits. Among the available mitigation methods, Thermal insulation has been widely used to reduce frost penetration into pavement subgrades. Full-scale experiments have shown that extruded polystyrene (XPS) insulation provides stable long-term performance in high-speed railway subgrades under cold-region conditions [25]. Recent experimental and numerical studies have compared alternative insulating materials, including foamed concrete, foam glass aggregate, and tire chips, against conventional polymer boards in terms of both thermal performance and cost[26, 27] and multi-physics simulations have quantified the anti-frost-heave effect of foamed-concrete and composite insulation subgrade structures in seasonally frozen regions [28].

Lime stabilization and subgrade drainage are two other commonly used methods for reducing frost damage. Lime treatment decreases the plasticity and frost susceptibility of fine-grained soils while improving their performance under repeated freeze-thaw cycles [29, 30] The required lime content is generally determined using the standard lime-demand test ASTM D6276 [31]. Drainage, on the other hand, reduces frost heave by limiting the amount of water available for ice-lens formation. Design guidelines recommend maintaining the groundwater table below the freezing depth using drainage

systems or capillary barriers [32], while laboratory studies have shown that lowering the water table reduces both frost heave and water migration toward the freezing front [33].

Although considerable progress has been made in understanding frost heave and developing numerical models, there is still a need for a simple and reliable finite-element approach that can predict frost heave using a limited number of measurable soil properties. In addition, very few studies compare the effectiveness of thermal insulation, lime stabilization, and subgrade drainage within a single modelling framework under identical conditions.

The model has three main features. First, it performs a transient coupled temperature-displacement analysis in which latent heat is represented using the apparent heat-capacity method, while frost heave is simulated through a calibrated temperature-dependent expansion. This allows the surface heave to be predicted directly. Second, the frost-heave parameter is calibrated using a measurable soil property and validated against literature results. Finally, a parametric study is carried out to evaluate and compare the effectiveness of thermal insulation and subgrade drainage.

2. Theoretical framework

2.1 Coupled thermo-mechanical formulation

The freezing pavement is treated as a material in which heat flow and deformation occur together. Heat transfer with freezing is governed by transient conduction equation given below as Eq. (1) [18, 34].

$$\rho \frac{c_{app} \partial T}{\partial t} = \nabla \cdot (k \nabla T)$$

1

Where, ρ is the density, k is the thermal conductivity, T is the temperature, and t is time [18, 34] The latent heat released as pore water freezes is represented using an apparent (effective) specific heat, as shown in Eq. (2), which is applied only over a small temperature range around the freezing point [23].

$$c_{app} = c + L \left(\frac{\partial \theta_i}{\partial T} \right) \quad \text{for } T_{sol} \leq T \leq T_f \quad (2)$$

Where, c is the specific heat of the soil, L is the latent heat of fusion of water, θ_i is the volumetric ice content, and $[T_{sol}, T_f]$ represents the temperature range over which freezing occurs. This apparent heat-capacity approach represents the heat released during freezing, slowing the movement of the freezing front in a manner consistent with experimental observations [23]. This approach has been used since the earliest numerical models of freezing soil [12], and provides a stable and reliable treatment of the phase change [23].

The quasi-static equilibrium condition governing the mechanical response is expressed below as Eq. (3) and strain-displacement relation under the small-strain assumption is given as Eq. (4),

$\nabla \cdot \sigma + \rho b = 0 \quad (3)$
$\epsilon = \frac{1}{2} (\nabla u + \nabla u^T) \quad (4)$

The model adopts a thermo-elastic constitutive law in which the total strain is decomposed into an elastic component and a frost-heave (eigen) strain component, as shown in Eq. (5) [18, 21].

$$\sigma = D : (\epsilon - \epsilon_{th})$$

5

where σ is the stress tensor, b is the body force (gravity), u is the displacement, ϵ is the total strain, D is the isotropic elastic stiffness tensor, and ϵ_{th} is the frost-heave eigenstrain described in Section 2.2. Eq. (1–5) are solved together in a single coupled temperature-displacement analysis. The temperature field calculated from Eq. (1) is then used to determine the frost-heave eigenstrain through Eq. (6), allowing the thermal and mechanical responses to be analysed simultaneously.

2.2 Equivalent frost-heave expansion

Frost heave is caused by the formation of discrete ice lenses from pore water ahead of the freezing front; the amount of heave depends on the frost susceptibility of soil and the availability of water [1, 2]. Although a complete analysis requires coupled thermal, hydraulic, and mechanical modelling [18, 34], the overall heave can be simulated more efficiently using an equivalent thermal-expansion approach. In this approach, the expansion caused by freezing is represented as a volumetric eigenstrain in the frost-susceptible soil [23]. The frost-heave eigenstrain is expressed in thermoelastic form, as shown in Eq. (6),

$$\epsilon_{th(T)} = \beta(T) (T - T_{ref}) \cdot I$$

6

where I is the second-order identity tensor, T_{ref} is the reference freezing temperature, and $\beta(T)$ is the temperature-dependent expansion coefficient. The value of $\beta(T)$ is taken as zero at and above the freezing point, while below 0°C it becomes negative to represent the soil expansion caused by ice-lens growth. The magnitude of this expansion is determined from the free (unconfined) volumetric heave strain ϵ_v of soil, which is a measurable material property. The corresponding linear heave strain is calculated as $\epsilon_l = \frac{\epsilon_v}{3}$, and the expansion coefficient is specified at selected temperature values [1, 23, 35]. The temperature-dependent expansion coefficient is determined from the reference values as shown in Eq. (7),

$$\beta (0^{\circ} C) = 0, \beta (-1^{\circ} C) = -\epsilon_l, \beta (-15^{\circ} C) = -\frac{\epsilon_l}{15}$$

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Thus, fully frozen soil ($T \leq -1^{\circ}C$) develops a constant expansion of approximately ϵ_l , while the strain increases linearly from zero to this value across the freezing range (0 to $-1^{\circ}C$). Since the eigenstrain defined in Eq. (6) develops only when $T < T_f$, the pavement surface heave is calculated by integrating the frost-heave strain over the predicted frozen depth. Therefore, the surface heave is obtained as a model prediction based on the computed temperature field rather than being imposed as a displacement. The only calibration parameter in the frost-heave model is the free (unconfined) volumetric heave strain (ϵ_v), which is determined by matching the model with measured free-heave data as detailed in Section 4. Typical values for frost-susceptible silts have been reported in the literature [1, 35].

2.3 Modelling of subgrade drainage

Subgrade drainage helps reduce frost heave by limiting the amount of pore water available for ice-lens formation. Because the frost-heave eigenstrain depends on the amount of segregated ice, which is directly related to the water content of the freezing soil. The effect of drainage is represented by relating the free-heave strain to the degree of saturation, S_r , following the reduced-saturation approach proposed by Dong et al. [23]. The linear relationship used in Eq. (8) is a simplifying assumption adopted in this study.

$$\epsilon_v(S_r) = S_r \epsilon_{v,sat}$$

8

where $\epsilon_{v,sat}$ is the free-heave strain under fully saturated condition. As the degree of saturation decreases, the free-heave strain and the resulting frost-heave eigenstrain decrease in the same proportion, while the temperature field described by Eq. (1) remains unchanged. In this way, the model captures the primary effect of subgrade drainage on reducing frost heave [23], without modelling water flow, consistent with the simplified thermo-mechanical approach used in this study.

3. Methodology

3.1 FE Model (geometry and mesh)

A two-dimensional plane-strain cross-section 8.0 m wide represents a unit length of road, as shown in Fig. 1. From top to bottom it comprises an asphalt concrete surface (0.2032 m), a granular base (0.1524 m), and a 1.0 m thick frost-susceptible silt subgrade. For the insulation cases, a 0.0762 m thick insulation board is placed between the base and the subgrade, whereas, the lime stabilization and drainage cases use the same pavement geometry as the baseline model, with only the subgrade

material properties or degree of saturation being modified. To simulate differential frost heave, a 2.0 m wide frost-susceptible zone is defined at the centre of the subgrade, following Dong et al. [23] and assigned a free-heave strain of 1.4%, which is 40% higher than the 1.0% assigned to the surrounding subgrade. This difference in heave strain produces differential (uneven) ground uplift, causing the bound pavement layers to bend, which can lead to cracking, whereas uniform heave would mainly cause vertical movement without significant bending. The model is discretised using four-node coupled temperature-displacement plane-strain elements (CPE4T). The baseline mesh consists of 800 elements and 861 nodes, with a finer mesh provided near the pavement layers where higher stress concentrations are expected. The complete modelling procedure is shown in Fig. 2.

3.2 Material properties

The effective material properties used for the pavement layers are shown in Table 1. The selected values represent a typical flexible pavement in cold regions and are consistent with values reported in the validation study [23]. The asphalt concrete and granular base are modelled as linear-elastic materials. The silt subgrade is modelled with the frost-heave formulation given in Eqs. (6) and (7), together with the apparent heat capacity used to account for latent heat during freezing. The three insulation boards have similar mechanical properties but differ mainly in their thermal conductivity, which determines their effectiveness in reducing heat flow into the subgrade.

Table 1
Material Parameters of the Layer Model

Layer / material	ρ (kg m ⁻³)	E (Pa)	ν	k (W m ⁻¹ K ⁻¹)	c (J kg ⁻¹ K ⁻¹)	w	ϵ_v	Source
Asphalt concrete	2400	8.0×10 ⁹	0.35	1.5	920	0	-	Huang [36]
Granular base	2200	5.0×10 ⁸	0.35	2.0	900	0.02	-	Huang [36]
Subgrade silt (field)	1900	5.0×10 ⁷	0.40	1.8	1200	0.22	0.010	Frozen-silt properties (Andersland & Ladanyi [35]) ϵ_v calibrated (this study)
Subgrade silt (lens)	1900	5.0×10 ⁷	0.40	1.8	1200	0.22	0.014	Frozen-silt properties (Andersland & Ladanyi [35]) ϵ_v calibrated (this study)
Polystyrene board	30	1.5×10 ⁷	0.30	0.030	1300	0	-	Dong et al. [37]
Polyurethane board	40	2.0×10 ⁷	0.30	0.025	1400	0	-	Dong et al. [37]
Glass-fibre board	80	2.5×10 ⁷	0.25	0.040	840	0	-	Dong et al. [37]
Lime stabilised soil	1900	7.0×10 ⁸	0.30	1.8	1200	0.22	0.001	Little [29], dosage as per ASTM D6276 [31]
ρ = density (kg/m ³), E = Young's modulus (Pa), ν = Poisson's ratio, k = thermal conductivity (W/m·K), c = specific heat (J/kg·K), w = gravimetric water content, ϵ_v = free-heave volumetric strain								

The thermal expansion model uses a latent heat of fusion of 334 kJ kg⁻¹, released gradually over a freezing interval of -1 to 0°C with a reference temperature of 0°C. This interval represents the progressive freezing of pore water below 0°C in fine-grained soils [36], and distributing the latent heat over it ensures a numerically stable phase-change solution, consistent with Dong et al. [23]. Together with the layer

properties given in Table 1, these values provide all the inputs required for Eq. (1–7). The material properties are adopted from values commonly reported for cold-region pavements and are similar to those reported by Dong et al.[23] while the free-heave strain, ϵ_v is the only calibrated parameter.

3.3 Thermal and boundary conditions

At the start of the analysis, the entire pavement is assumed to have a uniform temperature of + 5°C, so no frost-heave strain is present. During the simulation, the pavement surface temperature is gradually reduced from + 5°C to – 15°C over a 120-day winter period. The bottom boundary is maintained at a constant + 5°C to represent the stable deep-ground temperature, while the side boundaries are assumed to be thermally insulated, preventing lateral heat transfer and representing a long, uniform pavement section. For the mechanical boundary conditions, the bottom of the model is fully fixed ($U_x=U_y=0$), the side boundaries are constrained against horizontal movement ($U_x=0$) but allowed to move vertically, and gravity is applied throughout the model.

3.4 Coupled solution

Temperature and displacement are solved together in Abaqus in a single transient coupled temperature-displacement step [24]. A stable backward-Euler time integration method is used for the thermal field, while the coupled thermal-mechanical system is resolved by full Newton iteration at each increment, with large-deformation effects included [38]. The time step is chosen automatically, limited to a maximum temperature change of 5°C per increment, over the 120-day season. Temperature (NT11), displacement (U) and stress (S) are extracted; the surface heave is the largest upward surface displacement, and the critical stress is the peak maximum principal (tensile) value in the bound layers.

4. Calibration and validation

The only model parameter requiring calibration is the subgrade free-heave strain (ϵ_v), which is a measurable property representing the frost-heaving potential of the soil. Calibration was performed by adjusting ϵ_v until the predicted surface heave of the baseline model closely matched the published reference value of 14.7 mm reported by [23]. Throughout the calibration, the selected values were kept within the range commonly reported for frost-susceptible silts. Because the predicted surface heave varies almost linearly with the free-heave strain, ϵ_v , only a few trial values were needed to identify the calibrated parameter. A value of 6% produced a surface heave of 90.8 mm, which was much higher than the reference value. However, a free-heave strain of 1%, representing a frost-susceptible silt, resulted in a surface heave of 14.3 mm, less than 3% different from the literature benchmark. A frost-heave strain of 1% was assigned to the surrounding subgrade, while a higher value of 1.4% was applied to the central zone to represent a locally more frost-susceptible region. This 40% increase reflects the natural spatial variability of fines content and moisture in the subgrade, resulting in differential frost heave that induces bending of the pavement layers. These values were then used throughout the remaining simulations, ensuring that any differences in the predicted response were due to the mitigation measures rather than changes in the model parameters. To verify the reliability of the calibration, a sensitivity analysis was

performed by varying the free-heave strain (ϵ_v), from 1% to 6% as shown in Fig. 3, the predicted surface heave increases almost linearly with increasing ϵ_v . A least-squares regression gives the following relationship shown as Eq. (9),

$$\text{Heave} = 15.3 \epsilon_v - 1.5 \quad (9)$$

where the heave is expressed in millimetres and ϵ_v is given in percent. The resulting coefficient of determination ($R^2 = 0.9998$) confirms an almost perfect linear relationship between the free-heave strain and the predicted surface heave, confirming that the adopted free-heave strain of 1% is not simply a calibration value but a physically meaningful parameter within a well-defined linear trend.

Figure 4 shows the predicted pavement behaviour at the end of the freezing season. The vertical displacement shown in Fig. (4a) indicates a maximum surface heave of 14.3 mm, occurring over the central frost-susceptible region. This value is close to the 14.7 mm reported by [23], with a difference of about 3%. The maximum principal (tensile) stress shown in Fig. (4b) reaches 2.76 MPa in the pavement layers above the edges of the frost-susceptible region, where uneven frost heave causes the pavement to bend. Since tensile stress is responsible for crack initiation, this region is the most vulnerable to frost damage. The temperature distribution in Fig. (4c) shows the 0°C isotherm moving downward from the pavement surface, representing the progression of frost penetration during the freezing season. Overall, the predicted surface heave, the distribution of maximum tensile stress, and the movement of the freezing front closely match the expected behaviour of frost-affected pavements, showing that the model can reliably simulate frost-heave behaviour.

5. Results and discussion

With the validation of frost heave produced by the baseline model, it was used to evaluate three frost-mitigation strategies, namely thermal insulation, lime stabilization, and subgrade drainage. Each strategy was analysed under the same modelling conditions as the baseline case to ensure a direct comparison. Although these measures reduce frost heave through different mechanisms, their performance is evaluated using the same response parameters, namely surface heave, maximum principal tensile stress, and frost penetration.

5.1 Mitigation by thermal insulation

Three insulation materials (polystyrene, polyurethane, and glass fibre), with thermal conductivities of 0.030, 0.025, and 0.040 W m⁻¹ K⁻¹, respectively, were placed between the base and the subgrade. All three insulation boards reduced the predicted surface heave by about 99%, from 14.3 mm to 0.18–0.19 mm. As shown in Fig. 5, only a small and uniform downward displacement (less than 0.2 mm) remains, indicating that frost heave has been effectively eliminated. Maximum principal tensile stress was also eliminated, leaving the pavement layers in compression and removing the risk of frost-induced tensile cracking. The insulation layer reduces heat transfer from the pavement surface to the subgrade, keeping the frost-susceptible soil close to or above the freezing temperature. As a result, only a small amount of

ice forms, and frost heave is greatly reduced. The three insulation materials produced very similar results, indicating that the presence of an insulation layer is more important than the type of insulation material used. Therefore, the final selection of insulation material can be based on practical considerations such as cost, durability, and availability. A similar reduction in frost heave was reported by Dong et al. [37].

5.2 Mitigation by lime stabilisation

Treating the upper 0.30 m of the subgrade with lime significantly reduced frost heave. The surface heave decreased from 14.3 mm to 3.8 mm, representing a 73% reduction, while the maximum principal (tensile) stress decreased from 2.76 MPa to 0.63 MPa, a reduction of 77% as shown in Fig. 6. The reduction in heave occurs because the lime-treated layer is much less susceptible to frost action, limiting ice-lens formation in the upper part of the subgrade. The remaining heave is mainly caused by the untreated soil below the stabilised layer, where some freezing can still occur. An additional advantage is that it improves the engineering properties of the subgrade without requiring an additional insulation layer. In practice, the required lime content depends on the soil type and is generally determined using the ASTM D6276 [31] lime-demand test. The results also indicate that the effectiveness of lime stabilization depends on the treatment depth, with deeper treatment expected to provide greater reductions in frost heave.

5.3 Mitigation by subgrade drainage

Subgrade drainage was represented by reducing the degree of saturation, as described in Section 2.3. At 80% and 60% saturation, the predicted surface heave decreased to 11.4 mm and 8.5 mm, corresponding to reductions of 20% and 41%, respectively shown in Fig. 7(a) and 7(b). Similar reductions were also observed in the maximum principal (tensile) stress as shown in Fig. 7(c) and 7(d). Unlike thermal insulation, drainage does not prevent the subgrade from freezing. Instead, it reduces the amount of water available for ice-lens formation, resulting in a smaller but still noticeable frost-heave bulge over the frost-susceptible. Therefore, the effectiveness of drainage depends on how much pore water can be removed from the subgrade, which is consistent with the trend reported by [23]. It also agrees with unidirectional freezing experiments on soils from the study region, in which specimens below a threshold moisture content exhibited little or no frost heave [4].

Table 2 summarises the surface heave, maximum principal (tensile) stress, and their reductions for all mitigation measures. In the field, lower saturation is usually achieved by lowering the groundwater table or installing drainage systems and capillary barriers, thereby reducing the amount of pore water available for frost heave [32, 33].

Table 2
Mitigation results and reductions relative to the baseline

Case	Mechanism	Heave (mm)	Tensile Stress (MPa)	Heave reduction	Stress reduction
Baseline	-	14.3	2.76	-	-
Polystyrene	Insulation, $k = 0.030 \text{ W m}^{-1} \text{ K}^{-1}$	0.19	≈ 0	98.7%	$\approx 100\%$
Polyurethane	Insulation, $k = 0.025 \text{ W m}^{-1} \text{ K}^{-1}$	0.19	≈ 0	98.7%	$\approx 100\%$
Glass-fibre	Insulation, $k = 0.040 \text{ W m}^{-1} \text{ K}^{-1}$	0.18	≈ 0	98.7%	$\approx 100\%$
Lime	Soil stabilisation	3.8	0.63	73.4%	77.0%
Drainage 80%	$S_r = 80\%$	11.4	2.20	20.3%	20.2%
Drainage 60%	$S_r = 60\%$	8.5	1.64	40.6%	40.4%

The performance of the three mitigation strategies is compared in Fig. 8 using surface heave, maximum principal (tensile) stress, and their respective reductions relative to the baseline case. The results show a clear difference in their effectiveness. Thermal insulation is the most effective, reducing surface heave by about 99% and preventing the development of tensile stress in the pavement layers. The three insulation materials produce almost identical results. Lime stabilization is the second most effective method, reducing surface heave by about 73% and maximum principal (tensile) stress by about 77% by reducing the frost susceptibility of the upper subgrade. Subgrade drainage provides the smallest improvement, with heave reductions of 20% and 41% at 80% and 60% saturation, respectively, because it reduces the amount of water available for ice-lens formation but does not prevent freezing. Figure 9 shows that the peak maximum principal (tensile) stress increases almost linearly with the maximum surface heave across all simulated cases ($R^2 \approx 0.999$). This indicates that differential frost heave is the main cause of tensile stress in the pavement. All three mitigation strategies reduce the cracking risk by limiting differential heave.

6. Concluding remarks

This study showed, the frost heave in flexible pavements can be predicted using a simplified thermo-mechanical approach without the need for the large number of hydraulic and freezing-related parameters required by fully coupled thermo-hydro-mechanical models. The proposed model estimates frost heave directly from the temperature field using a single physically meaningful parameter, the free-heave strain. After calibration, the model reproduced the literature benchmark results with good accuracy, and the nearly linear relationship between free-heave strain and surface heave indicates that the same calibrated value can be used for similar soil types under different design conditions. This simple calibration

procedure makes the model practical for pavement engineering applications, where detailed soil-freezing data and computationally intensive analyses are often unavailable. The comparison of mitigation measures also provides useful guidance for pavement design. Each strategy acts by reducing one of the conditions required for frost heave. Thermal insulation limits frost penetration into the subgrade and was the most effective measure, reducing both surface heave and tensile stress to almost zero. The similar performance of the three insulation materials indicates that the presence of a low-conductivity thermal barrier is more important than the specific insulation material, allowing material selection to be based on factors such as cost, durability, and availability. Lime stabilisation also performed well by reducing the frost susceptibility of the upper subgrade while improving its mechanical properties. In comparison, drainage reduced frost heave by limiting the amount of water available for ice formation, but effectiveness of drainage was lower than that of insulation and lime treatment. Therefore, drainage is more suitable as a supplementary measure than as a standalone solution.

The proposed model is intended for the rapid evaluation and comparison of frost-mitigation measures. In future work, the proposed model can be extended to include thaw settlement and traffic loading. It can also be validated against laboratory frost-heave experiments and instrumented field observations, together with a formal mesh-convergence study.

Declarations

Author Contribution

Shahrukh Ahmed: Conceptualisation, Methodology, Software Analysis, Data Curation, Investigation, Validation, Visualization, Writing – Original Draft
Vikas Pratap Singh: Conceptualisation, Methodology, Writing – Review and Editing, Overall supervision

Disclosure statement

The author reports that there are no competing interests to declare.

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Figures

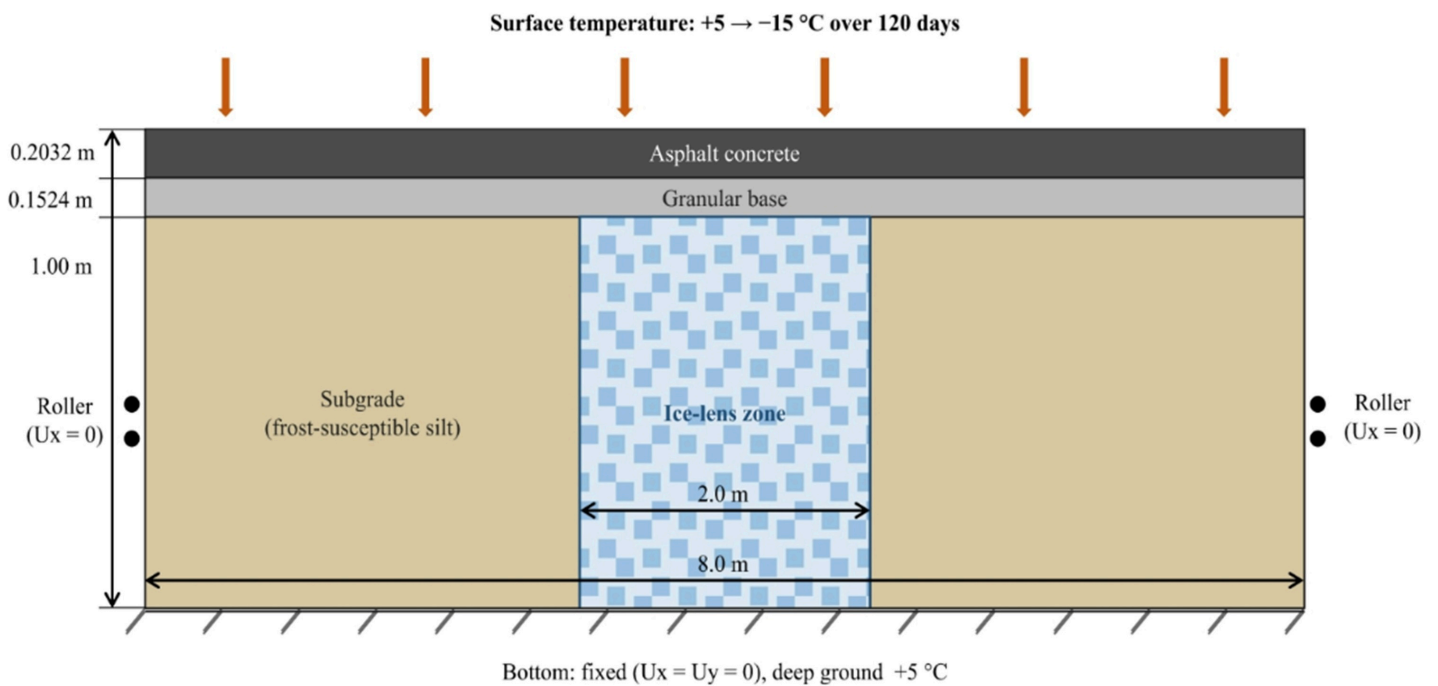


Figure 1

Pavement cross-section model

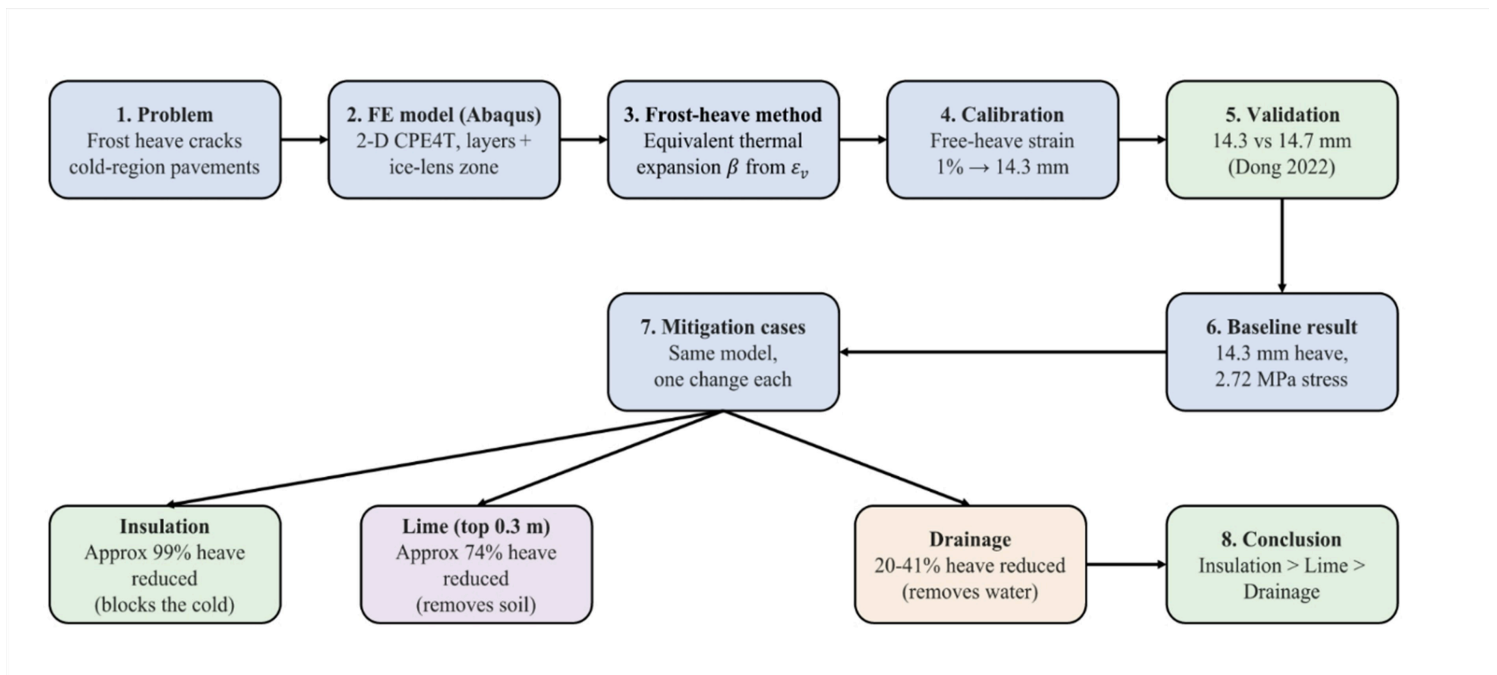


Figure 2

Modelling and analysis workflow

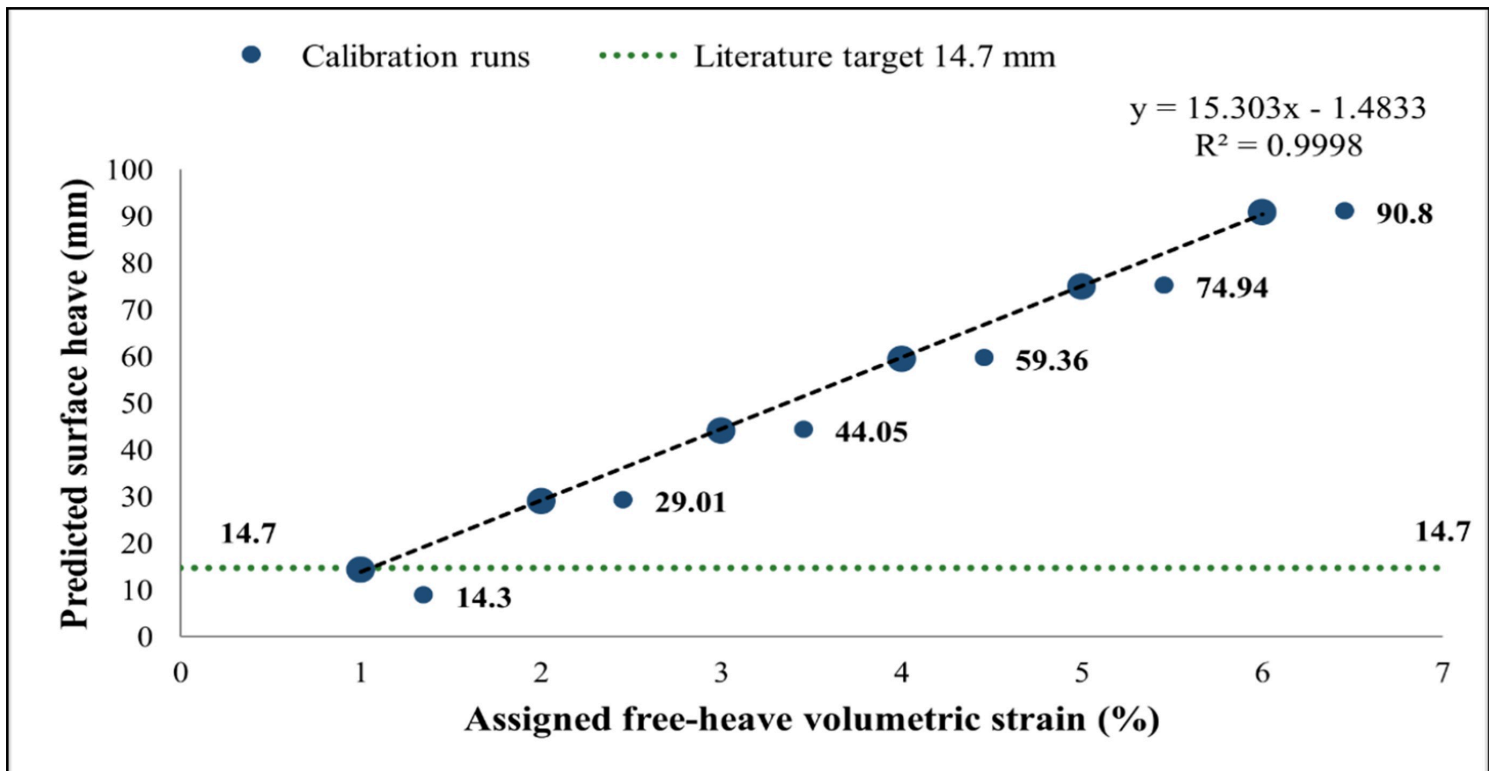


Figure 3

Predicted surface heave versus assigned free-heave volumetric strain

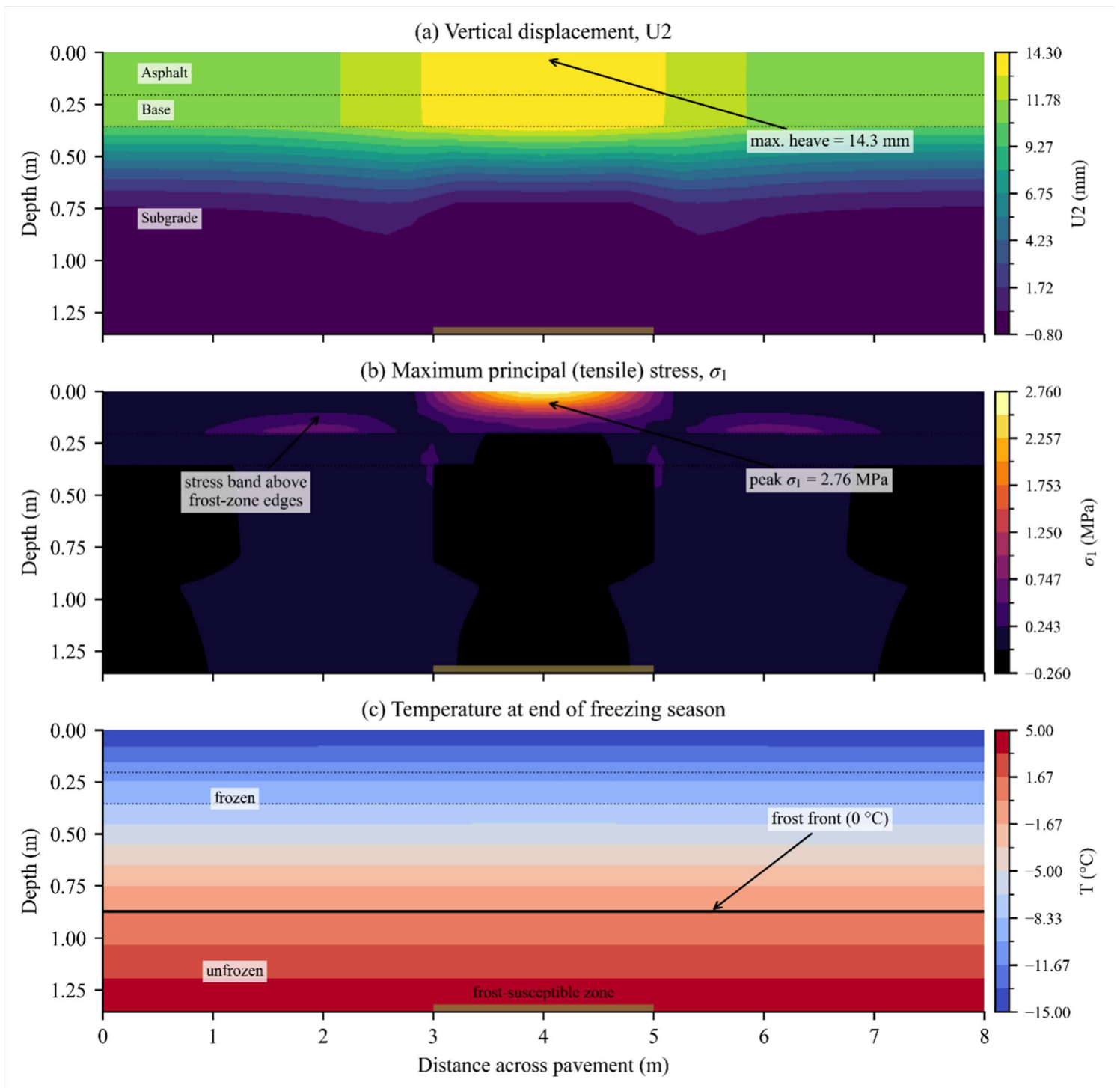


Figure 4

Predicted frost-heave behaviour of the baseline pavement model at the end of the freezing season

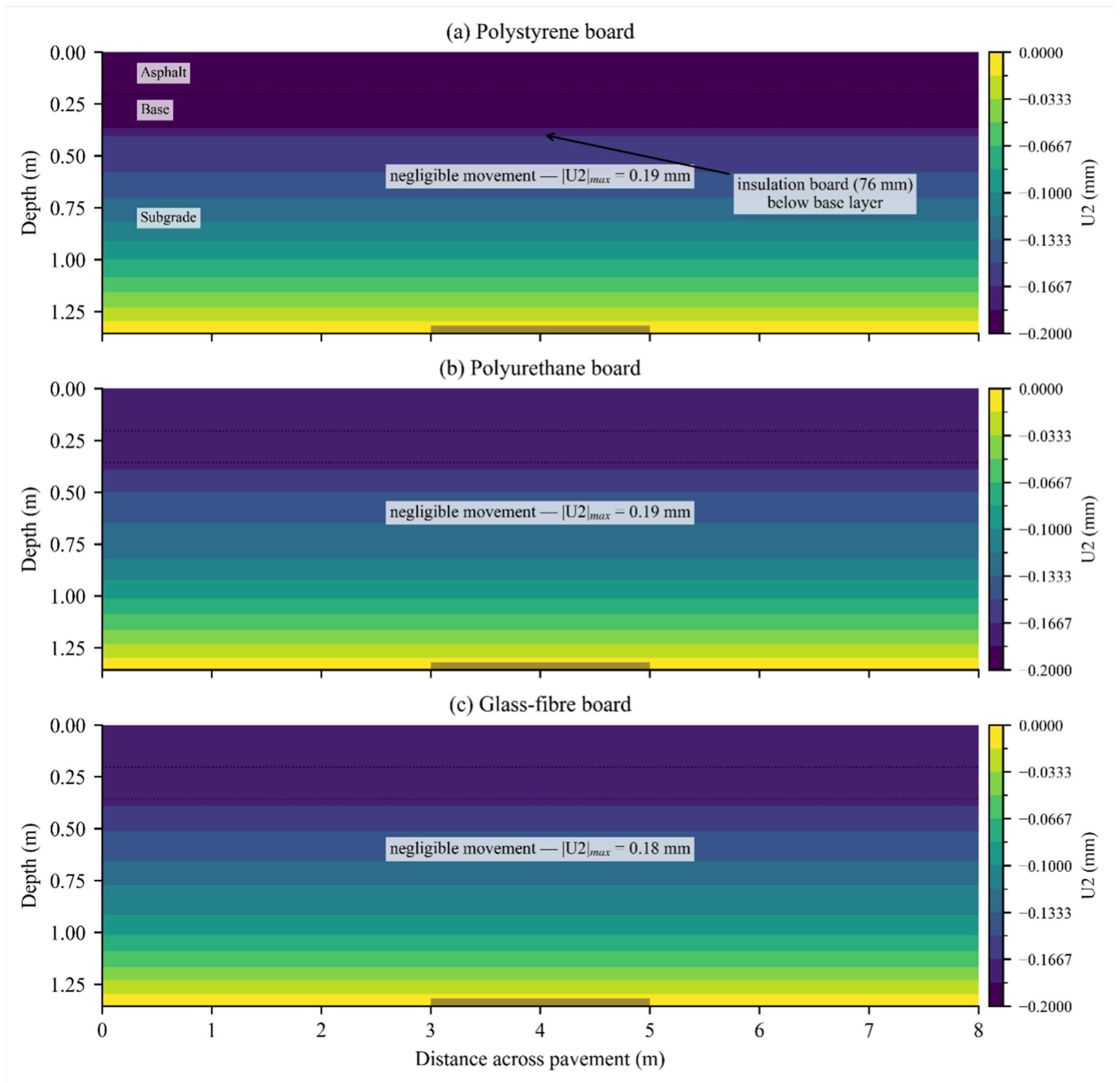


Figure 5

Predicted vertical displacement (U2) with various insulation board

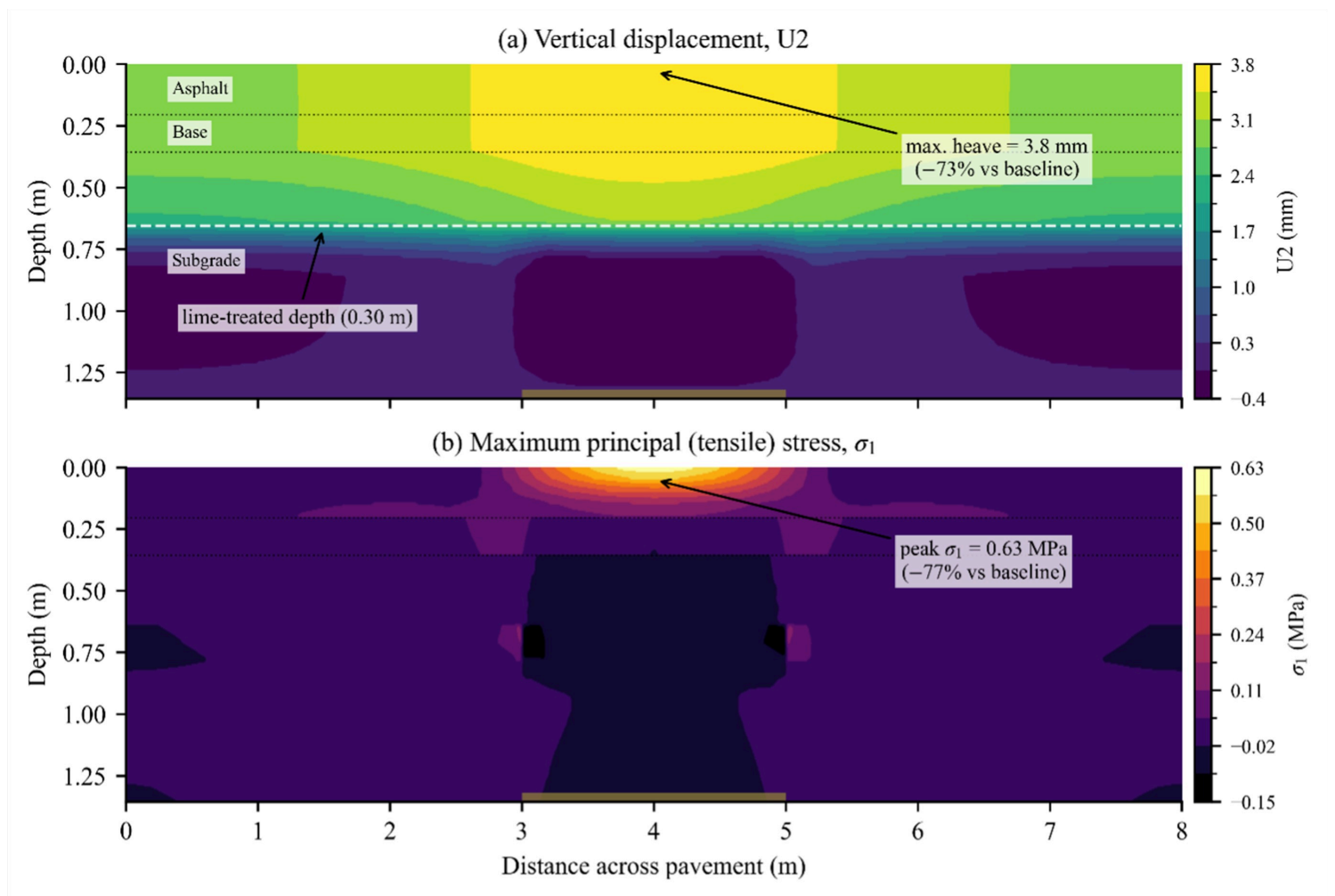


Figure 6

Predicted response with lime stabilisation of the upper 0.30 m of the subgrade: (a) vertical displacement and (b) maximum principal (tensile) stress

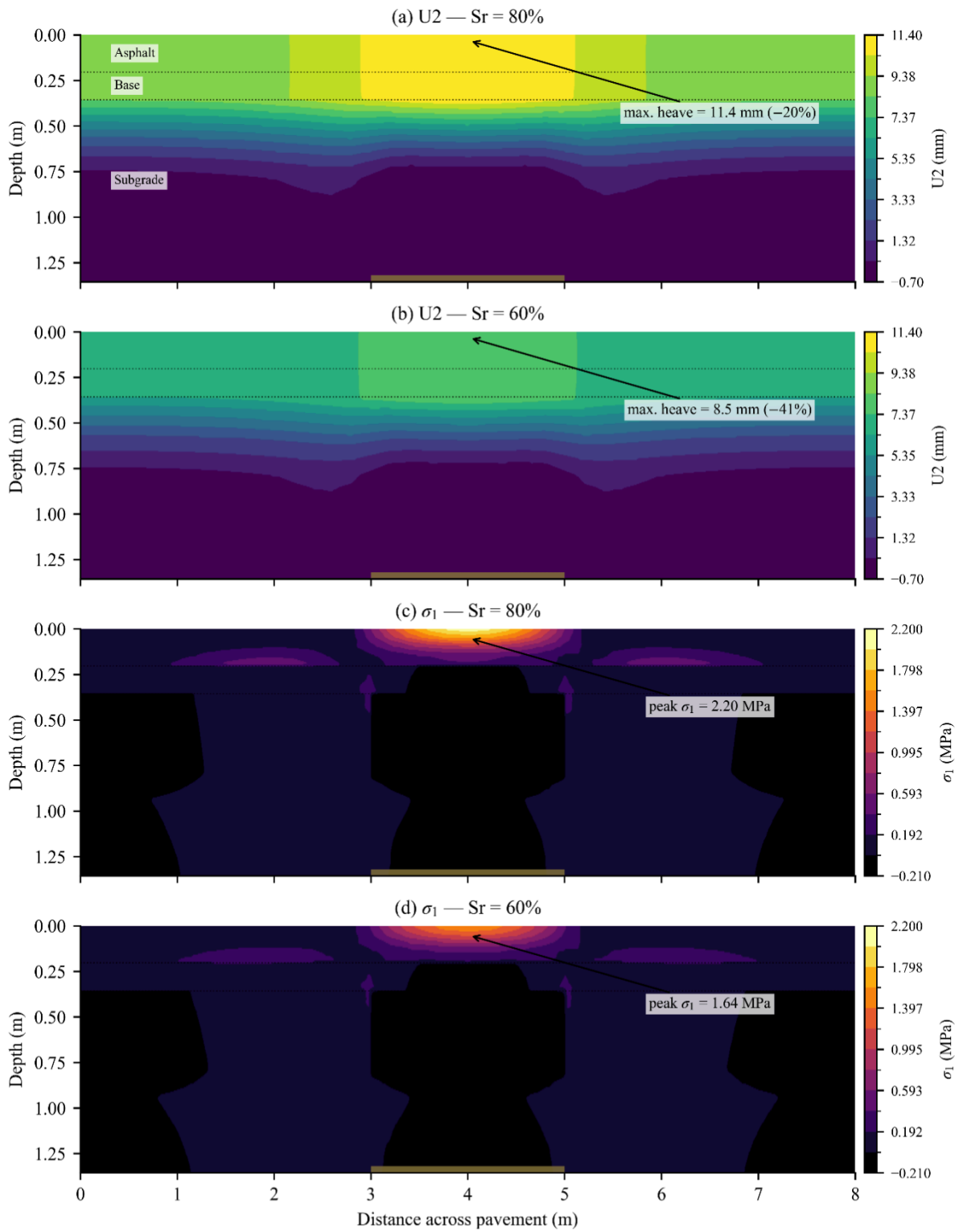


Figure 7

Predicted response with subgrade drainage: (a, b) vertical displacement at $S_r = 80\%$ and 60% ; (c, d) maximum principal (tensile) stress at $S_r = 80\%$ and 60%

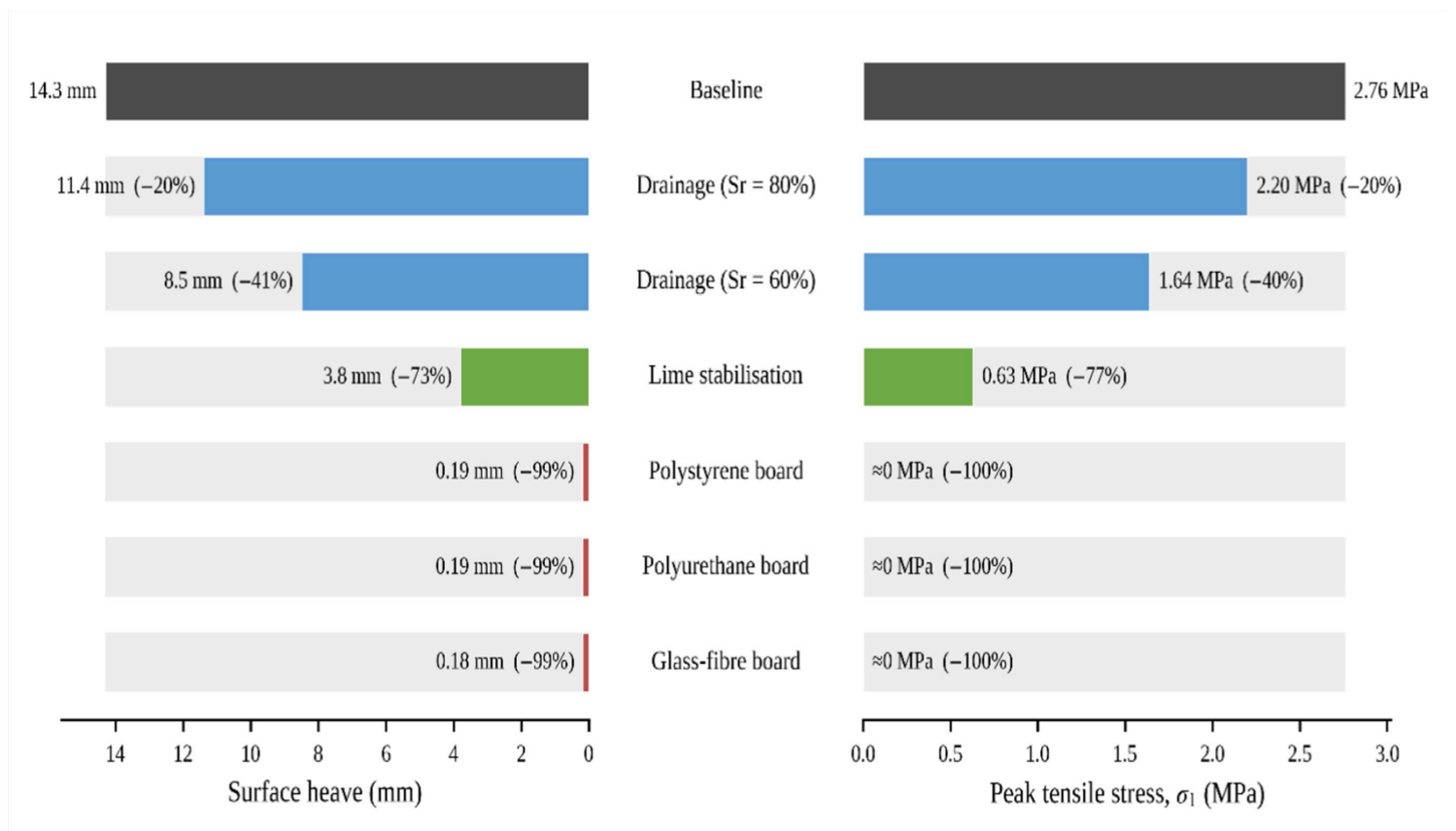


Figure 8

Reduction in maximum surface heave (left) and peak tensile stress, σ_1 (right) achieved by each mitigation strategy relative to the baseline

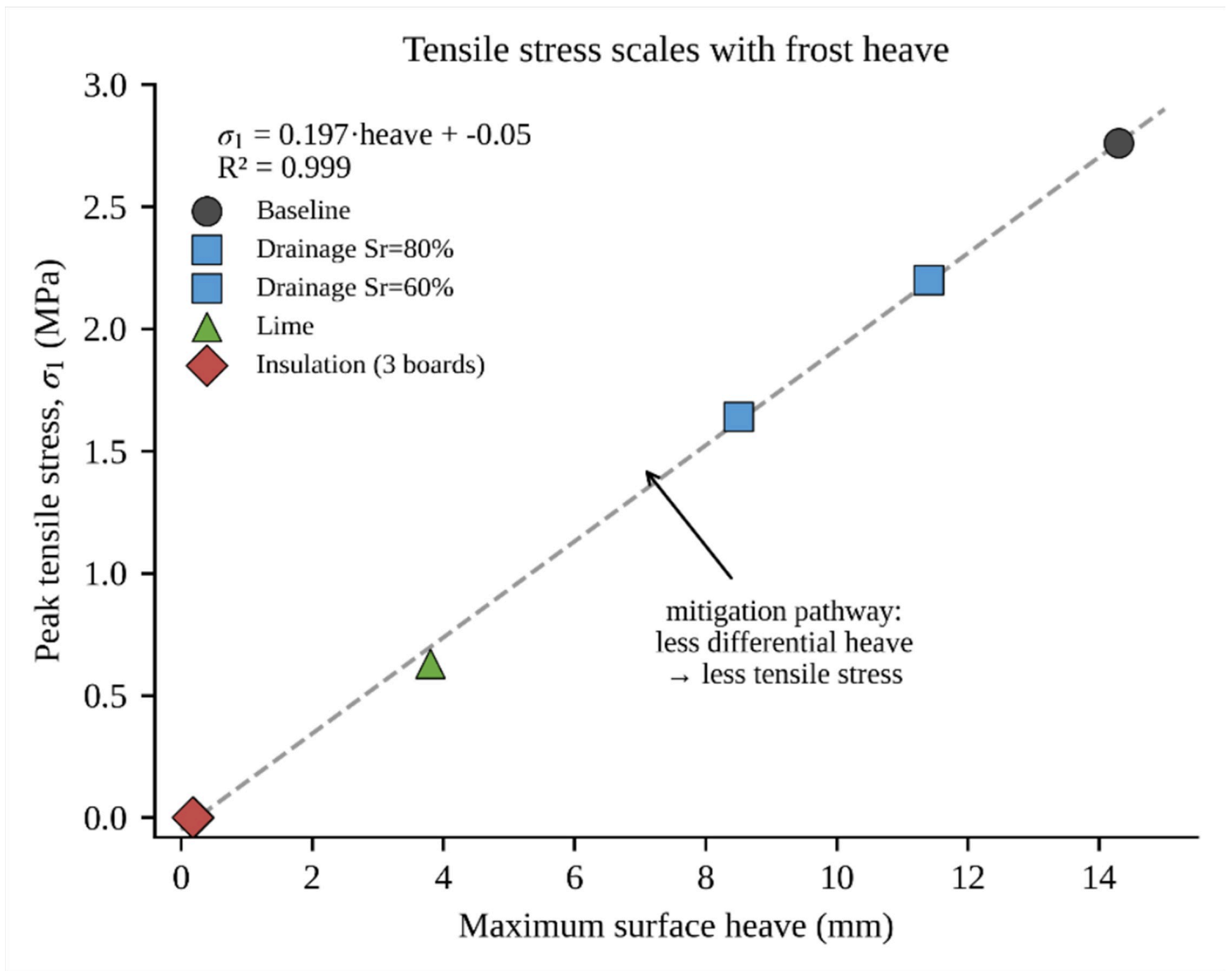


Figure 9

Relationship between peak maximum principal (tensile) stress and maximum surface heave for all simulated cases