

Building and Plumbing Commission Research Grant Program

Guidelines to mitigate structural damage due to water content change in Victoria's expansive soils

Final report

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Abstract

This report examines how climate change may affect expansive soils across Victoria and the potential impacts on residential buildings and underground infrastructure. Expansive soils are clay-rich soils that shrink during dry conditions and swell when wet. This natural ground movement can cause cracking and distortion in buildings and contribute to damage in buried infrastructure such as water pipes. As climate conditions become hotter and drier in some parts of Victoria, these soil movements are expected to become more severe in certain regions.

The study combines climate information, soil data, historical infrastructure records, and spatial mapping techniques to identify areas that may experience increased ground movement and associated risks in the future. Historical records of underground pipe failures were also examined to better understand how climate and soil conditions influence infrastructure performance over time.

Using these datasets, the report develops statewide maps showing projected expansive soil risk across Victoria under future climate conditions. The study also develops practical residential footing design guidance to help support more climate-resilient housing construction. Representative footing designs were assessed for different regions across Victoria to understand how future climate conditions may influence residential foundation requirements.

The findings indicate that even relatively modest increases in soil movement may lead to substantially greater demands on residential footing systems in some areas, potentially increasing construction requirements and long-term maintenance needs. The report also identifies regions where underground infrastructure may experience increased risk of building damage under future climate conditions.

Overall, the study highlights the importance of considering future climate conditions in residential construction, infrastructure planning, and long-term asset management within expansive soil regions. The framework developed through this project provides a practical basis for improving housing resilience and supporting climate-responsive planning and engineering practices across Victoria.

Executive summary

Expansive soils are widely distributed across Victoria and pose a persistent risk to residential buildings and buried infrastructure due to their sensitivity to moisture fluctuations. Variations in soil water content lead to shrink–swell behaviour, which in turn induces ground movement capable of causing cracking and distortion in footing systems and the buildings they support, and underground pipelines and other infrastructure. These issues are already evident under the current climate and are expected to escalate as climate change alters rainfall patterns, temperature regimes, and soil moisture dynamics. Addressing these challenges requires footing design methodologies that explicitly integrate soil behaviour with present and future climatic conditions.

This project provides a comprehensive, climate-responsive assessment of expansive soil behaviour in Victoria and its implications for residential footing design. The study integrates spatially distributed soil reactivity data, Thornthwaite Moisture Index (TMI), depth of seasonal suction change (H_s), and historical infrastructure failure records to quantify characteristic ground movement (y_s) under both current and projected future climate scenarios. By combining geotechnical datasets with climate projections, the work advances beyond traditional site-specific approaches and delivers a state-wide, forward-looking framework that anticipates future climate conditions that is suitable for planning and design.

A key outcome of the study is the development of high-resolution spatial maps of TMI, H_s , y_s , and predicted trends of building damage for Victoria under current climate conditions and under medium- and high-emission scenarios for 2050 and 2090. These maps clearly show that future climate conditions (characterised by higher temperatures, increased frequency of dry periods, and greater variability in rainfall) are likely to intensify soil suction variations over larger depths. As a result, characteristic ground movement is projected to increase in many regions, particularly in areas already underlain by highly to extremely reactive clays.

In this report, the term building damage refers primarily to serviceability-related impacts associated with expansive soil movement, including cracking of walls and slabs, distortion of frames, uneven floor movement, and loss of alignment of building elements. These forms of damage affect the usability, performance, appearance, and long-term durability of residential buildings but do not generally imply structural collapse.

In some instances, footing systems may also experience structural failure when ultimate limit state requirements, such as flexural strength or ductility capacity, are exceeded. These structural checks are evaluated in the CORD analysis in accordance with AS2870 (2011).

The term failure is otherwise used in this report primarily in relation to buried infrastructure, particularly pipe bursts, leaks, or other forms of loss of functionality in underground pipelines.

Analysis of historical pipe failure records confirms a strong seasonal and climatic signal in damage trends, with failure rates peaking during hot, dry periods when expansive soils are most prone to shrinkage. Regression-based correlations between climate variables, TMI, H_s , and failure rates provide further evidence that climate-driven soil behaviour plays a critical role in infrastructure performance. While the predictive relationships presented in this study are preliminary, they demonstrate clear trends that can inform proactive risk assessment and asset management strategies.

From a practical design perspective, the project translates the geotechnical and climate analyses into a set of climate-resilient residential footing design guidelines. Victorian suburbs and regional towns were categorised into 42 distinct geotechnical groups based on ranges of y_s and H_s , and representative footing systems were designed for each group using CORD software in accordance with AS2870 (2011). The results show that relatively modest increases in y_s and H_s can lead to substantial increases in design demand, including deeper beams, reduced beam spacing, and greater reinforcement quantities. Although only a small proportion of suburbs and towns are projected to experience moderate or critical shifts into higher reactivity categories, the implications for construction cost, material use, and long-term performance are significant.

To support implementation by practitioners, the project delivers an interactive, suburb/town-level design map that links local soil and climate parameters directly to recommended footing details. This tool provides engineers, builders, and regulators with an accessible, evidence-based means of selecting footing systems that are not only compliant with current standards but also better aligned with future climate conditions.

Overall, this study highlights the necessity of integrating climate change considerations into geotechnical engineering practice, particularly for residential construction on expansive soils. By combining climate science, soil mechanics, spatial analysis, and structural design, the project offers a robust framework for improving the resilience of housing and infrastructure in Victoria. The methodologies, datasets, and tools developed through this research can be readily updated as new climate projections and soil information become available, supporting adaptive design and long-term risk mitigation in an evolving climate.

1. Introduction

1.1. Research background

Expansive soils pose a significant geotechnical challenge across many parts of Victoria, Australia. These soils, which are rich in clay minerals such as montmorillonite, have the capacity to undergo substantial volume changes in response to moisture fluctuations. When wet, they swell; when dry, they shrink. This cyclical expansion and contraction can lead to serious structural issues, particularly in residential and light commercial buildings. The problem is especially pronounced in areas like Melbourne's western suburbs/towns.

The geotechnical implications of expansive soils are considerable. As the soil swells and shrinks, it causes ground movement that can result in cracking of walls and floors, distortion of building frames, and damage to pavements and underground infrastructure. These effects are often seasonal, with the most severe movements occurring during transitions between dry and wet periods. Victoria's climate, which includes extended dry spells followed by heavy rainfall, exacerbates this issue by causing extreme variations in soil moisture content.

To better understand and manage these risks, detailed site investigations were conducted in affected areas in the previous projects and works. In Melbourne's western suburbs, for example, researchers have employed neutron moisture probes and magnetic extensometers to monitor changes in soil moisture and ground movement over time. Laboratory testing complements these field studies, with analyses such as Atterberg limits (i.e. to determine soil plasticity), particle size distribution (i.e. to determine the range of particle sizes within the soil), and shrink-swell (i.e. to determine the shrink and swell capacities of soil) tests helping to characterize the soil's behaviour (Karunaratne et al., 2014; Kodikara et al., 2014). Instruments like miniature tensiometers and chilled mirror hygrometers are also used to measure soil suction (i.e. the tendency of unsaturated soil to draw in or retain water due to capillary and other forces, resulting in a negative pore-water pressure) and develop Soil Water Characteristic Curves, which are important for predicting soil response to moisture changes.

Engineering design is required to account for these soil responses, particularly in residential construction. The Australian Standard, AS2870: Residential slabs and footings (AS2870, 2011) provides guidelines for designing footings and slabs on reactive clay sites. It incorporates parameters such as surface suction variation, depth of seasonal moisture change, and the soil's shrink-swell index to calculate the expected surface movement. This information is critical for determining appropriate foundation depths and construction techniques. Additionally, updated

climate indices, based on recent climate data, are used to refine site classifications and improve the accuracy of movement predictions.

Mitigating the effects of expansive soils involves a combination of engineering and landscaping strategies. For residential buildings and footing systems, deep footings that extend below the active soil zone can improve stability, while moisture control measures such as proper site drainage, controlled watering, and strategic vegetation management help maintain more consistent soil moisture conditions around structures. In addition, construction details capable of accommodating limited ground movement are often adopted to reduce building damage. Examples include articulated masonry joints, reinforced stiffened raft slabs, flexible sealants at movement joints, and footing systems designed with increased stiffness and ductility.

For buried infrastructure such as pipelines, flexible pipe materials and joints are commonly used to accommodate differential ground movement caused by expansive soil shrink–swell behaviour. Examples include polyethylene (PE) pipes, ductile iron pipes with flexible joints, and rubber-ring joint systems, which can tolerate limited bending and displacement without loss of functionality. These approaches help reduce the likelihood of pipe bursts, leaks, and other forms of buried infrastructure failure associated with expansive soils.

1.2. Scope of the project

As discussed, variations in pore water pressure, driven by changes in soil moisture content, can significantly affect the performance of a wide range of geo-structures and sub-structures. Numerous studies have explored the influence of climate variables on soil moisture dynamics, matric suction, and the resulting changes in shear strength (Blight, 2003; Karim et al., 2020). The extent of these impacts can vary widely (from negligible to severe) depending on local climate conditions, projected climate change, site-specific characteristics, and the type of structure involved (Hughes et al., 2009; Ridley et al., 2004). The effects of changing rainfall patterns and temperature regimes have been shown to significantly influence the performance of various near-surface or sub-structures, including pavements (Swarna et al., 2021), infrastructure slopes (Alonso et al., 2003), embankments (Hughes et al., 2009; Ridley et al., 2004), and underground pipelines (Gallage et al., 2012).

The movement of expansive (or reactive) soils and the associated structural challenges have received limited attention in the context of climate factors (Karim et al., 2024). These soils undergo significant volumetric changes, swelling when wet and shrinking during dry periods,

leading to ground movement that can impose additional stresses on overlying structures. Seasonal moisture fluctuations, particularly between summer and winter, exacerbate these effects. With climate change expected to intensify these moisture cycles, the risks to infrastructure are likely to increase. Therefore, it is essential to integrate climate-responsive considerations into the design and planning of future infrastructure to enhance resilience.

The aim of this project is to investigate the environmental conditions such as expansive soil's behaviour, temperature and rainfall, and the impact those conditions have on the failure chance of footings of residential buildings. The peak of failures due to expansive soil in Melbourne is regularly observed during early summer due to the response of expansive soils. The soil movement can exert mechanical forces, which increases stress surrounding the footings of residential buildings and ultimately cracks them. Expansive soils are highly sensitive to changes in moisture content and undergo volumetric expansion during wetting and shrinkage during drying. In residential design practice, sites with characteristic surface movement y_s greater than 75 mm are classified as Extremely reactive (Class E) under AS2870 (2011)(see Table 1 for classifications) . Such levels of ground movement can induce significant differential heave and shrinkage, generating additional mechanical stresses on residential footing systems. If not adequately accommodated in design, these stresses can lead to cracking and serviceability damage in buildings.

Table 1. Description of reactivity of the site based on characteristic ground movement (AS2870, 2011)

Class	Range of y_s (mm)	Description
A	$y_s = 0$	Non-reactive
S	$0 < y_s \leq 20$	Slightly reactive
M	$20 < y_s \leq 40$	Moderately reactive
H1	$40 < y_s \leq 60$	Highly reactive (Lower bound)
H2	$60 < y_s \leq 75$	Highly reactive (Upper bound)
E	$y_s > 75$	Extremely reactive

The major soil property of clayey soil, relating to the degree of potential soil movement, is usually referred to as soil reactivity. Soil reactivity can be known as the soil volume change in response to the moisture change. However, spatial distribution of soil reactivity is not available in existing literature or soil databases. Therefore, this project aims to develop an interactive

map for soil reactivity and provide some suggestions for footing design in Victoria. Defining high-risk areas will allow proactive management strategies to mitigate the risks and reduce the operational expenditure.

2. Methodology

This chapter outlines the methodology used to evaluate expansive soil behaviour across Victoria and to assess how current and future climate conditions may influence ground movement and associated risks to residential buildings. The approach integrates soil reactivity data, climate information, and spatial analysis techniques to estimate characteristic ground movement (y_s) and depth of suction change (H_s) at a statewide scale. Rather than relying solely on site-specific investigation, the methodology provides a consistent and repeatable framework for comparing soil and climate conditions across different locations and future climate scenarios. The methods described in this chapter form the basis for the spatial maps, correlation analyses, and residential footing design guidance presented in the later sections of this report.

2.1. Characteristic ground movement determination

The soil data was collected from Gould (2011) and Zou (2015). Some of the collected soil data includes the soil reactivity index (I_{ps}) where a higher I_{ps} means the soil is more reactive. For the design purpose, the soil characteristic movement (y_s), i.e. higher y_s indicates that the soil will undergo large vertical and horizontal displacements due to these volume changes, should be determined to estimate the potential damage from soil to the structure. The below steps show the calculation steps from I_{ps} to y_s . According to Karunaratne (2024), the depth of soil suction change is 2.3 m (H_s) and the cracking depth is $0.75H_s$ (H_c) for the Melbourne area. However, it is noted that H_s is also influenced by the climate change (AS2870, 2011). Therefore, this parameter will be determined using the climate data in the later section. The change in suction at the soil surface is 1.2 pF for Melbourne, represents very low soil suction around 1.6kPa, corresponding to near-saturated soil conditions.

According to AS2870 (2011), the formulation of characteristic ground movement (y_s) can be addressed as

$$y_s = \Delta z \Delta u (\alpha I_{ps}) \quad (1)$$

where $\alpha = 2 - z/5$ above H_c and $\alpha = 1$ below H_c ; I_{ps} is soil reactivity; y_s is the characteristic movement. The formulation is based on the assumption that soil movement in expansive clays is driven by changes in soil suction caused by seasonal wetting and drying. A triangular suction

profile is assumed, with maximum suction change occurring at the ground surface and reducing linearly to zero at the depth of seasonal suction change (H_s). The soil profile is divided into two zones: an upper cracked zone with partial load transfer and a lower intact zone, represented by the reduction factor α .

*Note: I_{ps} and y_s are two related measures used to describe how expansive soils behave. The soil reactivity index (I_{ps}) represents how sensitive a soil is to changes in moisture, soils with higher I_{ps} values swell more when they become wet and shrink more when they dry. The characteristic surface movement (y_s), expressed in millimetres, estimates how much the ground surface is expected to move up and down as a result of this moisture-driven swelling and shrinkage, taking into account not only soil reactivity but also climate and the depth over which moisture changes occur. In simple terms, I_{ps} describes the soil's tendency to move, while y_s describes how much movement is likely to occur at the ground surface, and y_s is the key parameter used in footing design to assess the risk of cracking or damage to buildings.

*Note: The pF unit is normally used for soil suction; it relates to the water content in the soil. The suction is often measure in pF i.e. (Suction in pF) = $\log_{10}(\text{Suction in kPa}) + 1.01$.

2.2. *Kriging analysis*

To develop an interactive map based on the collected data at several locations (measured points) across Victoria, the kriging analysis is adopted. Kriging is a geostatistical interpolation technique that fits a mathematical model to a set of known data points (either a fixed number or all within a specified radius) to estimate values at unmeasured locations. The process involves several key steps: exploratory statistical analysis, variogram modelling to assess spatial structure, surface generation, and evaluation of prediction uncertainty through a variance surface. Kriging is particularly well-suited for datasets exhibiting spatial autocorrelation or directional trends, making it a preferred method in disciplines such as soil science and geology. Interactive maps were generated using kriging interpolation. Kriging is most reliable when data points are dense and well distributed; in sparsely sampled areas, especially less populated regions, its accuracy decreases. To account for this limitation, conservative soil parameter values are used in the design recommendations.

2.3. *CORD analysis*

The soil and climate parameters derived through the methodology described in this chapter were subsequently incorporated into the Code Oriented Raft Design (CORD) software in later stages of the study to evaluate representative residential footing systems in accordance with AS2870 (2011). While CORD is not used to determine the soil or climate parameters themselves, it forms an important part of the overall methodological framework by translating the estimated ground movement conditions into practical footing design requirements.

CORD is a mechanistic design tool commonly used in Australia for the analysis and design of footings on reactive soil sites. The software uses characteristic surface movement (y_s), depth of suction change (H_s), footing geometry, structural loading, and material properties to simulate soil-induced ground movement beneath residential footing systems. Based on these inputs, CORD evaluates footing performance against both serviceability and structural criteria, including footing stiffness, flexural strength, and ductility requirements. The outputs include recommended beam spacing, beam depth, and reinforcement details required to accommodate the expected ground movement. In this study, the derived y_s and H_s values under current and future climate scenarios were used as inputs to CORD to develop climate-responsive residential footing design guidance for different regions across Victoria.

3. Data related to soil properties, climate, *TMI* and building damage

This section presents the key soil, climate, and infrastructure datasets used throughout the study to investigate expansive soil behaviour across Victoria and to assess how climate conditions influence associated risks to residential buildings and buried infrastructure. The chapter describes the distribution and properties of expansive soils across the state, explains how climatic factors such as temperature and rainfall influence soil moisture conditions, and examines historical trends in underground pipe failures associated with expansive soil movement.

Particular attention is given to the relationship between climate variability, soil suction changes, and the shrink–swell behaviour of reactive clay soils, which can lead to ground movement capable of causing building damage and buried pipe failures. The section also introduces the Thornthwaite Moisture Index (TMI), which is used in this study as an indicator of long-term climatic wetness and dryness affecting soil moisture conditions. Historical infrastructure records are additionally examined to identify seasonal and climatic trends in pipe failures within expansive soil regions.

Together, these datasets establish the evidence base for the analyses and projections presented in the later sections of the report, including the estimation of characteristic ground movement (y_s), depth of suction change (H_s), projected future soil movement under climate change scenarios, and the development of climate-responsive residential footing design guidance. Understanding these relationships helps explain why some regions are more susceptible to expansive soil-related damage than others and why future climate change may increase pressures on residential buildings and underground infrastructure across Victoria.

3.1. Expansive soil's properties

Based on the collected data, the spatial distribution of soil properties in terms of characteristic ground movement (y_s) is plotted in Figure 1. The y_s map (Figure 1) was developed based on several resources (Gould, 2011; Karunaratne, 2016; Mann, 2003; Zou, 2015) through several data points. The climate data were collected for 99 locations, which were used to calculate the depth of suction change (H_s) as discussed in Section 4.1. Therefore, y_s values were determined for 99 locations based on the y_s map developed for several points using the extract value to point function in ArcGIS. Then, based on the determined y_s for 99 weather stations, the y_s distribution map for the state of Victoria was created using the Inverse distance weighting (IDW) function using the spatial analyst tool in ArcGIS, which was specifically used to preserve the peak y_s values and to avoid the smoothing effect of surface peak value. The y_s value indicates how reactive the soil is as shown in Table 1.

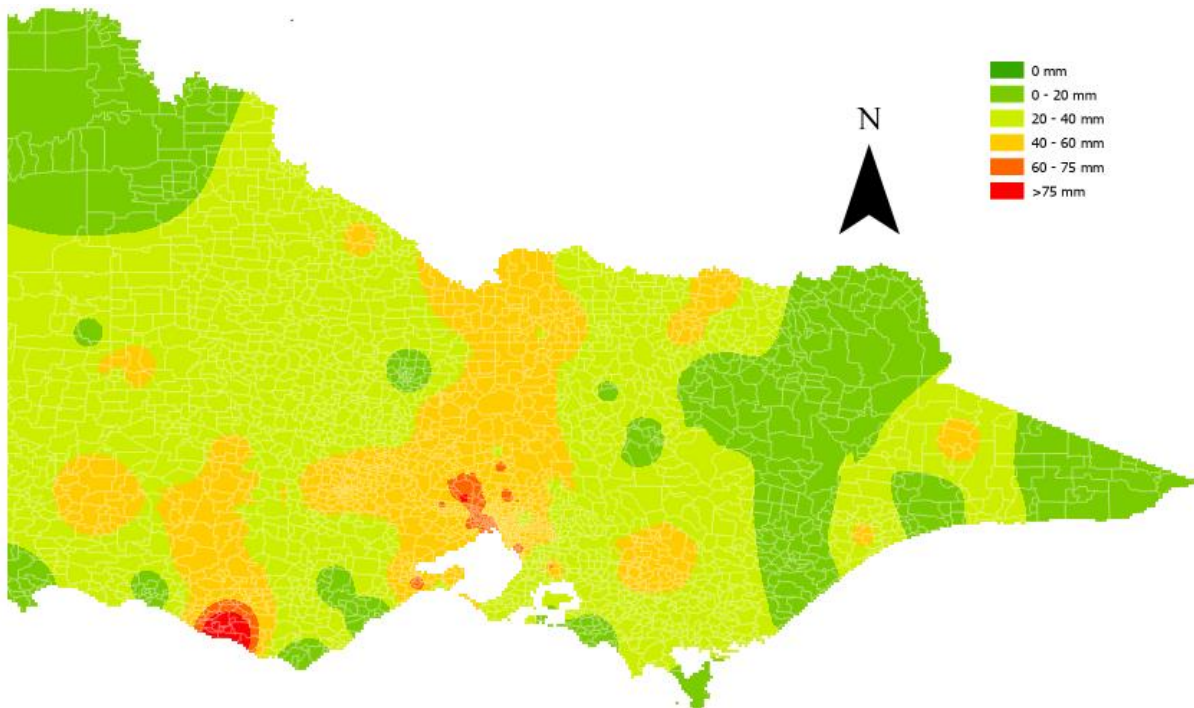


Figure 1. The spatial distribution of expansive soil in terms of characteristic ground movement (y_s) across Victoria in 2024.

3.2. Thornthwaite Moisture Index

Expansive soils are very sensitive to the surrounding climate that affects the water content of the soil mass. One of the approaches to account for the climate in the geotechnical design of a

footing system is through the Thornthwaite Moisture Index (*TMI*) (Thornthwaite, 1948). Some studies have been conducted across Victoria to estimate *TMI* (Karunaratne et al., 2016; Li & Sun, 2015; Sun, 2015; Sun et al., 2017; Sun et al., 2018) and *TMI* map of Victoria has been developed. Short-term *TMI* was also determined by Devkota et al. (2024) for Melbourne airport. Besides, other studies investigated the *TMI* for other Australia states. Reconciling existing *TMI* databases presents a significant challenge due to the diverse assumptions, methodologies, and data sources employed across different states and within a state. Variations in *TMI* values across maps are results of differing calculation techniques and inconsistencies in data quality. Mitchell (2013) emphasized the critical need for ongoing updates to design standards, ensuring they reflect the evolving impacts of climate change through revised *TMI* assessments. A unified *TMI* and depth of suction change database (H_s) for Australia, including Victoria, was developed by Karim et al. (2024) using a consistent methodology and up-to-date climate inputs. This report adopts that same methodology to calculate the relevant climate data.

3.3. Investigation of pipe failure records to implement the predictive model for failure due to expansive soil

The cracks on underground pressure pipes in expansive soils are common in Victoria (Gould, 2011). The longitudinal bending of pipes as shown in Figure 2 can contribute to the failure of pipes. During the dry season, soil shrinkage can cause pipes to bend downward as shown in Figure 2a, generating tensile strain in the overlying soil due to pipe–soil interaction. Conversely, in the wet season, expansion of the soil beneath the pipe leads to upward bending (Figure 2b), inducing compressive strain in the soil mass above. This seasonal movement can lead to the failure of pipes and become non-functional.

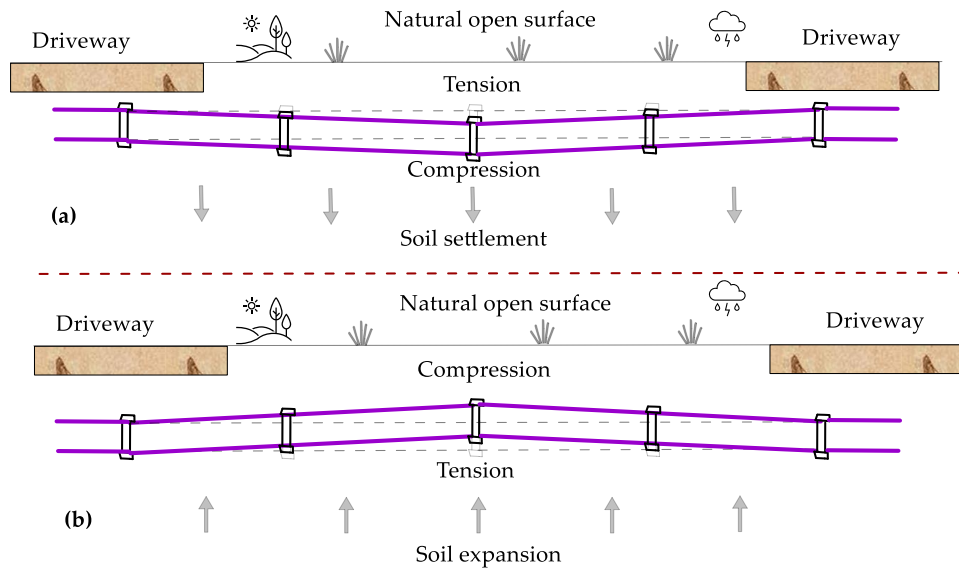
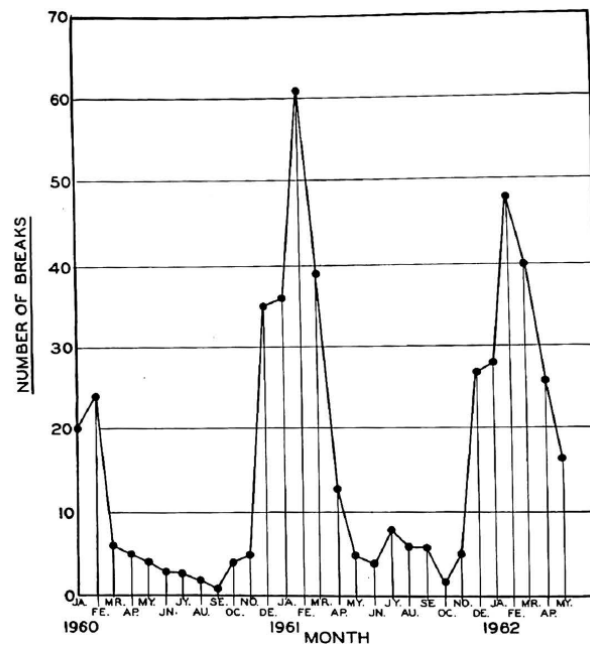


Figure 2. Vertical movement of pipe due to seasonal changes in water content in expansive soils (a) Dry and (b) wet season (Devkota et al., 2022).

The soil–pipe interaction mechanisms illustrated in Figure 2 are reflected in observed seasonal pipe failure trends in reactive clay regions of Victoria. Figure 3 presents the monthly distribution of pipe breaks recorded at Horsham, Victoria, where expansive soil movement has been linked to seasonal moisture variation. The shrink-swell index (reactivity) of the site was 2.2 %/pF (Zou, 2015) and the site has been classified as moderately reactive site following the Australian Standard AS2870 (2011). Pipes installed in expansive clay soils are primarily damaged by shrinkage forces during summer. Although some failures occur due to swelling pressures, these are relatively few compared to the number of breaks during the summer as shown in Figure 3. Irregular shrinkage forces acting on underground pressure pipes in expansive soils are primarily caused by spatial variations in soil properties and non-uniform moisture conditions along the pipeline length. These moisture variations are influenced by factors such as vegetation, impermeable road and pavement surfaces, and local drainage characteristics. While this mechanism was first identified by Holland (1962), subsequent studies using contemporary pipe materials and Victorian utility data have confirmed that differential drying and wetting remain the dominant drivers of pipe bending and cracking in reactive clay soils (Chan et al., 2007; Gould, 2011; Gould et al., 2011).



Gould (2011) investigated the pipe failures across Melbourne by analysing the data provided by City West Water (CWW) Ltd. and South East Water (SEW) Ltd. Here it is to be noted that the information describing bursts, leaks, or other maintenance issues affecting buried reticulation pipes—collectively referred to as failures. The distribution boundaries of CWW and SEW are shown in Figure 4. The failure rates of two zones are shown in Figure 5, and it is clear to see that the west side was more affected than South East side over the observation period.

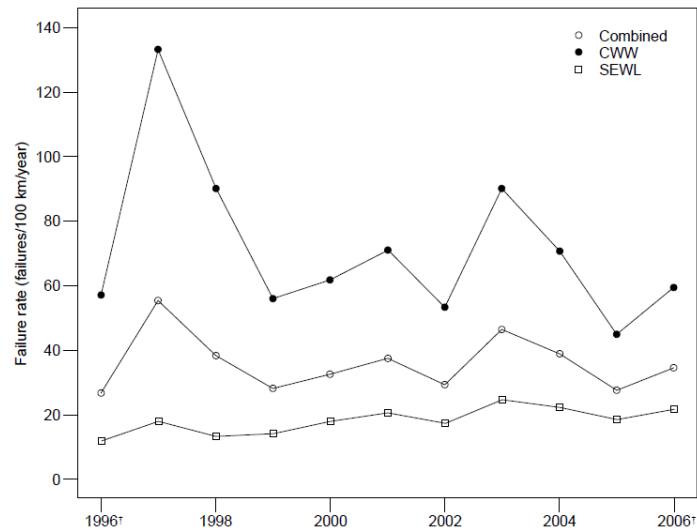


Figure 5. Yearly failure rate over a decade (Gould, 2011).

Figure 6 illustrates the monthly failure rates across each year of the observation period. A distinct peak is evident at the beginning of the year, typically aligning with mid to late summer. Please note that the dataset spans from September 1996 to August 2006. The seasonal peak is not consistent across all years. The intra-year variability in failure rates differs significantly throughout the observation period. Years 1999 and 2002 exhibited relatively stable monthly rates. In contrast, years like 1997, 2001, and 2003 showed much greater variability. Another study by Chan et al. (2007) in Melbourne also showed the significant failure rate around January, February and March as shown in Figure 7. The maximum average failure rate was about 14 failures per 100 km per month.

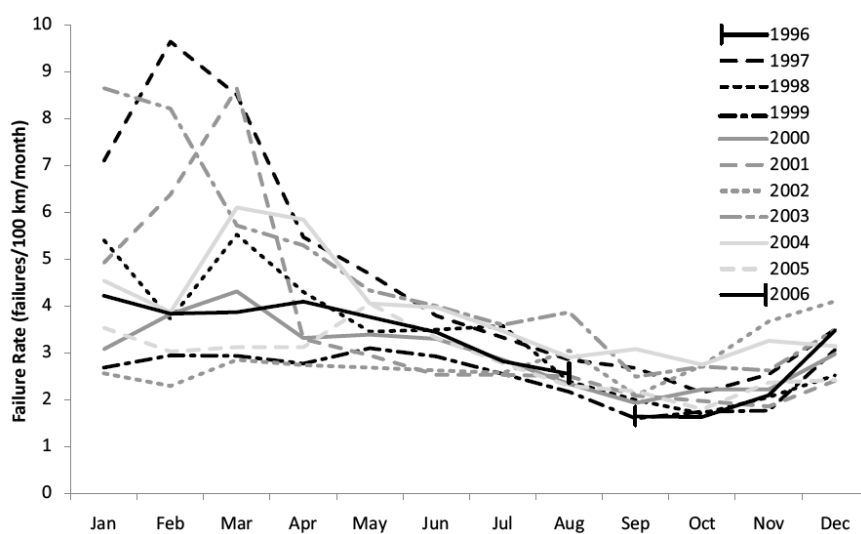


Figure 6. Monthly failure rate over a decade in Victoria (Gould, 2011).

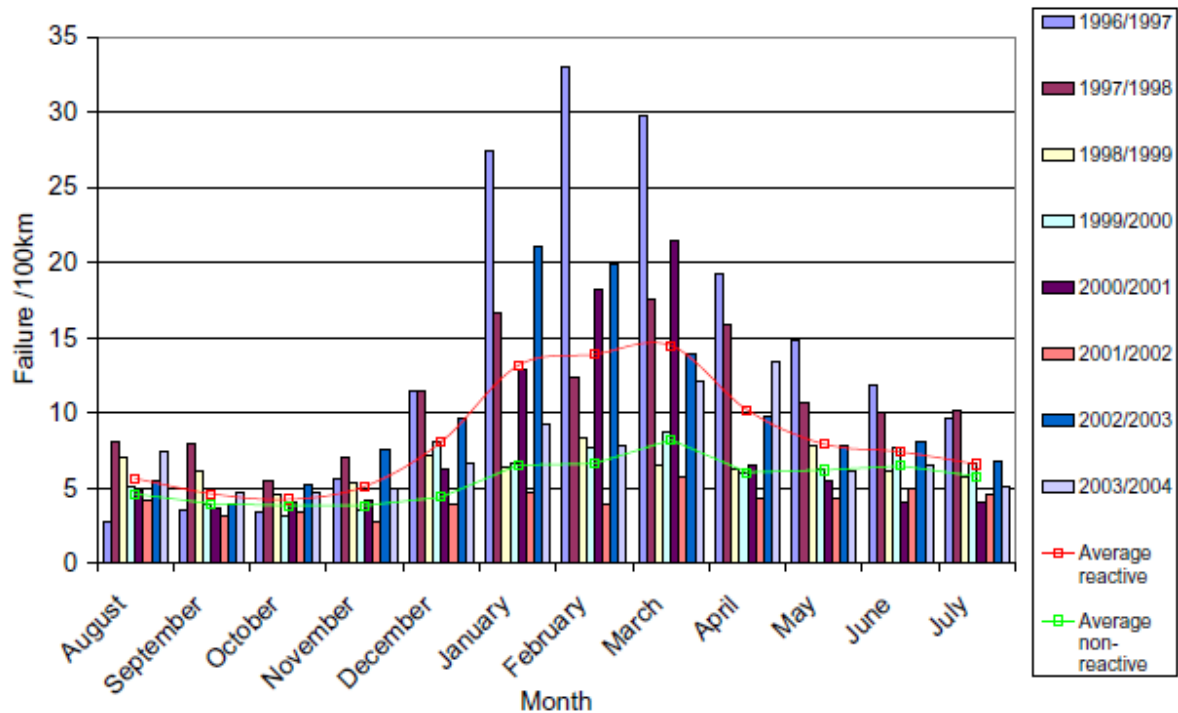


Figure 7. Monthly failure rate over a decade in Victoria (Gould, 2011).

4. Environmental and expansive soil parameters, and their correlation with failure trend

This section examines the interaction between climate conditions, expansive soil behaviour, and observed infrastructure performance across Victoria. Using climate data, spatial mapping, and statistical analyses, the chapter investigates how variations in rainfall and temperature influence soil moisture conditions, depth of suction change (H_s), characteristic ground movement (γ_s), and the likelihood of infrastructure damage in reactive clay regions.

The analyses presented in this section provide the critical link between environmental conditions and the engineering consequences of expansive soil movement. By combining climate projections with soil parameters, the study evaluates how current and future climate conditions may alter the severity and distribution of expansive soil-related risks across the state. The results also help explain why some regions are more susceptible to building damage than others and provide the basis for the predictive maps and climate-responsive footing design guidance presented in the later sections of this report.

4.1. *TMI under current and future climate*

This section presents the climatic analyses undertaken in this study to evaluate how current and future climate conditions may influence expansive soil behaviour across Victoria. The analyses are expressed using the Thornthwaite Moisture Index (TMI), which provides an indication of long-term climatic wetness and dryness based on rainfall and temperature conditions. The resulting TMI and depth of seasonal suction change (H_s) maps illustrate how climate conditions vary spatially across the state and how projected climate change may alter soil moisture conditions that govern expansive soil shrink–swell behaviour.

Because expansive clay soils are highly sensitive to changes in moisture content, variations in climate can significantly influence the magnitude and depth of ground movement experienced by residential footing systems. By comparing current and projected future climate scenarios, this section provides insight into how increasing temperatures, changing rainfall patterns, and prolonged dry periods may contribute to greater soil suction changes and increased expansive soil-related risks in different regions of Victoria.

As discussed in Section 3.2, existing TMI maps for Victoria are available from several sources in the literature. In contrast, a comprehensive and internally consistent mapping of both Thornthwaite Moisture Index (TMI) and depth of seasonal suction change (H_s) has recently been presented by Karim et al. (2024) at the national scale for Australia. In the present study, the methodology proposed by Karim et al. (2024) was adopted and applied to newly collected climate data from 99 weather stations across Victoria to develop updated, Victoria-specific TMI and H_s maps under current (2024) and future climate scenarios. The TMI and H_s map of Victoria has been presented here for the most current (2024) and future climate scenarios. There are two approaches to estimate TMI, one of them is year-by-year and another is average-year method. The later method was used here. The detailed calculations of TMI are shown in Appendix B.

TMI is used in this study as a simple way to describe how wet or dry the local climate is and how this affects soil moisture conditions near the ground surface. TMI combines rainfall and temperature information to indicate whether, over the long term, an area tends to gain moisture or lose it through evaporation. Higher (more positive) TMI values represent wetter climatic conditions, where soils are more often close to saturation, while lower (more negative) TMI values indicate drier conditions, where soils are more prone to drying and suction development. For expansive clay soils, this climatic wetness or dryness is critical because it controls how

much the soil swells during wet periods and shrinks during dry periods. In footing design, TMI is therefore used as a proxy for the climatic influence on soil moisture changes, which in turn governs the depth of seasonal suction change (H_s) and the magnitude of ground movement that a residential footing system must accommodate.

The average of monthly temperature and annual rainfall data were collected from 1995 to 2024 from Queensland Government (2024) for 99 grid points which is referred to as current climate onwards. Although administered by the Queensland Government, the SILO database provides nationally consistent historical climate data for all regions of Australia, including Victoria. The *TMI* values developed using current climate was named current *TMI*. Then the effect of climate change was investigated using the future projections of climate parameter for different representative concentration pathway (*RCP*) scenarios (Climate Change in Australia, 2020). The average of projected median seasonal changes in climate parameters available in Climate Change in Australia (2019) were used to generate future climate scenarios. Out of several *RCP*s, *RCP8.5* and *RCP4.5* for years 2024 and 2090 were used here and represented by high and medium emission scenarios in this study.

The average concentration of greenhouse gases (*GHGs*) in the atmosphere is continuously rising globally. The annual average carbon dioxide (CO_2) level reached 410 ppm in 2019 which is 1.47 times greater than the pre-industrial (the year 1750) level of 278 ppm (CSIRO & BOM, 2020). The future concentration of *GHGs* in the atmosphere will depend on socio-economic changes, changes in technologies, energy use, land use trends and other factors (Van Vuuren et al., 2011). Climate Change in Australia (2019) presented outcomes from up to 40 *GCM* simulations and came up with future predictions for four different representative concentration pathway (*RCP*) scenarios. Variations in eight climate parameters including rainfall and temperature are projected. Out of four *RCP*s as shown in Table 2 (Climate Change in Australia, 2020), three *RCP*s (*RCP8.5*, *RCP4.5* and *RCP2.6* which are termed as high, medium and low emission scenarios respectively) were considered in this study.

Table 2. Representative concentration pathways presented by Climate Change in Australia (2020).

<i>RCP</i>	Future scenario	CO ₂ concentration by 2100
<i>RCP8.5</i>	• Rapid rise of CO₂ concentration continues with little emissions restriction.	940 ppm
<i>RCP6</i>	• A less rapid rise in CO₂ concentration than <i>RCP8.5</i> be achieved through the application of mitigation measures and technologies generating lower emissions.	660 ppm
	• Stabilization of radiative forcing occurs just after 2100.	
<i>RCP4.5</i>	• Reduced rate of rise in CO₂	540 ppm
	• Peak emissions occur around the year 2040.	
<i>RCP2.6</i>	• Peaking of emissions around the year 2020 followed by rapid reduction.	420 ppm (slowly declines from the concentration by 2040 of 440 ppm)

*ppm = parts per million

*RCP2.6: This most ambitious scenario demands early effort from all countries (emitters and developing countries) with the active application of atmospheric CO₂ removal technologies.

Similar to the global trend, Australia is expected to be warmer in the future with an increased number of hot days, a few extreme cooler days and more frequent heavy rainfall events across Australia (Climate Change in Australia, 2021). According to the report by CSIRO and BOM (2015) the projected annual mean temperature will increase by 0.6 to 1.3°C beyond the reference temperature of 1986-2005 by 2030 under the *RCP4.5* emission scenario with small differences among different *RCPs* whereas larger temperature differences among *RCPs* is expected by the year 2090 (for *RCP2.6*, 0.6-1.7°C; for *RCP4.5*, 1.4-1.7°C; and for *RCP8.5*, 2.8 to 5.1°C). The temperature rise is expected to rise steadily in the foreseeable future for the *RCP8.5* case, for *RCP4.5* the warming will plateau beyond 2060 and for *RCP2.6* it will peak around the year 2045.

The projected ranges of rainfall changes in the southern Australian region by the year 2030 will be approximately -10% to small change under the *RCP4.5* scenario and these projections are -10 to 5% in other parts of Australia (CSIRO & BOM, 2015). Furthermore, according to this report, by the year 2090 projected ranges of rainfall changes under the *RCP8.5* scenario in

southern Australia, eastern Australia, Rangelands, and northern Australia will be approximately -25 to 5%, -25 to 10%, -30 to 20% and -25 to 25% respectively whereas more moderate changes are expected under *RCP2.6*.

Considering the latest climate scenarios, biophysical aspects and probable climate change trends, Australia has been regionalized into eight natural resource management clusters as shown in Figure 8 (Climate Change in Australia, 2019). The average of forecasted median seasonal changes in temperature and rainfall under different emission scenarios (Climate Change in Australia, 2019) were used to generate future climate scenarios. Averaging was used to simplify the calculation procedure. Although the projected rainfall increased in some seasons in some climate clusters, average annual rainfall reduced in general. Figures 9-13 and Figures 14-18 shows *TMI* and *H_s* maps for different climate scenarios considered in this project, respectively.

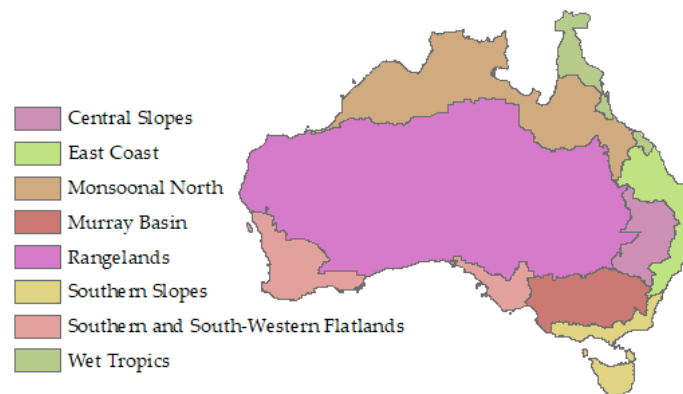


Figure 8. Climate regions of Australia; shapefile from Climate Change in Australia (2019).

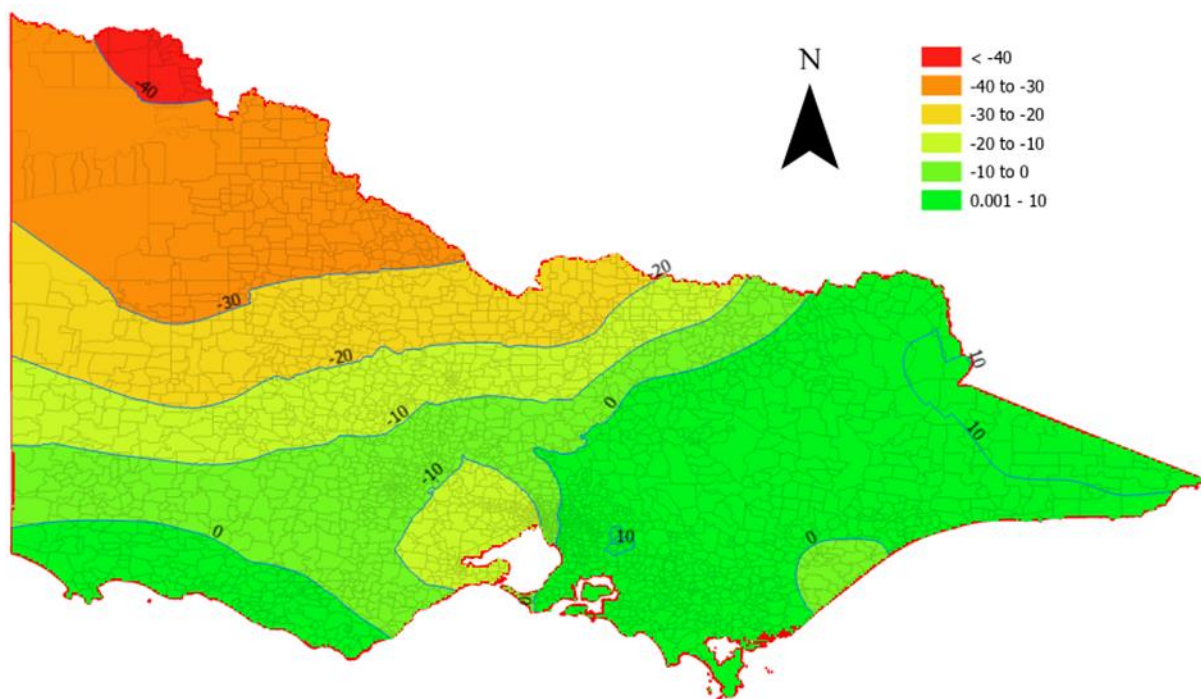


Figure 9. TMI map of Victoria under current climate.

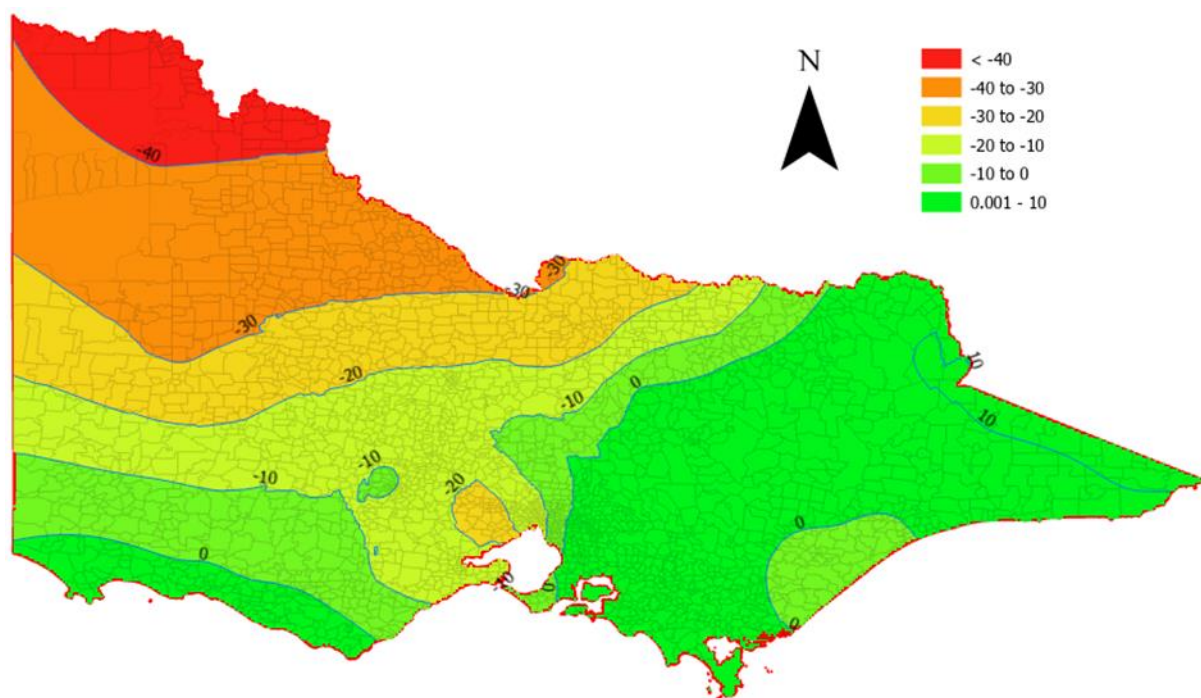


Figure 10. TMI map of Victoria under 2050 medium emission scenario.

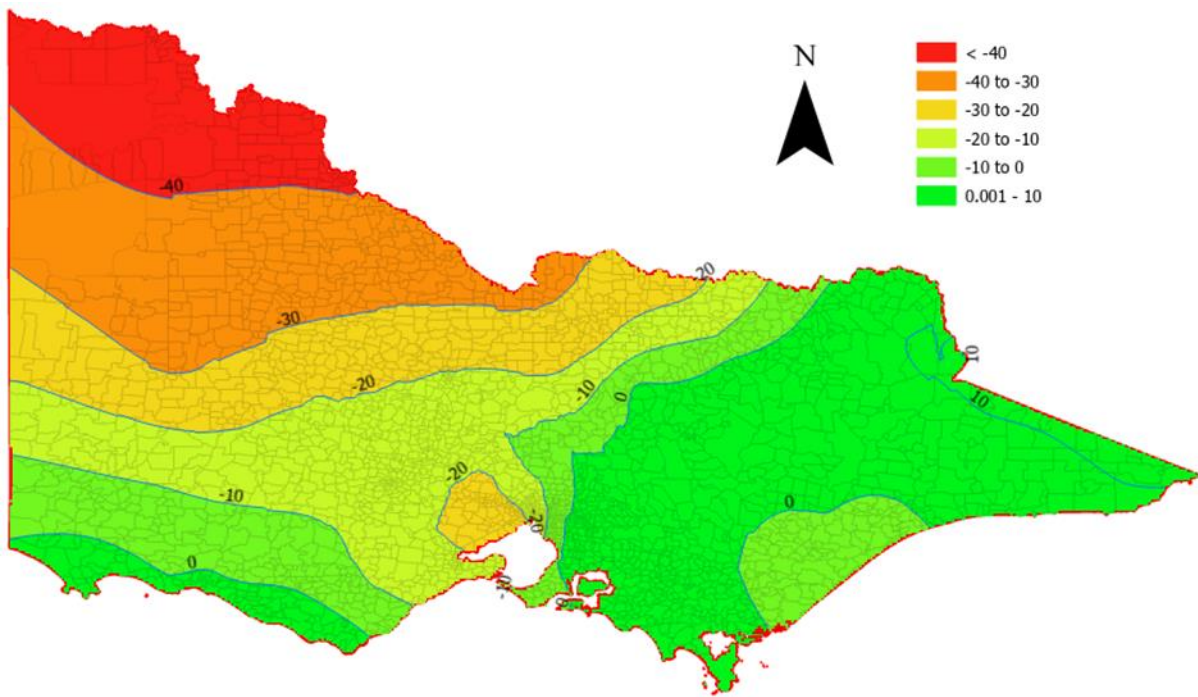


Figure 11. TMI map of Victoria under 2050 High emission scenario.

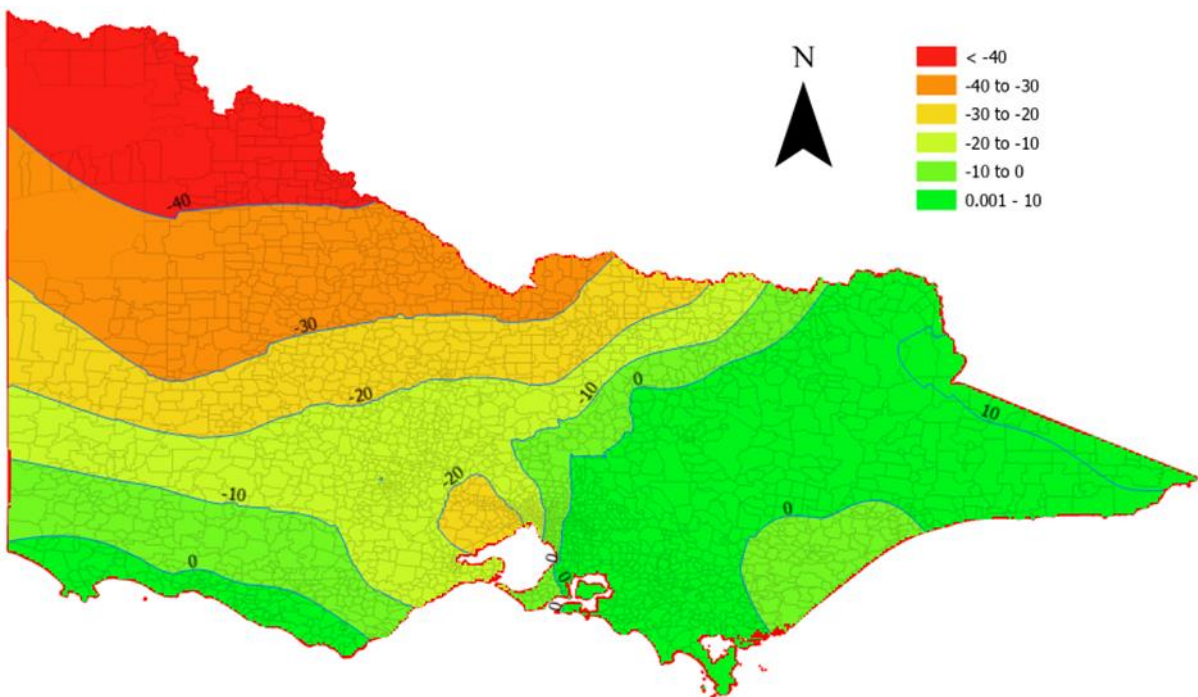


Figure 12. TMI map of Victoria under 2090 medium emission scenario.

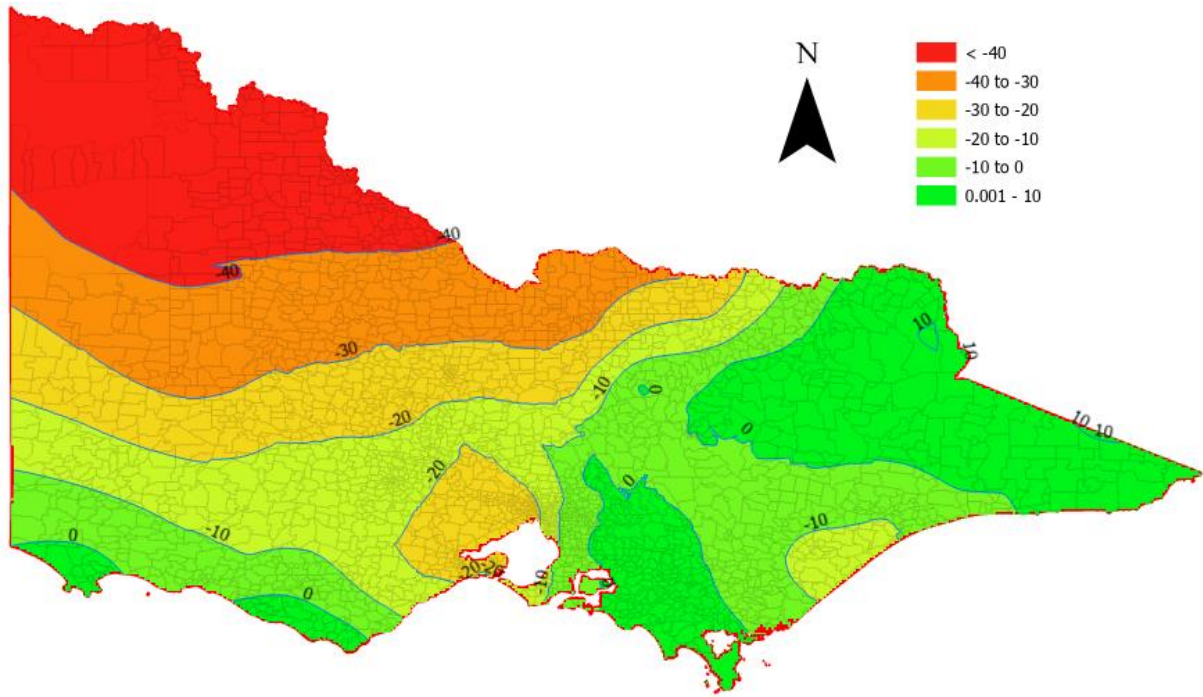


Figure 13. TMI map of Victoria under 2090 high emission scenario.

H_s values were calculated using the lower bound relationship between H_s and TMI as shown in Equation 2 developed by Karim et al. (2024), who collected data of TMI and relevant H_s from AS2870 (2011) then performed regression to establish the relationship between TMI and H_s . TMI values greater than +10 are capped at +10 in this study to maintain consistency with AS2870 (2011). The Australian Standard defines site climatic wetness only up to $TMI > +10$ (refer Table 2.4 and Figure 2.1 of AS 2870), with no distinction provided for higher values. As a result, higher calculated TMI values cannot be translated into additional footing design adjustments within the standard framework.

$$H_s = 0.0007TMI^2 - 0.0306TMI + 1.7043 \quad (2)$$

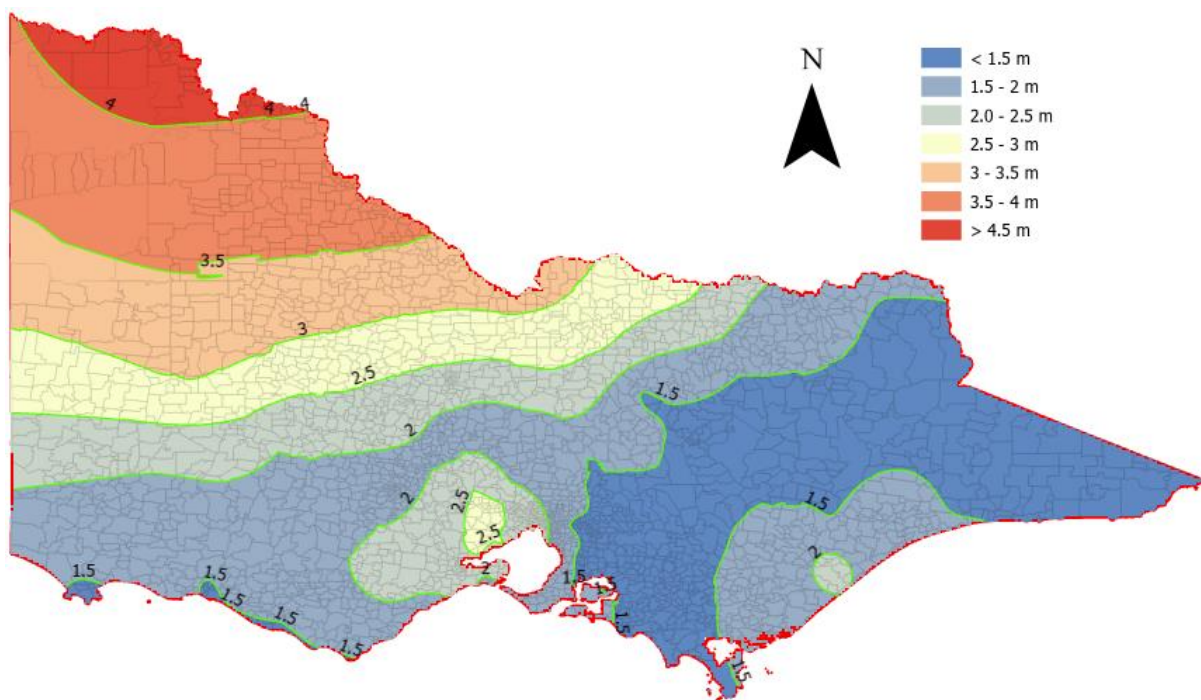


Figure 14. Hs map of Victoria under current climate.

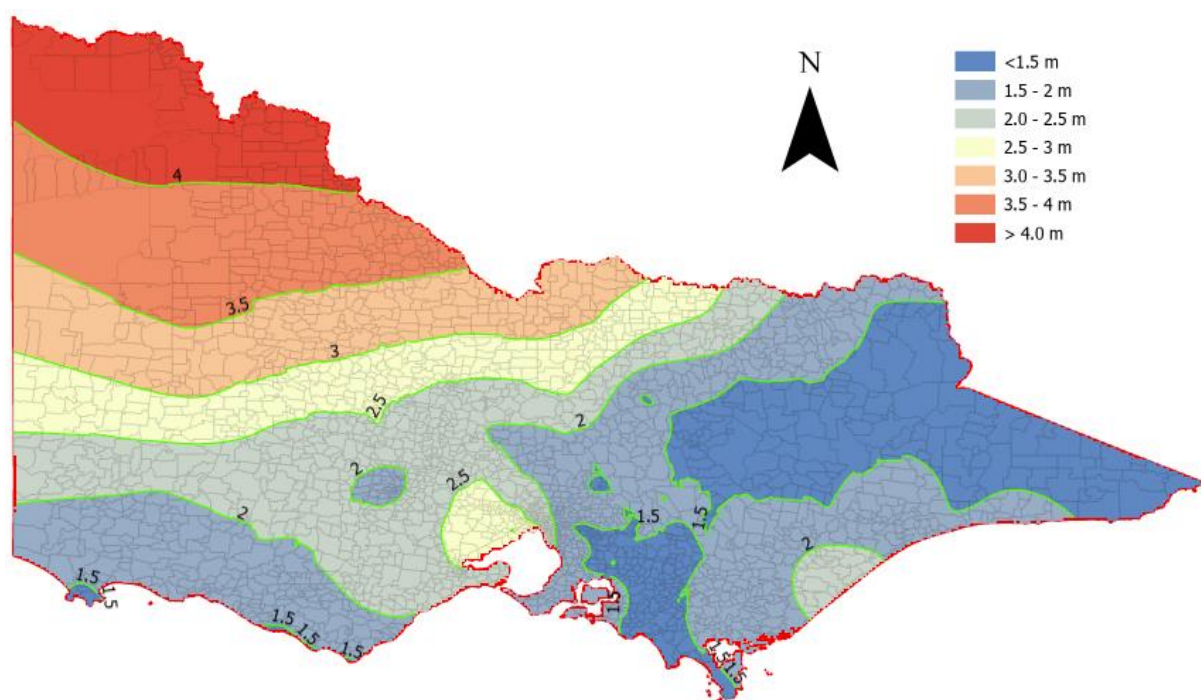


Figure 15. Hs map of Victoria under 2050 medium scenario

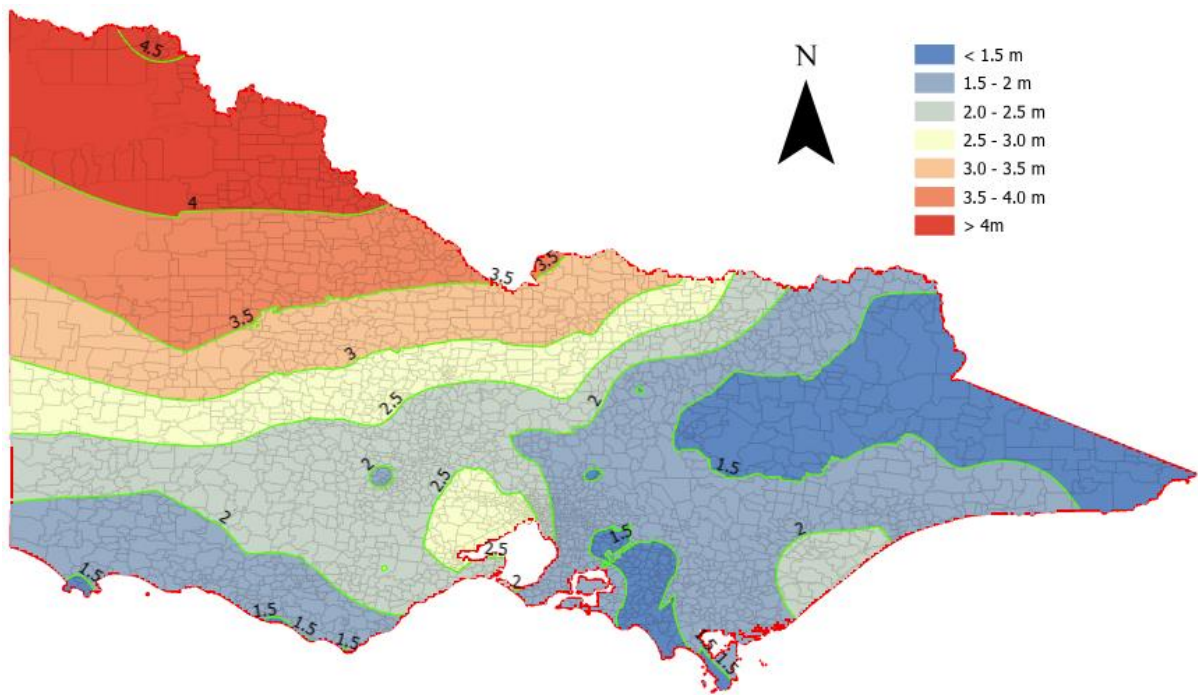


Figure 16. Hs map of Victoria under 2050 high scenario

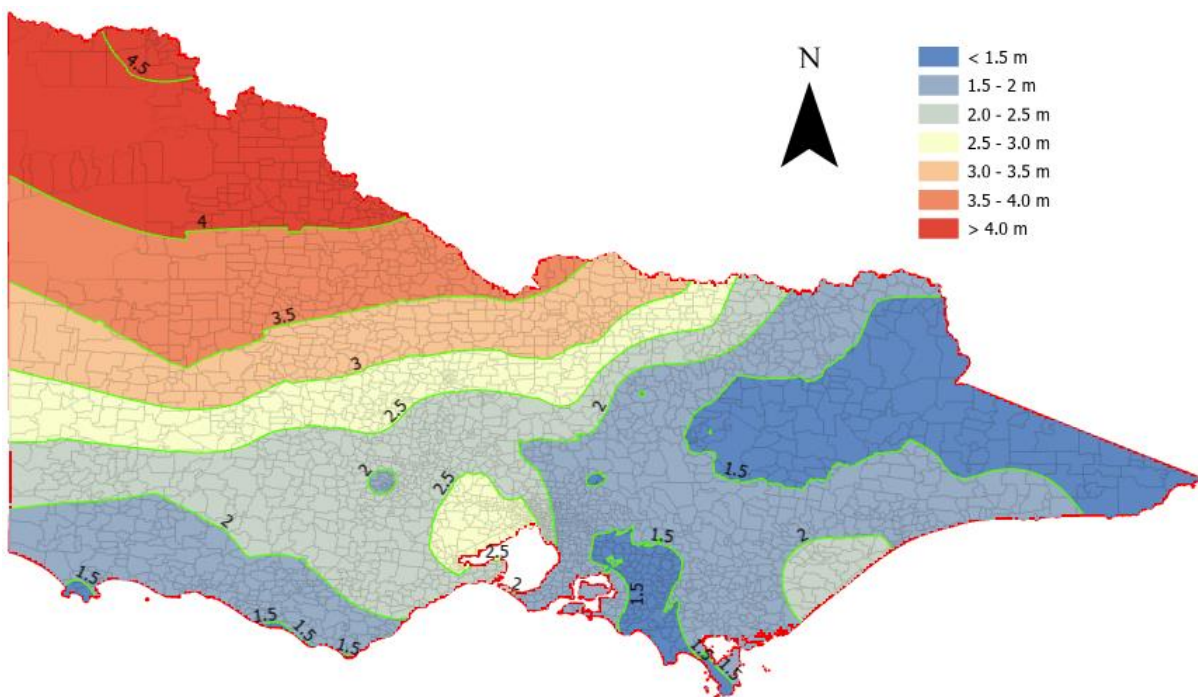


Figure 17. Hs map of Victoria under 2090 medium scenario

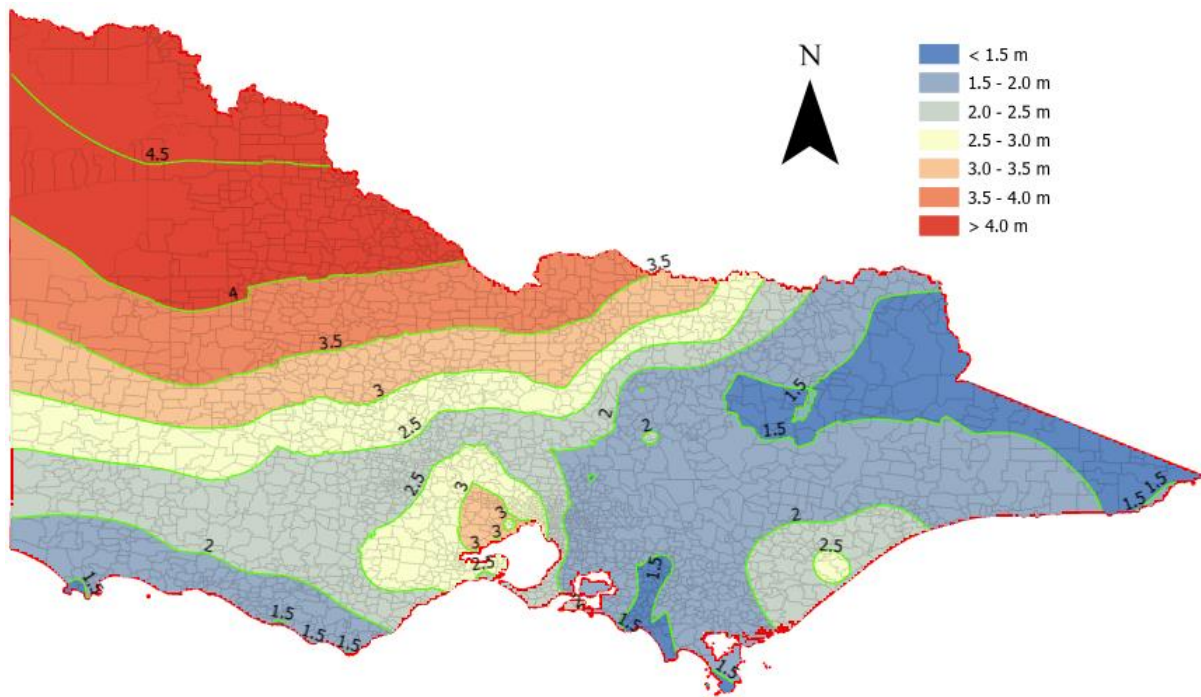


Figure 18. Hs map of Victoria under 2090 high scenario

4.2. Correlation between climate and soil parameters and pipe failures

This section examines the relationship between climate-driven expansive soil behaviour and observed buried infrastructure performance, with a particular focus on underground pipe failures. By analysing correlations between climate parameters, soil movement indicators, and historical pipe failure records, the study investigates how changes in temperature, rainfall, and soil moisture conditions influence the likelihood of damage to buried pipelines. The analysis provides insight into the interaction between climate variability and expansive soil movement, helping to explain why pipe failure rates tend to increase during prolonged hot and dry conditions. These relationships also form the basis for the preliminary predictive models developed later in this report.

To quantify the relationship between climatic conditions and failure rates, a linear regression analysis was conducted using a statistical analysis tool SPSS - Statistical Package for the Social Sciences (IBM, 2023). This statistical approach aimed to identify correlations between failure frequency and key climate variables, including average monthly temperature and precipitation levels. This analysis provides preliminary evidence of the relationship between environmental factors, such as temperature fluctuations and rainfall patterns, and the occurrence of failures in expansive soil regions. These insights highlight the critical role of climate-driven soil behaviour in influencing geotechnical performance. The findings not only contribute to a better

understanding of these interactions but also lay the groundwork for developing predictive models. Such models can inform more effective risk assessment and mitigation strategies, ultimately supporting the design, construction, and maintenance of resilient infrastructure in areas underlain by expansive soils. In the analysis of these parameters, the relationship between failure rates (Chan et al., 2007) and climate data can be expressed as the following equation:

$$FR_m = 0.007 \times T - 0.424 \times R + 30.777 \quad (3)$$

where FR_m is the monthly failure rate per 100 km, T is average monthly temperature, and R is average monthly rainfall. The relationship indicates that higher temperatures combined with low rainfall increase the likelihood of failures associated with expansive soils. This is consistent with observations by Gould (2011) and Gould et al. (2011), who reported that such failures in Victoria typically occur during the summer months. During this period, expansive soils can lose significant moisture, leading to shrinkage, settlement, and cracking beneath substructures. It is important to note that this represents only a preliminary analysis of the collected data to highlight trends in failures caused by expansive soils. To develop practical guidelines for practitioners, an analysis using regression methods is required. The relationship between failure, TMI and H_s can be expressed as the following equation:

$$FR_m = 0.01 \times TMI + 3.562 \times H_s + 0.402 \quad (4)$$

Based on TMI , H_s and y_s , the CORD analysis was conducted to suggest some practical guidelines for residential footing.

*Note: The correlations in Equations 3 and 4 were established based on the average monthly failure rates acquired from Chan et al. (2007). Average monthly rainfalls for 30 years in Equation 3 were collected from the Queensland Government (2024) for 99 weather stations. The monthly average temperatures (average of mean daily maximum and minimum temperatures for a month) in Equation 3 were collected from the same source. Monthly TMIs in Equation 4 were calculated based on the rainfall and temperature in Equation 3 using TMI equations in B1-B5 in Appendix B (Witczak et al., 2006). Then, monthly H_s were calculated based on these TMI values using Equation 2 (AS2870, 2011).

5. Spatial distribution of predicted building damage

This section presents the results of the spatial analyses undertaken in this study, illustrating how expansive soil behaviour and associated risks may vary across Victoria under future climate conditions. Using the collected data and relationships developed in the previous sections, the maps and analyses in this chapter show the projected distribution of characteristic ground movement (y_s) across the state. The results highlight areas where climate-driven changes in soil moisture conditions are expected to increase ground movement and associated

risks to residential buildings and underground infrastructure. By combining spatial soil information with projected climate scenarios, this section translates the earlier technical analyses into a geographic representation of future risk patterns across Victoria.

5.1. *Predicted y_s under future climate scenario*

This section presents the projected changes in characteristic ground movement (y_s) across Victoria under future climate scenarios. Using the climate analyses described in the previous sections, the study evaluates how projected changes in temperature and rainfall may alter soil moisture conditions and increase expansive soil movement over time. The resulting maps highlight regions where climate-driven increases in H_s are expected to produce greater ground movement compared with current climate conditions.

Because characteristic ground movement is one of the key parameters governing the performance of residential footing systems on reactive clay soils, increases in y_s may lead to higher risks of building damage and increased stress on footing. By comparing current and future conditions, this section provides a spatial representation of how climate change may influence expansive soil-related risks across different parts of Victoria and identifies areas where more robust footing design considerations may be required in the future.

The climate data were collected for 99 locations, which were used to calculate H_s as discussed in Section 4.1. The H_s values corresponding to current climate were referred to as current H_s . The y_s values determined in section 3.1 for 99 locations were considered as current y_s . The y_s values were estimated under the future climate scenario as shown in Equation 5 from the guidelines provided by AS2870 (2011). The procedure to formulate Equation 5 is shown in Appendix A. The future y_s map for Victoria is shown in Figure 19.

$$y_{s2} = \frac{0.6375H_{s2} - 0.0065625H_{s2}^2}{0.6375H_{s1} - 0.0065625H_{s1}^2} \times y_{s1} \quad (5)$$

where y_{s1} and y_{s2} are the ground movement under current and future climate, and H_{s1} and H_{s2} are the depth of suction change under current and future climate, respectively.

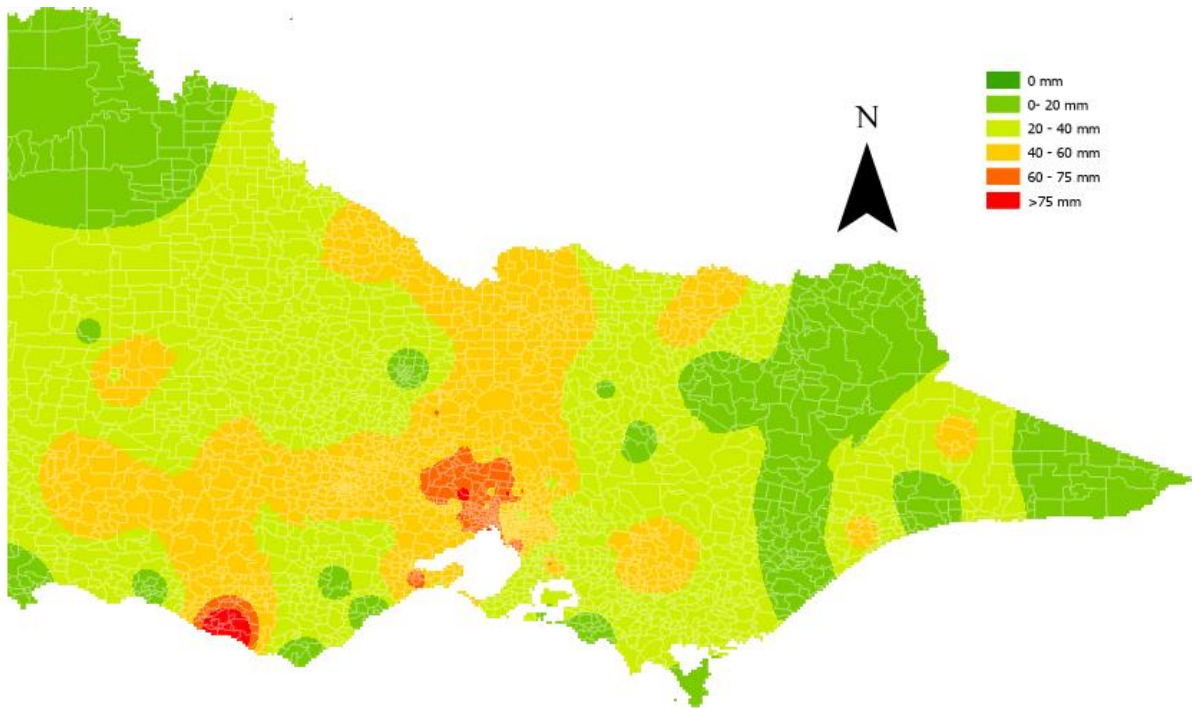


Figure 19. y_s map of Victoria under 2050 medium scenario

5.2. The prediction of building damage

This section presents the projected spatial distribution of expansive soil-related risk zones across Victoria under future climate conditions. The analysis adopts relationships reported in previous studies between climate conditions, expansive soil behaviour, and buried pipe failure records to identify areas where climate-driven soil movement is likely to become more severe. Because underground pipelines are highly sensitive to differential ground movement caused by expansive soils, historical pipe failure trends provide a useful indicator of regions experiencing significant soil shrink-swell activity.

The resulting maps therefore represent indicative expansive soil risk zones derived using buried pipe failure relationships reported in the literature. Although the predictive relationships were developed using buried infrastructure performance data, the mapped risk patterns may also provide useful insight into regions where increased expansive soil movement could contribute to higher risks of building damage and increased footing design demand under future climate conditions. Consequently, the maps may assist in identifying areas where more detailed geotechnical assessment and climate-responsive residential footing design considerations may be warranted.

Figure 20 shows the projected building damage for Victoria under 2050 medium emission scenario. Equation 4 was used to generate this map. The maximum failure rate predicted was

15.8 failures per 100 km which can be assumed to be reasonable maximum observed failure rate of 14 failures per 100 km by Chan et al. (2007). All the calculations (TMI , H_s , y_s and building damage rate) were presented in the separate file under supplementary material (S1).

Missing a small portion of the western region of Victoria in Figure 20 corresponds to a localised area where insufficient input data were available for application of Equation 4 within the kriging interpolation analysis. Consequently, raster values could not be reliably estimated for this portion of the map, and it therefore appears as a no-data area in the spatial output. The full geographic extent of Victoria has otherwise been retained in the figure.

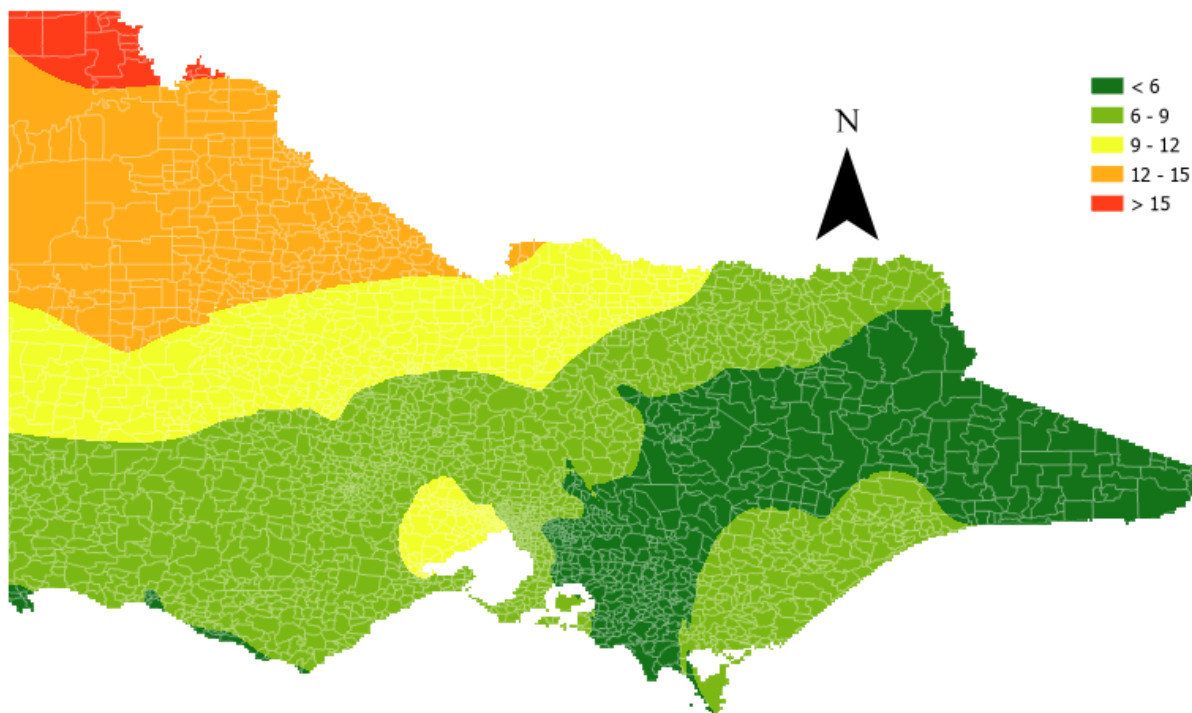


Figure 20. Predicted building damage rate of Victoria under 2050 medium scenario

6. Guidance for residential house footing design

This section translates the soil, climate, and expansive soil movement analyses presented in the earlier chapters into practical guidance for residential footing design across Victoria. The chapter explains how the derived soil and climate parameters, particularly characteristic ground movement (y_s) and depth of seasonal suction change (H_s), were used to categorise suburbs and regional towns into different expansive soil conditions and to develop representative footing design recommendations for each category. The analyses demonstrate how projected future climate conditions may influence footing design demand and how climate-responsive design

considerations can be incorporated into residential construction practice in accordance with AS2870 (2011).

This chapter is particularly relevant for engineers, builders, regulators, planners, and policy-makers because it provides a practical framework for linking statewide expansive soil risk assessments with residential footing design requirements. The methodology moves beyond traditional site-specific interpretation by combining spatial soil data, climate projections, and mechanistic footing analysis to develop regionally applicable design guidance for reactive clay sites across Victoria.

Chapter 6 consists of two main components. Sections 6.1 and 6.2 describe the analytical approach used to translate the soil and climate parameters derived earlier in the report into representative residential footing designs using the CORD software. The practical residential footing design guidance developed from this analysis is presented in Section 6.2 and summarised in Table 4, where suburbs and regional towns are grouped into design categories based on characteristic ground movement (y_s) and depth of seasonal suction change (H_s). Sections 6.3 and 6.4 then demonstrate how the guidance can be applied spatially across Victoria and how future climate conditions may influence footing design requirements over time.

6.1. Code Oriented Raft Design (CORD)

This section describes the methodology used to develop representative residential footing designs for reactive clay sites across Victoria. The approach incorporates the characteristic ground movement (y_s) and depth of seasonal suction change (H_s) derived in the earlier sections of the report into the footing design process using the Code Oriented Raft Design (CORD) software in accordance with AS2870 (2011). These parameters represent the expected magnitude and depth of climate-driven soil movement that residential footing systems may experience under expansive soil conditions.

The section provides the engineering basis for the practical footing design guidance presented later in this chapter by explaining how soil movement, footing stiffness, beam dimensions, and reinforcement requirements are evaluated within the design framework. It also demonstrates how projected future climate conditions may influence footing performance and increase design demand in reactive soil environments. The analyses presented here therefore establish the link between the statewide climate and soil assessments undertaken earlier in the report and the practical residential footing recommendations developed for different regions across Victoria.

Footing design guidance in this study were developed using the Code Oriented Raft Design (CORD) software, version 8.0 (FMG, 2012), which provides a mechanistic, code-based framework for the analysis and design of stiffened raft foundations on reactive clay sites in accordance with AS2870 (2011). CORD models the footing-soil system by explicitly incorporating characteristic ground movement (y_s) and depth of seasonal suction change (H_s) as primary drivers of soil-induced deformation. These parameters are translated into imposed ground movements acting on the footing, which are then analysed under governing distortion modes, including edge heave, centre heave, and differential beam deformation.

In this study, CORD was used not merely as a design tool but as an analytical platform to investigate the sensitivity of footing performance to climate-driven changes in soil behaviour. Systematic parametric analyses were conducted in which y_s and H_s were varied across defined ranges corresponding to different suburb/town categories and future climate scenarios. The results demonstrate a nonlinear response between soil movement parameters and structural demand, whereby incremental increases in y_s and/or H_s can result in disproportionately larger increases in required beam depth and reinforcement. This behaviour reflects the increasing footing stiffness and bending resistance needed to control curvature and tensile strain as imposed ground movement intensifies.

In CORD, the footing–soil system is assessed by combining geometric and loading information of the house and footing with y_s and H_s . Based on these inputs, the software evaluates both the required and provided structural performance of the footing system in terms of stiffness, flexural strength, and ductility. The primary serviceability requirement is that the footing possesses adequate flexural stiffness, quantified through the moment of inertia, $I=bh^3/12$ or, equivalently, the flexural rigidity EI , where b is the beam width, h is the beam depth, and E is Young’s modulus of concrete. Adequate stiffness is required to limit curvature and differential deformation induced by soil heave or shrinkage associated with changes in y_s and H_s .

In addition to stiffness, CORD evaluates ultimate limit state performance by checking that the footing has sufficient flexural capacity to resist the bending moments generated by imposed ground movements and structural loads. This safeguard against flexural failure ensures that cracking and reinforcement yielding remain within acceptable limits under design actions. Finally, CORD enforces ductility requirements by verifying that the footing section is under-reinforced and capable of sustaining rotations without brittle failure. Ensuring ductile behaviour is particularly important for stiffened raft footings on expansive soils, where

soil-induced deformations are unavoidable and controlled redistribution of internal forces is essential for satisfactory long-term performance. An example of CORD analysis is shown in the below figure.

CORD Results Preview - Rectangle 1					
		Centre Heave		Edge Heave	
		Required	Actual	Required	Actual
Direction 1 Length = 15 m	Moment of Inertia ($\times 10^9 \text{ mm}^4 / \text{m}$)	0.379	1.226	0.138	1.226
	Flexural Strength (kNm / m)	18.6	32.6	8.1	25.1
	Ductility Check (kNm / m)	25.6	40.8	14.3	31.4
	Flange Width (m)	External	Internal		
		1.8	3.3		
Direction 2 Length = 10 m	Moment of Inertia ($\times 10^9 \text{ mm}^4 / \text{m}$)	0.575	1.155	0.474	0.506
	Flexural Strength (kNm / m)	21.9	33.0	19.1	27.7
	Ductility Check (kNm / m)	25.2	41.2	15.5	34.6
	Flange Width (m)	External	Internal		
		1.3	2.3		
Young's Modulus of Concrete = 17.308 GPa					
RETURN TO DESIGN			NEXT RECTANGLE		

Figure 21. An example of CORD analysis

As shown in Figure 21, CORD provides the required and actual values of moment of inertia (stiffness), flexural strength and ductility of the system. The design is safe when all actual values are higher than the required values.

After achieving a safe design for a certain combination of y_s and H_s , the design outputs generated by CORD include beam spacing, beam depth, critical reinforcement requirements, and governing heave condition (edge- or centre-controlled). These outputs were critically reviewed and interpreted rather than directly adopted. Upper-bound values of y_s and H_s within each category were intentionally selected to account for spatial uncertainty in soil properties and the inherent variability of climate projections. In addition, minimum beam depth and practical beam spacing limits were enforced in accordance with AS2870 (2011), recognising that software-generated minimum solutions may not always represent robust or constructible designs. This combination of analytical modelling and engineering judgement ensures that the recommended footing systems are conservative, code-compliant, and resilient to future climate-induced soil movements.

6.2. Category of suburbs/towns based on y_s and H_s

This section presents the residential footing design guidance developed in this study by grouping suburbs and regional towns across Victoria into categories based on H_s and y_s . These

parameters reflect the combined influence of expansive soil reactivity and climate-driven moisture variation on expected ground movement conditions. By categorising locations into representative y_s - H_s ranges, the study establishes a practical framework for linking regional soil and climate conditions with appropriate footing design requirements.

The resulting categories form the basis of the climate-responsive footing design guidance summarised in Table 4. For each category, representative footing parameters were developed using CORD analyses in accordance with AS2870 (2011), including beam spacing, beam depth, and reinforcement requirements. This approach enables location-specific design recommendations to be developed at a suburb or regional town level while maintaining consistency with the broader statewide climate and geotechnical assessments presented earlier in the report.

The residential house footings were designed for the suburbs and towns in Victoria based on the H_s and y_s as shown in Figures 15 and 19, respectively. The upper limit of y_s range in Figure 19 was taken in the design being conservative to compensate the uncertainties on estimation of y_s values. The H_s values under the medium emission scenario (RCP4.5) for the year 2050 were adopted in the footing analyses to reflect the typical design life of residential buildings and associated footing systems, which is commonly assumed to be approximately 50 years in engineering design practice. By considering projected climate conditions over a representative residential design life, the study aims to develop footing guidance that is more resilient to future climate-driven expansive soil movement rather than relying solely on historical climate assumptions. The summary of design details including inputs to the software is presented in Table 3. The representative footing designs developed in this study were based on a typical single-storey residential house with articulated brick veneer construction, as this form of construction is widely used in residential developments across Victoria and represents the dominant residential wall system in the available Building Permit data provided by the Building and Plumbing Commission (BPC). The BPC data indicate that brick veneer construction accounts for more than 60% of residential housing approvals, and it is also commonly adopted in footing design examples within Australian residential engineering practice. The structural loading assumptions used in the CORD analyses, including wall weights and superstructure characteristics, therefore reflect a representative brick veneer dwelling rather than all possible residential construction types.

It is important to note that different wall systems and superstructure materials may alter footing design requirements because they influence the magnitude and distribution of structural loads acting on the footing system. For example, lightweight framed construction systems may impose lower structural loads and may therefore require reduced footing stiffness and reinforcement demand, whereas heavier masonry or multi-storey construction may increase footing stiffness and reinforcement requirements. Consequently, the footing guidance presented in this study should be interpreted as representative guidance for typical articulated brick veneer residential construction rather than a universal design solution applicable to all building types.

Nevertheless, the broader relationships identified between climate change, expansive soil movement, and increasing footing design demand remain applicable to other forms of residential construction. Site-specific geotechnical assessment and structural design should therefore still be undertaken for individual developments, particularly where building geometry, loading conditions, construction materials, or site conditions differ substantially from the representative assumptions adopted in this study.

Table 3. Important design details of the footing.

	Design information
Footing size	20 m × 12 m
Wall type	Brick veneer
Superstructure	Articulated masonry veneer
Wall height (Internal and External)	2.7 m
External wall weight	2.5 kN/ m ²
Internal wall weight	0.5 kN/ m ²
Roof type	Tiled–Conventional (0.85 kPa)
Slab live load	0.75 kPa
Concrete compressive strength	20 MPa
Yield strength of reinforcement	500 MPa
Slab thickness	100 mm
Slab cover	20 mm
Slab mesh (SL82)	227 mm ² /m
Beam depth	To be designed
Beam width	300 mm
Beam reinforcement	To be designed

The suburbs and towns in Victoria were categorised in 42 categories based on y_s and H_s as shown in Table 4 and supplementary material (S2). The design guidance for residential footing in different suburbs/towns is presented in Table 4. Based on the CORD outcomes, maximum

spacing of beams has been shown in Table 4. Either spacing as shown in Table or maximum spacing of 6 m can be adopted in the design for the suburbs/towns of y_s values of up to 40 mm and maximum spacing of 3.9 m can be adopted for the sites of y_s values higher than 40 mm and up to 75 mm. Likewise, maximum spacing of 2.9 m can be adopted for the sites of y_s values higher than 75 mm. Please note that although two beams in both directions are sufficient in the design through software, one beam in long direction and two beams in short direction have been added to maintain the spacing of beam in the reasonable range. Likewise, the design requires some beams with depth less than 300mm, however following the Section 3 of Australian Standard AS2870 (2011), 300 mm deep beam has been adopted as a minimum depth.

The residential footing design guidance developed in this study is based on the classification of suburbs and regional towns across Victoria into 42 suburb categories defined by combinations of y_s and H_s , as summarised in Table 4. These categories reflect the combined influence of expansive soil reactivity and climate-driven moisture variation on expected ground movement conditions and therefore provide the basis for understanding regional differences in footing performance and design demand.

Representative footing designs were developed for each category using the CORD software in accordance with AS2870 (2011). The footing parameters presented in Table 4, including beam spacing, beam depth, and reinforcement requirements, therefore represent indicative design guidance for the corresponding y_s - H_s conditions under the adopted future climate scenario. To provide conservative guidance and account for spatial uncertainty in soil and climate parameters, the upper-bound y_s and H_s values within each category were adopted in the footing analyses.

The results presented in Table 4 demonstrate that relatively modest increases in projected expansive soil movement may lead to substantially higher footing design requirements in some locations. This occurs because residential footing design is governed by threshold-based structural and serviceability criteria within the CORD analysis framework rather than simple linear relationships between ground movement and footing dimensions. Consequently, once projected soil movement exceeds certain design thresholds, comparatively small increases in reactivity may require disproportionately larger increases in footing stiffness, beam depth, and reinforcement demand to maintain acceptable footing performance.

For this reason, the study focuses on shifts between expansive soil reactivity categories under current and future climate conditions rather than percentage changes relative to a baseline

footing design. These classification shifts provide a more meaningful representation of how future climate conditions may influence residential footing requirements and associated construction demand across Victoria.

Note: Table 4 summarises the representative footing design guidance developed for each ys–Hs category. A complete listing of the suburbs and regional towns assigned to each category is provided in S2.

Table 4. Residential footing design guidance for suburb/town categories across Victoria based on the 2050 medium emission scenario (RCP4.5).

Suburb/ Town Category	H_s (m)	y_s (mm)	Soil classific ation	No. of long beam/ spacing cc, mm	No. of short beam/ spacing cc, mm	Beam width (mm)	Beam depth (mm)	Bar size (mm)	Number of Bars				Edge/ Centre Heave critical
									External beam		Internal beam		
									Top	Bottom	Top	Bottom	
1	1.5	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
2	1.5	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
3	1.5	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
4	1.5	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Edge
5	1.5	75	H2	4/3900	6/3940	300	350	12	-	3	-	3	Edge
6	1.5	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
7	2	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
8	2	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
9	2	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
10	2	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Edge
11	2	75	H2	4/3900	6/3940	300	350	12	-	3	-	3	Centre
12	2	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
13	2.5	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
14	2.5	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
15	2.5	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
16	2.5	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Edge

Suburb/ Town Category	H_s (m)	y_s (mm)	Soil classific ation	No. of long beam/ spacing cc, mm	No. of short beam/ spacing cc, mm	Beam width (mm)	Beam depth (mm)	Bar size (mm)	Number of Bars				Edge/ Centre Heave critical
									External beam		Internal beam		
									Top	Bottom	Top	Bottom	
17	2.5	75	H2	4/3900	6/3940	300	360	12	-	3	-	2	Centre
18	2.5	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
19	3	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
20	3	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
21	3	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
22	3	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Edge
23	3	75	H2	4/3900	6/3940	300	370	12	-	3	-	2	Edge
24	3	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
25	3.5	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
26	3.5	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
27	3.5	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
28	3.5	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Edge
29	3.5	75	H2	4/3900	6/3940	300	380	12	-	3	-	2	Centre
30	3.5	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
31	4	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
32	4	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
33	4	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge

Suburb/ Town Category	H_s (m)	y_s (mm)	Soil classific ation	No. of long beam/ spacing cc, mm	No. of short beam/ spacing cc, mm	Beam width (mm)	Beam depth (mm)	Bar size (mm)	Number of Bars				Edge/ Centre Heave critical
									External beam		Internal beam		
									Top	Bottom	Top	Bottom	
34	4	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Centre
35	4	75	H2	4/3900	6/3940	300	390	12	-	2	-	2	Edge
36	4	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge
36	4.5	0	A	3/5850	4/6567	300	300	12	-	2	-	2	Edge
38	4.5	20	S	3/5850	4/6567	300	300	12	-	2	-	2	Edge
39	4.5	40	M	3/5850	4/6567	300	300	12	-	2	-	2	Edge
40	4.5	60	H1	4/3900	6/3940	300	300	12	-	2	-	2	Centre
41	4.5	75	H2	4/3900	6/3940	300	400	12	-	2	-	2	Edge
42	4.5	100	E	5/2925	6/3940	300	730	16	2	6	-	6	Edge

6.3. *Interactive map for design details according to suburb/town based on the medium emission scenario (RCP4.5) - 2050*

This section introduces the interactive spatial map developed as part of this project to support the application of the residential footing design guidance across Victoria. The map links individual suburbs and regional towns to their corresponding expansive soil and climate categories together with the representative footing design guidance developed from the CORD analyses. By integrating the statewide soil, climate, and footing design datasets into a spatial platform, the map provides a practical tool for visualising regional differences in expansive soil conditions and associated footing design requirements.

The interactive map is intended to function as a high-level planning and decision-support tool for engineers, planners, regulators, and practitioners. It enables users to identify indicative footing design categories for different locations across Victoria under the adopted future climate scenario. However, the map is not intended to replace site-specific geotechnical investigation, structural design assessment, or professional engineering judgement, particularly where local soil conditions, building characteristics, or environmental factors differ from the representative assumptions adopted in this study.

From the spatial analysis, each of the suburbs/towns of Victoria was assigned a certain y_s and H_s value range, where y_s ranged from 0 to 100 mm in 6 categories while H_s ranged from 1.5 m to 4.5 m in 7 categories. Based on the assigned y_s and H_s ranges for the suburb/town, the foundation design was divided into 42 groups (Table 4), each with unique y_s and H_s values. For the foundation design, the maximum value within each range group was used for both y_s and H_s as discussed in Section 6.1. These 42 different foundation designs were then incorporated into each suburb/town according to their assigned y_s and H_s values from the spatial analysis. An example design detail for the suburb of Coorriemungle is shown in Figure 22 as an interactive map.

The interactive map developed in this study can be accessed and viewed using ArcGIS Pro software. The map integrates the spatial distributions of y_s , H_s , suburb categories, and the corresponding residential footing design guidance developed in this project. Users can select individual suburbs or regional towns across Victoria to identify the applicable y_s - H_s category and associated representative footing design parameters summarised in Table 4.

The interactive map is intended to function as a planning and decision-support tool for engineers, planners, regulators, and practitioners by providing a spatial interface for interpreting the statewide expansive soil and climate analyses undertaken in this study. The map is intended to support preliminary assessment and climate-responsive footing design considerations and should be used in conjunction with site-specific geotechnical investigation, structural design assessment, and professional engineering judgement.

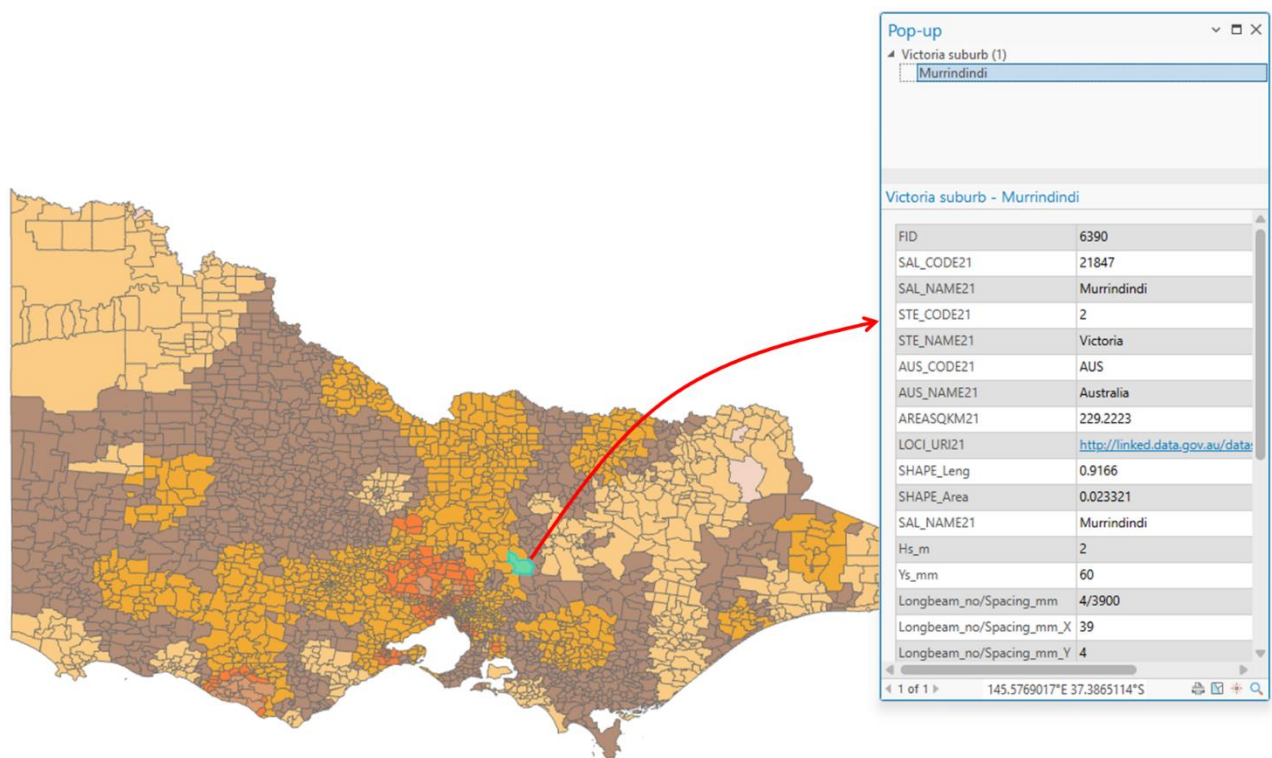


Figure 22. Interactive map for Victorian suburbs/towns showing a design details for the residential footing based on the medium emission scenario (RCP4.5) - 2050

6.4. Effect of climate change on footing design

This section compares representative residential footing design requirements under current and projected future climate conditions to illustrate how climate change may influence residential construction demand across Victoria. The comparison demonstrates that future climate conditions may increase the severity of expansive soil movement in some regions, leading to greater structural demand on footing systems and potentially requiring deeper beams, increased reinforcement, and reduced beam spacing in residential foundations.

The analysis indicates that future climate conditions are likely to influence soil behaviour, particularly through changes in moisture variability, which affect both characteristic ground movement (y_s) and the depth of suction change (H_s). The results show that a proportion of

localities fall within the moderate to critical shift categories, indicating that climate change may lead to increased soil reactivity and foundation movement risk in these areas.

- A ‘critical shift’ was assigned when a locality’s y_s value moved into the greater than 75 mm range from any lower range under the current climate.
- A ‘moderate shift’ applied when it shifted into the 60–75 mm range from below it.
- A ‘minor shift’ described a shift into the 40–60 mm range from a lower category.
- Localities showing smaller shifts than those defined above were classified as ‘insignificant shift’.

Only 0.27% of localities exhibited a critical shift, 3.5% moderate, and 4.99% minor; the remainder were insignificant. Localities with moderate and minor shifts are detailed in Appendix C. Emphasis is placed on y_s , although site classifications follow H_s values per AS2870 (2011).

The design requirements for the selected suburbs/towns with critical shift in are presented in Table 5. It is clear to see that under the considered future climate scenario, the depth of beam is significantly higher than the current climate condition. Similarly, the number and size of the re-bars increased significantly.

Table 5. Comparison of residential footing design guidance under current (2024) and 2050 climate conditions for the suburbs/towns undergoing critical shift in y_s

Suburb/Town	Climate scenario	Soil classification	No of long beams	No of short beams	Beam depth (mm)	Beam width (mm)	Bar size (mm)	Number of bars			
								External beam		Internal beam	
								Top	Bottom	Top	Bottom
Epping Wollert	Current (2024)	Highly reactive (H2)	4	6	350	300	12	-	3	-	3
	2050 medium	Extremely reactive (E)	5	6	730	300	16	2	6	-	6
Brookfield	Current (2024)	Highly reactive (H1)	4	6	300	300	12	-	2	-	2
	2050 medium	Extremely reactive (E)	5	6	730	300	16	2	6	-	6
Harkness Melton West	Current (2024)	Highly reactive (H2)	4	6	370	300	12	-	3	-	2
	2050 medium	Extremely reactive (E)	5	6	730	300	16	2	6	-	6
Newport Williamstown Williamstown North	Current (2024)	Highly reactive (H2)	4	6	360	300	12	-	3	-	2
	2050 medium	Extremely reactive (E)	5	6	730	300	16	2	6	-	6

7. Conclusion

This study presents a comprehensive, state-wide assessment of expansive soil behaviour in Victoria and its implications for the performance of residential footings and buried infrastructure under both current and projected future climate conditions. By integrating spatially distributed soil reactivity data, Thornthwaite Moisture Index (TMI), depth of seasonal suction change (H_s), climate projections, and historical infrastructure failure records, the project moves beyond traditional site-specific approaches and provides a climate-responsive framework for geotechnical design and risk assessment.

The results demonstrate that projected climate change, characterised by higher temperatures, more frequent dry periods, and increased rainfall variability, is likely to intensify seasonal soil moisture fluctuations and increase characteristic ground movement (y_s) across many regions of Victoria. Although only a relatively small proportion of suburbs/towns are projected to undergo moderate or critical shifts into higher reactivity categories, the analysis highlights that even modest increases in y_s and H_s can result in disproportionate increases in footing design demand. In several cases, relatively incremental changes in climate parameters lead to substantially deeper beams, tighter beam spacing, and significantly higher reinforcement requirements. This nonlinear response underscores the sensitivity of residential footing systems to climate-driven soil behaviour and highlights the potential implications for construction cost, material use, and long-term serviceability if future climate conditions are not adequately considered at the design stage.

Correlation analyses between climate variables, soil parameters, and buried pipe failure records reinforce the strong influence of seasonal drying, elevated temperatures, and reduced rainfall on damage trends in expansive soils. While the regression-based relationships developed in this study are preliminary and intended to illustrate trends rather than provide deterministic predictions, they offer valuable insight into the mechanisms linking climate variability and infrastructure performance. These findings support the case for more proactive, climate-informed planning of residential foundations and underground assets in reactive soil environments.

From a practical perspective, a key outcome of the project is the translation of technical analysis into practical, climate-responsive guidance for residential footing design for 42 geotechnical categories across Victoria, supported by an interactive suburb/town-level design map. By

linking local soil characteristics and climate parameters directly to representative footing designs, the project provides an accessible and evidence-based tool for engineers, builders, and regulators. Importantly, the recommended designs remain aligned with the intent of AS2870 (2011) while extending its application through updated climate data and forward-looking assumptions consistent with typical residential design life.

For residential buildings, the primary consequence of increased expansive soil movement is building damage associated with differential ground movement rather than structural collapse. Even relatively moderate increases in projected soil movement may impose substantially greater demand on residential footing systems, potentially leading to increased cracking, slab distortion, differential movement, and higher long-term maintenance requirements if these effects are not adequately considered during design. The footing analyses undertaken in this study demonstrate that projected future climate conditions may require substantially deeper beams, increased reinforcement, and reduced beam spacing in some regions to maintain acceptable footing performance over the design life of residential structures.

For buried infrastructure, particularly pressurised water pipelines, the analyses demonstrate a clear relationship between climate-driven expansive soil behaviour and functional infrastructure failures such as pipe bursts, leaks, and cracking. Historical failure records indicate that failure rates tend to increase during prolonged hot and dry periods when expansive soils undergo significant shrinkage and differential ground movement. The projected future climate scenarios considered in this study suggest that these conditions may become more severe in some regions of Victoria, potentially increasing stresses on buried infrastructure and contributing to higher future pipe failure risk.

Notwithstanding its contributions, the study is subject to several limitations. Uncertainty remains in future climate projections, particularly at local scales, and spatial gaps in soil data influence the reliability of interpolated maps in sparsely sampled regions. In addition, the failure prediction relationships are based on historical datasets that pre-date recent changes in construction practices and asset management strategies. These limitations point to the need for ongoing refinement as new climate projections, higher-resolution soil datasets, and updated infrastructure performance records become available.

It is important to note that the residential footing guidance developed in this study is based on a representative single-storey articulated brick veneer residential house reflecting common housing construction practices in Victoria. Consequently, the design recommendations should

be interpreted as indicative guidance for typical residential construction rather than universal design solutions applicable to all building forms, sizes, or structural systems. Nevertheless, the methodology, datasets, spatial analyses, and climate-responsive design framework developed through this project provide a strong foundation for future studies involving a broader range of residential building types, construction systems, footing configurations, and site-specific design scenarios across expansive soil regions.

8. References

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Appendix A: Estimation of characteristic ground movement

Procedure to estimate characteristic ground movement, y_s , under future climate scenario:

Equation 1 was used to estimate y_s assuming triangular variation of suction profile, zero at depth H_s and 1.2 pF at the surface. The depth of crack (H_c) was assumed to be $0.75 H_s$.

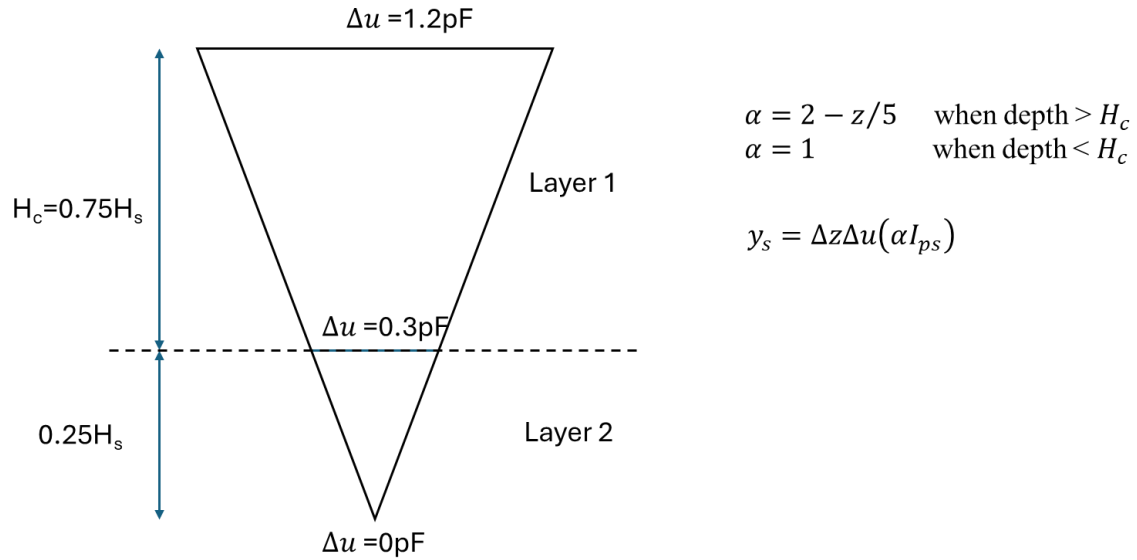


Fig. A1. Detailed triangular distribution of suction change for calculating y_s

The soil profile is divided into two distinct layers. The characteristic ground movement (y_s) is calculated for each layer separately and then combined to obtain the total ground movement. The detailed calculations are shown below:

Layer 1

At the top of Layer 1:

$$\alpha = 1 \text{ when depth} < H_c$$

$$\Delta u = 1.2 \text{ pF}$$

At the bottom of Layer 1:

$$\alpha = 1 \text{ when depth} < H_c$$

$$\Delta u = 0.3 \text{ pF}$$

Average value for layer 1

$$\alpha = 1$$

$$\Delta u = 0.75 \text{ pF}$$

Thickness of layer 1, $\Delta z = 0.75 H_s$

The ground movement of layer 1: $y_{s1} = \Delta z \Delta u (\alpha I_{ps}) = 0.75 H_s \times 0.75 \times 1 \times I_{ps} = 0.5625 H_s I_{ps}$

Layer 2

At the top of Layer 2, $z = 0.75 H_s$

$$\alpha = 2 - z/5 = 2 - 0.75 H_s / 5 = 2 - 0.15 H_s \quad \text{when depth } z > H_c$$

$$\Delta u = 0.3 \text{ pF}$$

At the bottom of Layer 2, $z = H_s$

$$\alpha = 2 - z/5 = 2 - H_s / 5 = 2 - 0.2 H_s \quad \text{when depth } z > H_c$$

$$\Delta u = 0 \text{ pF}$$

Average value for layer 2

$$\alpha = 2 - 0.175 H_s$$

$$\Delta u = 0.15 \text{ pF}$$

Thickness of layer 2, $\Delta z = 0.25 H_s$

The ground movement of layer 2:

$$y_{s2} = \Delta z \Delta u (\alpha I_{ps}) = 0.25 H_s \times 0.15 \times (2 - 0.175 H_s) \times I_{ps} = 0.075 H_s I_{ps} - 0.0065625 H_s^2 I_{ps}$$

Total ground movement combining both layers:

$$y_s = y_{s1} + y_{s2} = (0.6375 H_s - 0.0065625 H_s^2) I_{ps}$$

The calculated value of y_s for current climate (y_{sI}) is shown in Equation A1.

$$y_{s1} = (0.6375H_{s1} - 0.0065625H_{s1}^2) \times IP_s \quad (A1)$$

where I_{ps} is the laboratory reactivity index assumed to be constant throughout the depth H_s . I_{ps} can be estimated as below:

$$I_{ps} = \frac{y_{s1}}{0.6375H_{s1} - 0.0065625H_{s1}^2} \quad (A2)$$

Considering I_{ps} constant, the y_s for future climate, y_{s2} can be estimated as shown below which is Equation 9.

$$y_{s2} = \frac{0.6375H_{s2} - 0.0065625H_{s2}^2}{0.6375H_{s1} - 0.0065625H_{s1}^2} \times y_{s1} \quad (A3)$$

Appendix B: Calculation of TMI

The following steps to calculate *TMI* were followed. The monthly average temperature was calculated averaging of the minimum and maximum temperature. Equation B1 was used to estimate the annual heat index (H_y).

$$H_y = \sum_i^{12} (0.2t_i)^{1.514} \quad (B1)$$

where t_i is the monthly air temperature (avg.) in °C of the i^{th} month (can be taken as the average of the average minimum and average maximum air temperature). Non-adjusted potential evapotranspiration (pe_i) was calculated using Equation B2.

$$pe_i = 1.6 * \left(\frac{10t_i}{H_y} \right)^a \quad (B2)$$

where a is the coefficient ranges between 0 and 4.25, and related to yearly heat index H_y as

$$a = 0.000000675(H_y)^3 - 0.000071(H_y)^2 + 0.01792H_y + 0.49239 \quad (B3)$$

Day length correction factor and total days of a certain month were used to determine adjusted potential evapotranspiration (PET_i) was calculated using day length correction factor and days of a month as in Equation B4.

$$PET_i = pe_i \left(\frac{d_i N_i}{30} \right) \quad (B4)$$

where d_i is the day length correction factor for the i^{th} month, N_i is the number of days of a related month. d_i depends on latitude and can be assumed to be constant for a particular month. Equation B5 proposed by Witczak et al. (2006) was followed to estimate the *TMI* at various locations.

$$TMI = 75 \left(\frac{P}{PET} - 1 \right) + 10 \quad (B5)$$

Appendix C: The details of the y_s change in future climate in all suburbs and towns

The tables in this section provide the details of the changes in soil categories i.e. ‘minor shift’, ‘moderate shift’ and ‘critical shift’ discussed in section 6.4.

Table C1. The details of y_s change in the suburbs and towns in the “minor shift” category.

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Amor	M	2	40	H1	2	60
Appin South	M	3.5	40	H1	4	60
Ardmona	M	3	40	H1	3	60
Athlone	M	1.5	40	H1	1.5	60
Balwyn North	M	2	40	H1	2	60
Barnawartha North	M	2	40	H1	2.5	60
Beechworth	M	2	40	H1	2.5	60
Belgrave South	M	1.5	40	H1	1.5	60
Berringa	M	2	40	H1	2.5	60
Blind Bight	M	1.5	40	H1	2	60
Boole Poole	M	2	40	H1	2	60
Boorhaman North	M	2.5	40	H1	3	60
Boweya	M	2.5	40	H1	3	60
Bradvale	M	2	40	H1	2.5	60
Brimin	M	2.5	40	H1	3	60
Brit Brit	M	2.5	40	H1	2.5	60
Buckley	M	2.5	40	H1	2.5	60
Bundoora (Vic.)	M	2	40	H1	2.5	60
Burkes Bridge	M	3.5	40	H1	4	60
Cannons Creek	M	1.5	40	H1	2	60
Cargerie	M	2.5	40	H1	2.5	60
Carrum	M	2	40	H1	2	60
Chesney Vale	M	2.5	40	H1	2.5	60
Chum Creek	M	1.5	40	H1	1.5	60
Clarendon (Vic.)	M	2.5	40	H1	2.5	60
Cohuna	M	3.5	40	H1	4	60
Cosgrove (Vic.)	M	3	40	H1	3	60
Cullen	M	3.5	40	H1	4	60
Dadswells Bridge	M	3	40	H1	3.5	60
Daltons Bridge	M	3.5	40	H1	4	60
Dandenong South	M	2	40	H1	2	60
Dereel	M	2.5	40	H1	2.5	60
Dixons Creek	M	1.5	40	H1	1.5	60
Donvale	M	2	40	H1	2	60
Dookie	M	3	40	H1	3	60
Doveton	M	2	40	H1	2	60

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Dropmore	M	2	40	H1	2	60
Eagle Point	M	2	40	H1	2	60
Elaine	M	2.5	40	H1	2.5	60
Eldorado	M	2	40	H1	2.5	60
Ellaswood	M	2	40	H1	2	60
Eltham North	M	2	40	H1	2	60
Englefield	M	2.5	40	H1	2.5	60
Everton Upper	M	2	40	H1	2.5	60
Gannawarra	M	3.5	40	H1	4	60
Gembrook	M	1.5	40	H1	2	60
Glenbrae	M	2	40	H1	2.5	60
Gonn Crossing	M	4	40	H1	4	60
Gowangardie	M	2.5	40	H1	2.5	60
Grenville	M	2.5	40	H1	2.5	60
Healesville	M	1.5	40	H1	1.5	60
Horfield	M	3.5	40	H1	4	60
Illabarook	M	2	40	H1	2.5	60
Invergordon (Vic.)	M	3	40	H1	3.5	60
Jungaburra	M	3.5	40	H1	3.5	60
Kallista	M	1.5	40	H1	1.5	60
Kalorama	M	1.5	40	H1	2	60
Keely	M	3.5	40	H1	4	60
Kewell	M	3.5	40	H1	3.5	60
Koondrook	M	4	40	H1	4	60
Laharum	M	3	40	H1	3.5	60
Lake Meran	M	3.5	40	H1	4	60
Langi Kal Kal	M	2	40	H1	2.5	60
Lilydale (Vic.)	M	1.5	40	H1	2	60
Limestone (Vic.)	M	2	40	H1	2	60
Lindenow	M	2	40	H1	2	60
Lindenow South	M	2	40	H1	2	60

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Lismore (Vic.)	M	2	40	H1	2.5	60
Loddon Vale	M	3.5	40	H1	4	60
Longwood East	M	2.5	40	H1	2.5	60
Lucknow (Vic.)	M	2	40	H1	2	60
Macleod (Vic.)	M	2	40	H1	2	60
Macorna	M	3.5	40	H1	4	60
Main Lead	M	2	40	H1	2.5	60
Mannerim	M	2	40	H1	2.5	60
Markwood	M	2	40	H1	2.5	60
Maroona	M	2.5	40	H1	2.5	60
McMillans	M	3.5	40	H1	4	60
Mead	M	3.5	40	H1	4	60
Meadow Creek	M	2	20	H1	2	60
Menzies Creek	M	1.5	40	H1	1.5	60
Meredith	M	2.5	40	H1	2.5	60
Mincha	M	3.5	40	H1	3.5	60
Mincha West	M	3.5	40	H1	4	60
Minyip	M	3.5	40	H1	3.5	60
Mockinya	M	3	40	H1	3	60
Modewarre	M	2.5	40	H1	2.5	60
Moglonemby	M	2.5	40	H1	2.5	60
Molesworth (Vic.)	M	2	40	H1	2	60
Monbulk	M	1.5	40	H1	2	60
Mont Albert North	M	2	40	H1	2	60
Montmorency	M	2	40	H1	2	60
Mount Bute	M	2	40	H1	2.5	60
Mount Mercer	M	2.5	40	H1	2.5	60
Mount Taylor	M	2	40	H1	2	60
Moyhu	M	2	20	H1	2	60
Murra Warra	M	3.5	40	H1	3.5	60
Murrabit	M	4	40	H1	4	60

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Mywee	M	3	40	H1	3.5	60
Naring	M	3	40	H1	3.5	60
Nerring	M	2	40	H1	2.5	60
Newlands Arm	M	2	40	H1	2	60
Nunawading	M	2	40	H1	2	60
Nurrabiel	M	3	40	H1	3	60
Park Orchards	M	2	40	H1	2	60
Patterson Lakes	M	2	40	H1	2	60
Peechelba	M	2.5	40	H1	3	60
Peechelba East	M	2.5	40	H1	3	60
Pirron Yallock	M	2	40	H1	2	60
Point Lonsdale	M	2	40	H1	2.5	60
Powelltown	M	1.5	40	H1	2	60
Quantong	M	3	40	H1	3.5	60
Ruffy	M	2	40	H1	2.5	60
Rupanyup	M	3.5	40	H1	3.5	60
Russells Bridge	M	2.5	40	H1	2.5	60
Seaford (Vic.)	M	2	40	H1	2	60
Selby	M	1.5	40	H1	1.5	60
Springdallah	M	2	40	H1	2.5	60
Tamleugh	M	2.5	40	H1	2.5	60
Tatura	M	3	40	H1	3	60
Tatura East	M	3	40	H1	3	60
The Patch	M	1.5	40	H1	1.5	60
Thoona	M	2.5	40	H1	2.5	60
Thorpdale South	M	1.5	40	H1	2	60
Tonimbuk	M	1.5	40	H1	1.5	60
Toolamba West	M	3	40	H1	3	60
Tynong North	M	1.5	40	H1	1.5	60
Ulupna	M	3	40	H1	3.5	60
Upper Lurg	M	2	40	H1	2.5	60

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Wal Wal	M	3	40	H1	3.5	60
Wallinduc	M	2	40	H1	2.5	60
Warrandyte	M	2	40	H1	2	60
Wartook	M	3	40	H1	3	60
Waterloo (Vic.)	M	2.5	40	H1	2.5	60
Watsonia	M	2	40	H1	2	60
Wee Wee Rup	M	3.5	40	H1	4	60
Willowmavin	M	2	40	H1	2	60
Willowvale (Vic.)	M	2	40	H1	2.5	60
Winton (Vic.)	M	2.5	40	H1	2.5	60
Wonwondah	M	3	40	H1	3.5	60
Woodhouse	M	2	40	H1	2	60
Yabba North	M	3	40	H1	3	60
Yabba South	M	3	40	H1	3	60
Yallambie	M	2	40	H1	2	60
Yarra Glen	M	1.5	40	H1	2	60
Yarroweyah	M	3	40	H1	3.5	60
Youanmite	M	3	40	H1	3	60

Table C2. The details of y_s change in the suburbs and towns in the “moderate shift” category.

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Altona Meadows	H1	2.5	60	H2	3	75
Ashbourne (Vic.)	H1	2.5	60	H2	2.5	75
Beaumaris (Vic.)	H1	2	60	H2	2.5	75
Bentleigh East	H1	2	60	H2	2.5	75
Beveridge	H1	2	60	H2	2.5	75
Black Rock (Vic.)	H1	2.5	60	H2	2.5	75
Brighton (Vic.)	H1	2.5	60	H2	2.5	75
Broadmeadows (Vic.)	H1	2.5	60	H2	2.5	75
Brunswick (Vic.)	H1	2.5	60	H2	2.5	75
Brunswick West	H1	2.5	60	H2	2.5	75
Bullaharrie	H1	2	60	H2	2	75
Campbellfield	H1	2.5	60	H2	2.5	75
Carlton (Vic.)	H1	2.5	60	H2	2.5	75
Carlton North	H1	2.5	60	H2	2.5	75
Cherokee	H1	2.5	60	H2	2.5	75
Chintin	H1	2	60	H2	2	75
Clayton South	H1	2	60	H2	2	75
Coburg	H1	2.5	60	H2	2.5	75
Coburg North	H1	2.5	60	H2	2.5	75
Coimadai	H1	3	60	H2	3	75
Coolaroo	H1	2.5	60	H2	2.5	75
Dallas	H1	2.5	60	H2	2.5	75
Darley	H1	3	60	H2	3	75
Darraweit Guim	H1	2	60	H2	2.5	75
Deanside	H1	3	60	H2	3	75
Doreen	H1	2	60	H2	2	75
East Melbourne	H1	2.5	60	H2	2.5	75
Eden Park	H1	2	60	H2	2	75
Elwood	H1	2.5	60	H2	2.5	75
Essendon North	H1	2.5	60	H2	2.5	75
Fawkner	H1	2.5	60	H2	2.5	75
Geelong	H1	2.5	60	H2	3	75
Glenhope	H1	2	60	H2	2.5	75

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Glenroy (Vic.)	H1	2.5	60	H2	2.5	75
Hadfield	H1	2.5	60	H2	2.5	75
Hampton (Vic.)	H1	2.5	60	H2	2.5	75
Heathcote Junction	H1	2	60	H2	2	75
Hesket	H1	2	60	H2	2.5	75
Highett	H1	2	60	H2	2.5	75
Highton	H1	2.5	60	H2	2.5	75
Hoppers Crossing	H1	3	60	H2	2.5	75
Jacana	H1	2.5	60	H2	2.5	75
Kalkallo	H1	2	60	H2	2.5	75
Keilor Park	H1	2.5	60	H2	2.5	75
Kerrie	H1	2	60	H2	2.5	75
Keysborough	H1	2	60	H2	2	75
Kurunjang	H1	3	60	H2	3	75
Lalor	H1	2	60	H2	2.5	75
Lancefield	H1	2	60	H2	2.5	75
Laverton (Vic.)	H1	2.5	60	H2	3	75
Lerderderg	H1	3	60	H2	3	75
Meadow Heights	H1	2.5	60	H2	2.5	75
Melbourne	H1	2.5	60	H2	2.5	75
Melton (Vic.)	H1	3	60	H2	3	75
Merrimu	H1	3	60	H2	3	75
Mia Mia (Vic.)	H1	2	60	H2	2.5	75
Mill Park	H1	2	60	H2	2	75
Monegeetta	H1	2	60	H2	2.5	75
Moorabbin	H1	2	60	H2	2.5	75
Mount Cottrell	H1	3	60	H2	3	75
Mount Macedon	H1	2.5	60	H2	2.5	75
Myrniong	H1	2.5	60	H2	3	75
Naringal East	H1	2	60	H2	2	75
Newham	H1	2	60	H2	2.5	75
Newtown (Greater Geelong - Vic.)	H1	2.5	60	H2	2.5	75

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Niddrie	H1	2.5	60	H2	2.5	75
North Melbourne	H1	2.5	60	H2	2.5	75
Oak Park	H1	2.5	60	H2	2.5	75
Parkville (Vic.)	H1	2.5	60	H2	2.5	75
Pascoe Vale	H1	2.5	60	H2	2.5	75
Pascoe Vale South	H1	2.5	60	H2	2.5	75
Plenty (Vic.)	H1	2	60	H2	2	75
Plumpton (Vic.)	H1	3	60	H2	3	75
Point Cook	H1	2.5	60	H2	2.5	75
Princes Hill	H1	2.5	60	H2	2.5	75
Redesdale	H1	2	60	H2	2.5	75
Reservoir (Vic.)	H1	2.5	60	H2	2.5	75
Rochford	H1	2	60	H2	2.5	75
Romsey	H1	2	60	H2	2.5	75
Sandringham (Vic.)	H1	2.5	60	H2	2.5	75
Seabrook	H1	2.5	60	H2	3	75
South Wharf	H1	2.5	60	H2	2.5	75
Southbank	H1	2.5	60	H2	2.5	75
Springfield (Macedon Ranges - Vic.)	H1	2	60	H2	2	75
Springvale (Vic.)	H1	2	60	H2	2	75
Springvale South	H1	2	60	H2	2	75
St Kilda (Vic.)	H1	2.5	60	H2	2.5	75
St Kilda West	H1	2.5	60	H2	2.5	75
Strathmore (Vic.)	H1	2.5	60	H2	2.5	75
Tarneit	H1	3	60	H2	3	75
Thomastown	H1	2	60	H2	2.5	75
Travancore	H1	2.5	60	H2	2.5	75
Trentham East	H1	2.5	60	H2	2.5	75
Upper Plenty	H1	2	60	H2	2	75
Wandana Heights	H1	2.5	60	H2	2.5	75
Waterways	H1	2	60	H2	2	75
Waurin Ponds	H1	2.5	60	H2	2.5	75

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Whittington	H1	2.5	60	H2	2.5	75
Whittlesea	H1	2	60	H2	2	75
Williams Landing	H1	2.5	60	H2	2.5	75
Woodend (Vic.)	H1	2.5	60	H2	2.5	75
Woodstock (Vic.)	H1	2	60	H2	2	75
Yan Yean	H1	2	60	H2	2	75

Table C3. The details of y_s change in the suburbs and towns in the “critical shift” category.

Suburb/Town	Current soil classification	Current H_s , m	Current y_s , mm	Future soil classification	Future H_s , m	Future y_s , mm
Brookfield (Vic.)	H1	3	60	E	3	100
Epping (Vic.)	H2	2	75	E	2.5	100
Harkness	H2	3	75	E	3	100
Melton West	H2	3	75	E	3	100
Newport (Vic.)	H2	2.5	75	E	3	100
Williamstown (Vic.)	H2	2.5	75	E	3	100
Williamstown North	H2	2.5	75	E	3	100
Wollert	H2	2	75	E	2.5	100

Appendix D: How to use the ArcGIS pro map

In this project, there are five maps were created and compressed as “Packaged Project File” in ArcGIS Pro. As shown in the below figure

Name	Status	Type	Size
 Building damage rate map		Packaged Project File	126,150 KB
 Final interactive map		Packaged Project File	126,230 KB
 Hs maps		Packaged Project File	108,389 KB
 TMI maps		Packaged Project File	108,389 KB
 Ys map		Packaged Project File	126,594 KB

Figure D1. The ArcGIS Pro files from the project

- ‘TMI maps’: The file contains the data for Figures 9 to 13
- ‘Hs maps’: The file contains the data for Figures 14 to 18
- ‘Ys map’: The file contains the data for Figure 19
- ‘Building damage rate map’: The file contains the data for Figure 20
- ‘Final interactive map’: The file contains the data for Figure 22

To access the maps corresponding to the figures discussed above, the user can open the relevant map file in ArcGIS Pro. For the “Hs maps” and “TMI maps” files, different map layers can be viewed by selecting or deselecting the relevant layers within the Contents tab located on the left-hand side of the window (see Figure D2).

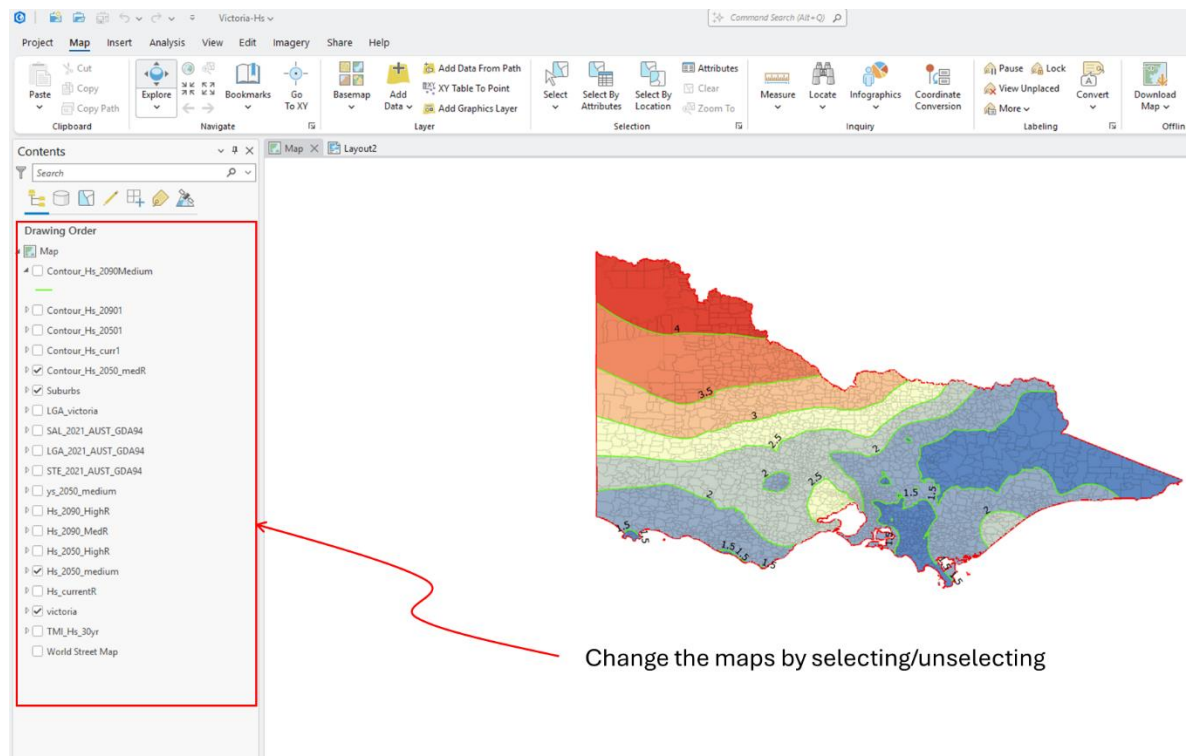


Figure D2. ArcGIS Pro window

To use the final interactive map, the user simply needs to open the file in ArcGIS Pro. Once opened, the interactive map will be displayed automatically. The user can then move the cursor to any suburb or regional town and click on the location to display the corresponding information window, as illustrated in Figure 22.

List of Symbols

Symbol	Description	Units
y_s	Characteristic surface movement	mm
H_s	Depth of seasonal suction change	m
TMI	Thornthwaite Moisture Index	—
CORD	Code Oriented Raft Design software	—
AS2870	Australian Standard for Residential Slabs and Footings	—
RCP4.5	Representative Concentration Pathway 4.5 climate scenario	—
RCP8.5	Representative Concentration Pathway 8.5 climate scenario	—
P	Annual precipitation / rainfall	mm
T	Mean annual temperature	°C
PET	Potential evapotranspiration	mm
I	Annual heat index used in TMI calculations	—
M	Moisture index parameter	—
z	Soil depth coordinate	m
u	Soil suction	kPa
Δu	Change in soil suction	kPa
Δw	Change in soil moisture content	%
γ	Unit weight of soil	kN/m ³
E	Young's modulus / elastic modulus	MPa
f'_c	Characteristic compressive strength of concrete	MPa

Symbol	Description	Units
f_y	Yield strength of reinforcement steel	MPa
M_u	Ultimate bending moment capacity	kN·m
ϕ	Capacity reduction factor	—
d	Effective depth of footing beam	mm
b	Width of footing beam	mm
s	Beam spacing	mm
A_s	Area of steel reinforcement	mm ²
L	Characteristic footing length/span	m
q	Applied foundation pressure	kPa
ε	Strain	—
σ	Stress	MPa
k	Soil stiffness parameter	—
r	Correlation coefficient	—
R^2	Coefficient of determination	—
GIS	Geographic Information System	—
ArcGIS Pro	Geographic information system software platform	—
BPC	Building and Plumbing Commission	—
PE	Polyethylene pipe	—
pF	Logarithmic measure of soil suction	—
θ	Volumetric moisture content	%

Symbol	Description	Units
Δh	Vertical ground movement / heave	mm
CR	Crack ratio / cracking index (if applicable)	—

Abbreviations

Abbreviation	Description
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A	Non-reactive site classification
S	Slightly reactive site classification
M	Moderately reactive site classification
H	Highly reactive site classification
E	Extremely reactive site classification
P Class	Problem site classification requiring site-specific assessment
ULS	Ultimate Limit State
SLS	Serviceability Limit State
SILO	Scientific Information for Land Owners climate database
BOM	Bureau of Meteorology
PE pipe	Polyethylene pipe