

# ASSESSING THE IMPACT OF EXTREME COLD WAVES ON BURIED WATER PIPELINES: AN INTEGRATION OF HISTORICAL PIPE FAILURE AND 3D SIMULATION

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**Abstract:** The increasing frequency and intensity of climate change-induced extreme weather events like cold waves have raised concerns about their impact on buried water pipelines. This study investigates the effect of severe cold waves on buried water pipelines by combining historical pipe failure data analysis with advanced 3D simulation techniques. We analyzed 19 years of pipe failure data from an urban area in Eastern China during cold wave periods, focusing on the correlation between cold wave failure rates and temperature parameters. Our findings reveal a significant increase in pipe failure rates during cold wave periods, particularly at very low temperatures. Furthermore, the relationship between the failure rate and the duration of the cold wave follows a 'bathtub curve.' A 3D finite element (FE) model was developed to simulate the thermo-mechanical behavior of buried water pipelines under cold wave-induced soil temperature conditions obtained from field data. The simulation results show that pipe peak stress varies with temperature changes, with a 0.3°C/hr increase in cooling rate resulting in a 4.8% increase in peak pipe hoop stress. Prolonged cold wave duration (DCW) increases pipe stress, with an increase in DCW from 48 hours to 120 hours leading to a 13.5% increase in stress. However, a small rise in the temperature difference between the inside and outside of the pipe does not significantly affect pipe stress, while a greater increase is expected to cause a notable rise in pipe stress. The results highlight the significant effect of cold wave-induced extreme temperatures on pipe failure rates and mechanical behavior. These findings are crucial for improving infrastructure resilience and informing future design and maintenance protocols in response to changing climatic conditions.

**Keywords:** Water pipeline; Extreme cold wave; Annual failure rate; Cold wave failure rate; Thermo-Mechanical model; Hoop stress

## 1. Introduction

Climate change directly impacts buried water pipelines (Wywiec et al., 2024; Bruaset and Sægrov, 2018). Rising global temperatures, shifting weather patterns, temperature fluctuations, and more frequent extreme weather events impose significant mechanical stress on buried water infrastructures (Fan et al., 2023). In regions like Eurasia and North America, warming has also increased the frequency of cold-air outbreaks and wintertime cold extremes, driven by Arctic warming and its link to mid-latitude climate patterns (Chen and Luo, 2017). These cold waves, characterized by prolonged periods of extreme low temperatures and heavy snowfall, severely affect water supply systems by altering the thermal state of the soil surrounding buried pipelines (Radović and Iglesias, 2019). Repeated freeze-thaw cycles during these events cause soil contraction and tensile stresses in pipelines, accelerating material fatigue, cracking, and bursting, particularly in older, brittle pipes like cast iron, leading to potential catastrophic failures and disruptions to water supply (Li et al., 2020). For example, Hu et al. (2024) reported that during Shanghai's extreme cold waves in late 2020 and early 2021, temperatures dropped to -3°C, leading to 70 burst pipes with diameters over 500mm.

This paper examines the impact of cold waves on buried water pipes in an Eastern China region, combining historical failure data analysis with advanced 3D simulations to estimate pipe failure rates during cold waves and investigate the mechanical behavior of pipes under temperature variations.

## 2. Climate change-induced extreme cold waves

The World Meteorological Organization (WMO) defines a cold wave as a sudden and rapid cooling of very cold air over a large area, sustained for a specified number of days and with temperatures consistently below certain thresholds. These thresholds depend on the rate at which the temperature drops and the minimum temperature which varies based on the region and time of year. Apart from the WMO definition, its specific definition and classification can vary based on geographical location. The U.S. National Weather Service defines a cold wave as a rapid drop in temperature within a 24-hour period. In contrast, the national Meteorological Administration of China defines a cold wave as a significant cooling weather phenomenon, where large amounts of cold air from high latitudes invade the

middle and lower latitude regions. The classification of cold wave according to the Standard “Cold wave Level” by the national Meteorological Administration of China is presented in Table 1.

Table 1 Definition of cold wave (Hu et al., 2024a).

Level	Temperature Drop Rate	Lowest Temperature
Normal Cold wave	e 8°C in 24h or e 10°C in 48h or e 12°C in 72h	d 4°C
Strong cold wave	e 10°C in 24h or e 12°C in 48h or e 14°C in 72h	d 2°C
Super cold wave	e 12°C in 24h or e 14°C in 48h or e 16°C in 72h	d 0°C

### 3. Historical Pipe failure incident during cold wave

The impact of climate change induced cold wave on buried water pipeline was closely monitored between 2003 and 2021 in an Eastern China region. During this period, the region experienced a total of 52 cold wave events resulting in 351 pipe failure incidents. On average, each cold wave causes about 7 pipe failures, with a yearly average pipe failure of 18.5 for an annual average cold wave of 2.7. The number of pipe failure and the ensuing number of cold waves during the 19 years is presented in Fig. 1. Clearly, the number of pipe failure varies as the frequency of pipe varies per year.

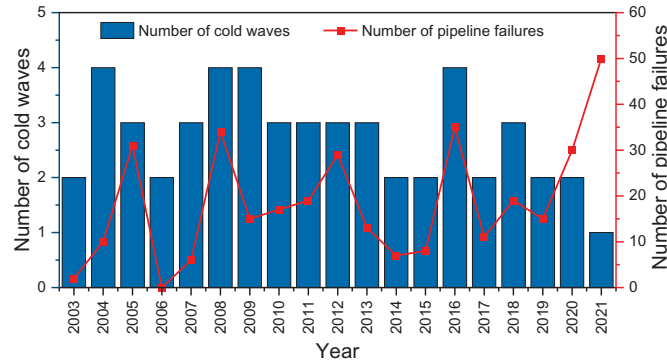


Fig. 1. Cold wave and pipeline failure frequency per winter

In order to investigate the impacts of cold waves on buried water distribution pipelines, a total of 3957 records related to water pipe failures during cold waves of the 19-years period was obtained for large diameter pipes (diameter of 500mm and more), including (i) water pipe failure records in the region between 2003 and 2021, (ii) weather data from the database of the National Oceanic and Atmospheric Administration (NOAA) for the cold wave periods and (iii) pipeline information from the study region’s geographic information system (GIS).

Data aggregation was conducted in order to properly organize the data and remove incomplete data. The key attributes in the data were mapped into seven separate variables, including the lowest temperature during the cold wave (LTCW), temperature cooling rate (CR), duration of the cold wave (DCW), highest temperature at the beginning of the cold wave (HTB), the lowest temperature on the day of failure (LTDF), and the maximum temperature difference (MTT). The HTB and DCW reflects the intensity of the cold waves, while the LTF and the MTT were added to cater for failures occurring within three days after the cold wave as they are important factors affecting pipe safety and have direct relationship with pipe failure (Kakoudakis et al., 2018).

#### 3.1 Analyses of failure rates

Given the pipeline failure data, the average failure rate of the pipeline during the cold wave with respect to different key attributes was obtained. This includes the number of failures per cold wave per year. The number of pipe failure per cold wave per year for a specific temperature attribute was obtained using Eqn. 1 below;

$$CWF\text{R} = \frac{1}{n} \sum_{i=1}^n \frac{N_{CW_i}}{CW_i} \quad (1)$$

where:  $CWF\text{R}$  is the Cold wave failure rate for pipelines with a given attribute;  $N_{CW_i}$  is the number of pipe failures during the cold wave occurring on pipelines with a specific attribute, in the  $i$ th year,  $CW_i$  is the number of unique cold wave events, in the  $i$ th year and  $n$  is the total number of years for which the failure data are available,  $n$  equals 19 in this research.

### 3.2 Analysis of cold wave failure rate results

The cold wave failure rate peaks for LTCW ranges of  $-7^{\circ}\text{C}$  to  $-5^{\circ}\text{C}$ , then drops to 1.11 for LTCWs between  $-5^{\circ}\text{C}$  and  $-3^{\circ}\text{C}$ , followed by a slight rise to 0.88 for LTCWs between  $+3^{\circ}\text{C}$  and  $+5^{\circ}\text{C}$ . This indicates that extreme cold (around  $-7^{\circ}\text{C}$ ) poses the greatest risk for pipeline failures, while significant risks also exist at warmer LTCWs, particularly around  $+4^{\circ}\text{C}$ . During the cold wave, 32% of pipes failed at an average cooling rate of  $10^{\circ}\text{C}/\text{day}$ , followed by 27% that failed at an average cooling rate of  $12^{\circ}\text{C}/\text{day}$ . The lowest cold wave failure rate was recorded with cooling rates between 21 and  $23^{\circ}\text{C}/\text{day}$ . The average cooling rate of  $10^{\circ}\text{C}/\text{day}$  is the most significant for pipe failure during the cold wave, consistent with the provisions of the Chinese Meteorological cold wave code. The cold wave failure rates of pipelines for different durations of cold waves (DCW) exhibit a pattern similar to a "Bathtub Curve" (Li et al., 2019). In the early days of a cold wave, pipeline stress has not reached equilibrium with rapid temperature changes, resulting in an increased rate of pipe damage. During a prolonged cold wave, pipes experience increased stress from cold-induced thermal stress, along with existing aging and corrosion defects, leading to accelerated structural damage and failure. The cold wave failure rate for a DCW between 3 and 9 days is about six times those of a DCW between 15 and 21 days, highlighting the significant effect of the cold wave on the pipeline's failure rate, especially in the early days. The highest failure rate occurred at an HTB between 8 and  $11^{\circ}\text{C}$ , accounting for about one-quarter of the total cold wave failure rate, while the lowest was at HTB between 23 and  $26^{\circ}\text{C}$ . The cold wave failure rate is high at LTDF between  $-7^{\circ}\text{C}$  and  $-4^{\circ}\text{C}$ , nearing 2 failures per cold wave per year, then steadily declines as temperatures rise. These trends suggest that extreme cold (around  $-7^{\circ}\text{C}$ ) leads to the most pipeline failures, but there are also risks at moderate temperatures. Overall, the data indicate that both extreme cold and certain warmer temperatures increase the likelihood of pipeline failures, emphasizing their vulnerability to temperature fluctuations. The cold wave failure rate peaks at 2.82 failures per cold wave per year at an average MTT of  $12.5^{\circ}\text{C}$ , accounting for 34.6% of the total failure rate during the cold wave.

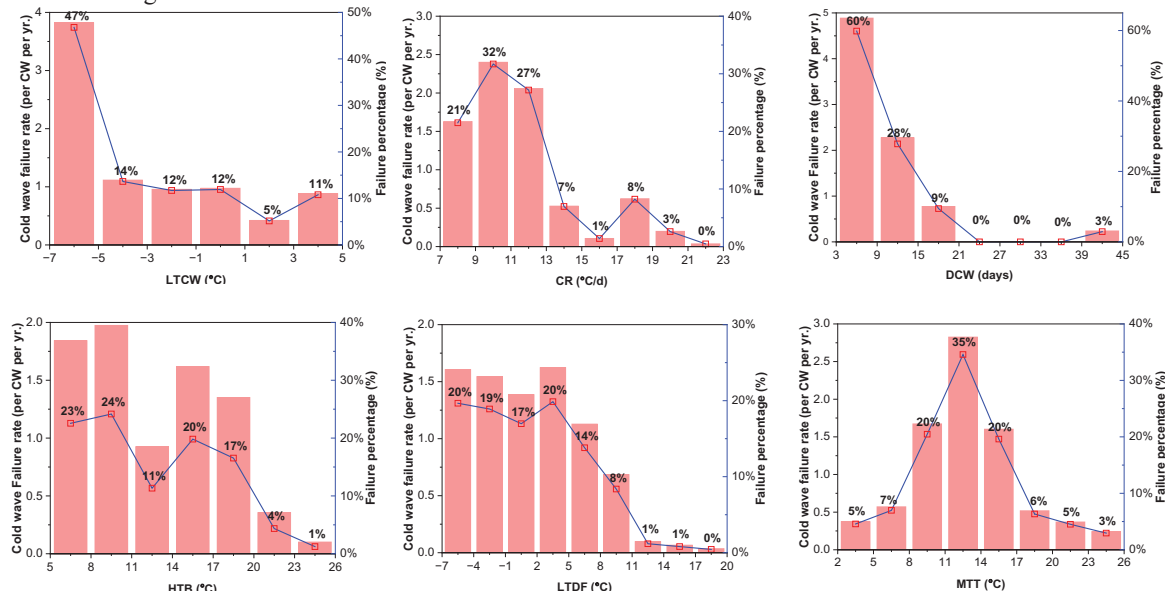


Fig. 2. Relationship between cold wave failure rate and key parameters

## 4. Finite Element Analysis

A 3D FE model was developed in ABAQUS v6.14-1 to simulate the mechanical behavior of the buried pipe under the influence of a typical cold wave-induced extreme temperature. The model was solved using a sequentially coupled thermo-mechanical analysis as it combines historical air, soil and water temperature data during a cold wave event with advanced simulation techniques to demonstrate how field data can be used as benchmarks for numerical models in understanding the mechanical response of buried pipes to thermal loads.

### 4.1 Numerical results and analysis

The numerical model considered the influence of three cold-wave-induced temperature factors (CR, DCW, and the temperature difference between the inside and outside of the pipe, "T) on the mechanical behavior of the soil-pipe model, utilizing the pipe peak hoop stress as an indicator. The effect of different cooling rates (0.2, 0.3, 0.4, and  $0.5^{\circ}\text{C}/\text{hr}$ ) on the mechanical behavior of the pipe indicates an increase in peak pipe hoop stress as the cooling rate increases. An increase in the temperature cooling rate from  $0.2^{\circ}\text{C}/\text{hr}$  to  $0.5^{\circ}\text{C}/\text{hr}$  resulted in a 4.8% increase in peak pipe hoop stress, indicating that the effect of increasing cooling rate on peak pipe hoop stress is moderate. For the

effect of different durations of the cold wave (48, 72, 96, and 120 hours), the result shows that as the cold wave duration increases, the peak hoop stress also rises, in agreement with the result of the statistical analysis. Specifically, extending the cold wave duration from 48 hours to 120 hours leads to a 13.5% increase in peak pipe hoop stress, highlighting the impact of prolonged cold exposure on pipe stress level. The result of an increase in the temperature difference between the inside and the outside of the pipe by 3°C, 6°C, and 9°C shows that the peak hoop stress increases by 0.22%, 0.24%, and 0.22% as the temperature difference grows from 0 to 3°C, 3 to 6°C, and 6 to 9°C, respectively. Overall, the total increase in peak hoop stress is just 0.69%, indicating that varying temperature differences have a negligible effect on the pipeline's mechanical behavior, particularly at low temperature differentials. However, as observed in related researches, greater increase in the temperature difference facilitates greater increase in the pipe peak hoop stress.

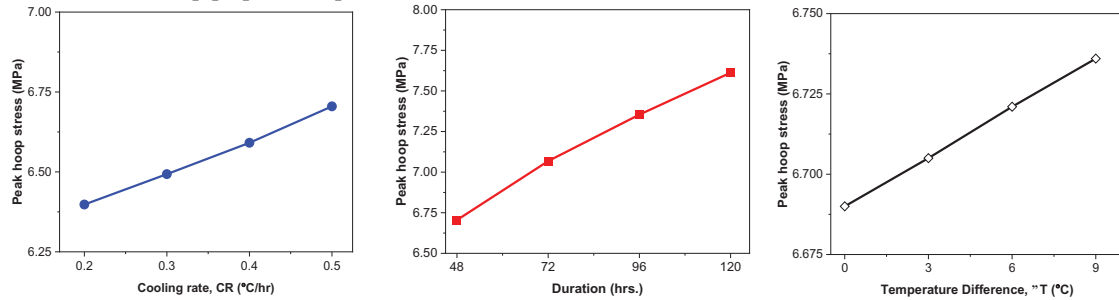


Fig. 3. Relationship between pipe peak hoop stress and (a) Cooling rate (b) Duration of cold wave, and (c) Temperature difference

## 5. Conclusions

The analysis of the region's pipe failure data during cold wave periods indicates a clear relationship between pipe failure and temperature variables. Climate change-induced extreme temperatures, such as cold waves, have led to increased pipe failures, as determined by cold wave temperature parameters. For instance, very low temperatures (around -7°C) pose a significant risk to pipeline safety, while considerable risks also exist at warmer LTCWs, particularly around +4°C. Pipe failures tend to increase significantly in the early days of a cold wave and during prolonged cold wave periods. Additionally, an increased cooling rate (intensity) of cold temperatures correlates with a higher rate of pipe failure, a conclusion supported by FEM results. The findings of this study will be reported in a future publication.

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