

# Strategies for Assessing the Mechanical Impact of Climate Change on Urban Networks Using Physical Modeling

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**RESUME** Understanding the impacts of climate change on urban infrastructure requires analyzing how extreme weather and climatic shifts affect the physical integrity of urban networks. This study presents a framework for assessing these impacts through a mechanical behavior perspective using advanced physical modeling. Scalable models replicate key components of buried water infrastructure, including soils and pipes, to simulate stressors such as temperature fluctuations and humidity changes. Monitoring sensors capture mechanical indicators with high precision in controlled environments, enabling robust vulnerability assessments. The analysis is conducted at the scale of a single network segment, but the results can be extrapolated to more complex urban networks. By integrating climatic uncertainties with experimental data, the framework identifies critical weaknesses and informs targeted strategies for enhancing resilience. The findings provide actionable insights for proactive risk management and urban planning, helping decision-makers develop effective mitigation measures to strengthen urban systems against climate-induced challenges.

**Mots-clefs** Urban Infrastructure, Climate Change, Reliability, Decision-Making Aid, Physical model.

## I. INTRODUCTION

Water distribution networks (WDNs) are a critical infrastructure of water supply system and a fundamental element for achieving sustainable development goals. There is increasing interest in optimization and control of coupled critical infrastructure systems to improve the systems' reliability, operational efficiency, and flexibility (e.g. Yingxu *et al.*, 2023). Underground water

pipes are subject to deterioration due to several parameters linked to i) the lithology of the formations on which the pipe is laid, ii) the material of the pipe and its installation conditions, iii) the urban, rural environments and the density of the road traffic, and iv) weather conditions influenced by global climate change (CC) with extreme events. Climatic variables, particularly changes in precipitation and temperature, are attributed to CC which refers to long-term shifts in average or extreme climatic conditions, notably temperature and precipitation (Giroto et al., 2024). Repeated cycles of flooding and drought, of varying duration and intensity, impact lithological formations, in particular by causing shrinkage and swelling phenomena in clayey soils (Chrétien et al., 2007). These lithological and environmental parameters affect the mechanical properties of underground pipes, and can lead to their failure, either at joints or through the appearance of cracks of varying sizes. Breakage in WDNs lead to considerable water and energy losses (Chambon et al., 2023) as well as disruption to water distribution. The analysis of deformation offers valuable insights into the behavior of underground pipelines under various load conditions over time. Accurate simulation and assessment of their performance and durability rely on both physical and numerical modeling, particularly for feeder pipelines, which serve as primary conduits transporting water from main supply sources to distribution systems. This study aims to replicate real-world conditions, including load effects, climatic influences, and time-dependent variations, through the development of a 1:30 scale model. By integrating both digital and physical models, it provides a comprehensive understanding of underground pipeline behavior in simulated field conditions.

## II. MECHANICAL ASSESSMENT FRAMEWORK FOR RESILIENCE IN URBAN NETWORKS

### A. Conceptual framework description

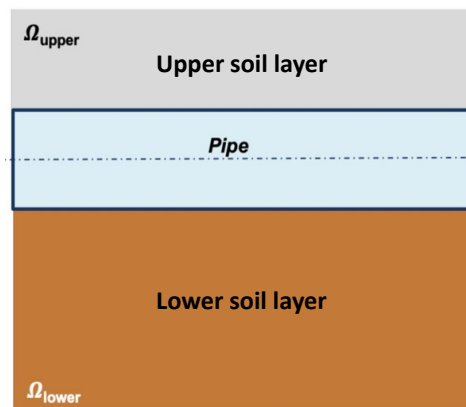
The performance analysis of a complex urban drinking water network is conducted at the scale of a linear feeder pipeline within the network. This approach enables a detailed evaluation of the confined system (illustrated in Fig. 1), composed of the soil and the pipeline, under various external and internal loads. It also incorporates the influence of climatic stressors, such as temperature fluctuations and humidity variations, on the mechanical behavior of the soil. The soil-pipeline system, depicted in Fig. 1, thus serves as a foundation for developing an accurate predictive model that accounts for uncertainties and spatial variability, as shown in (Yáñez-Godoy & Elachachi, 2023).

Climatic variations significantly affect soils, which serve as both support and protection against external loads. Their mechanical properties change due to the abrupt cycles between dry and wet periods. In the Nouvelle-Aquitaine region, certain areas are particularly affected by the swelling-shrinkage behavior of clays, causing soil deformations that can compromise the stability of infrastructure (e.g. Chrétien et al., 2007). In fact, Nouvelle-Aquitaine represents a significant share of metropolitan areas in France exposed to medium or high risk, accounting for 19.3% ([www.notre-environnement.gouv.fr](http://www.notre-environnement.gouv.fr)). Swelling clays are primarily unsaturated soils. However, their behavior can change as they approach saturation or become temporarily saturated, particularly due to heavy rainfall or flooding. The most relevant aspects for evaluating the

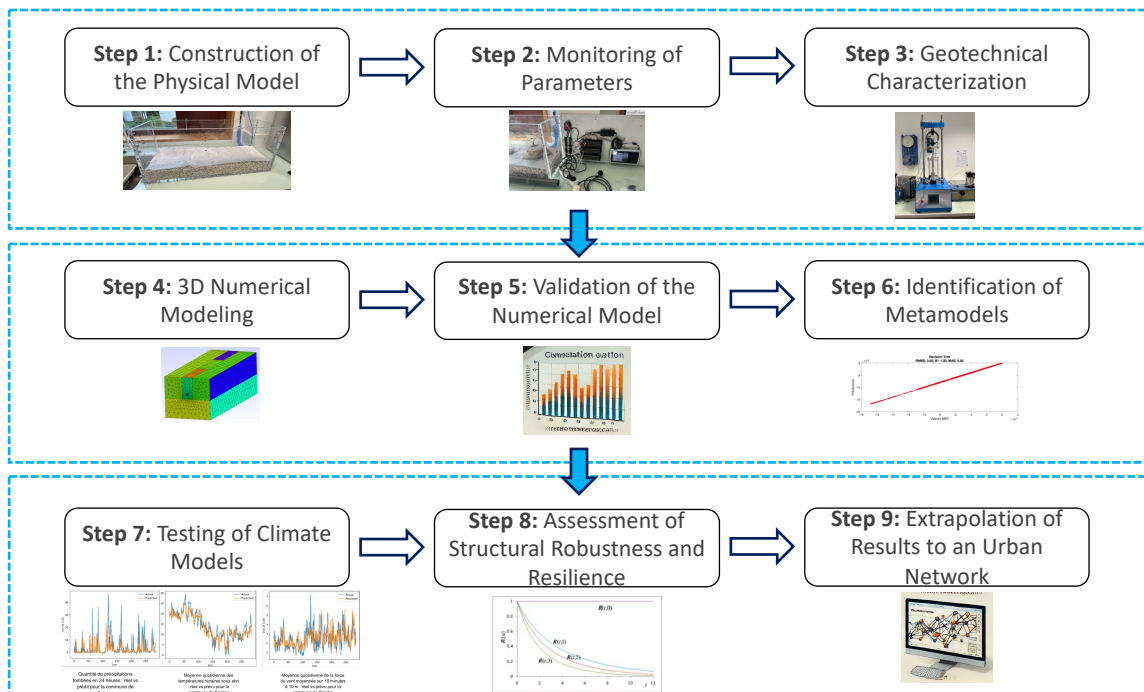
mechanical behavior of the soil-pipeline system lie in measuring and characterizing the influence of porosity and water content on the mechanical properties of clays. In particular, these factors affect key mechanical parameters such as the internal friction angle ( $\varphi$ ) and cohesion ( $c$ ) under varying conditions of normal and extreme dryness and humidity. The study by (Andrei S., 1977) highlights this influence, with a specific focus on unsaturated soils.

The framework outlined in this section provides a comprehensive methodology for analyzing and evaluating the behavior and performance of soil-pipeline systems under seasonal cyclic conditions. It integrates experimental, numerical, and predictive modeling approaches to deliver a robust understanding of the system's response to environmental variations. Figure 2 provides a visual representation of key steps of this process and they are detailed below. The subsequent sections will offer a comprehensive analysis of each key step implemented in this study.

- Step 1: Construction of a 1:30 scale model representing a 30-meter-long linear section of a feeder pipeline network.
- Step 2: Monitoring of the following parameters during simulated seasonal cycles in the laboratory: pipeline deformations, soil moisture content, and soil temperature at various points along the model.
- Step 3: Geotechnical characterization of the granular materials constituting the model at different moisture levels.
- Step 4: Development of a three-dimensional (3D) finite element numerical model to represent the physical scale model.
- Step 5: Validation of the numerical model.
- Step 6: Identification of metamodels from the 3D numerical model using machine learning (ML) models.
- Step 7: Testing of climate prediction models coupled with ML models to assess the performance of the linear network under extreme humidity variation conditions.
- Step 8: Assessment of the structural robustness and resilience of the linear network under extreme humidity variation conditions.
- Step 9: Extrapolation of the results from the linear network to a complete urban network.



**FIGURE 1.** Soil layers, pipeline, and component distribution in domains  $\Omega$  (longitudinal profile)



**FIGURE 2.** Integrated framework for characterizing soil-pipeline system behavior and evaluating performance under seasonal cyclic conditions

### III. PHYSICAL MODELING OF URBAN BURIED NETWORKS

The evolution of the mechanical properties of the soil-pipeline system is monitored in the laboratory using a physical model scaled down to 1:30 compared to real-field conditions. This model replicates controlled lithological and meteorological conditions, enabling a detailed analysis of the interactions between the soil and the pipeline under varying external and internal loads. The various components of the model are illustrated in Fig. 3a, providing a clear visual representation of the structure and interactions within the system.

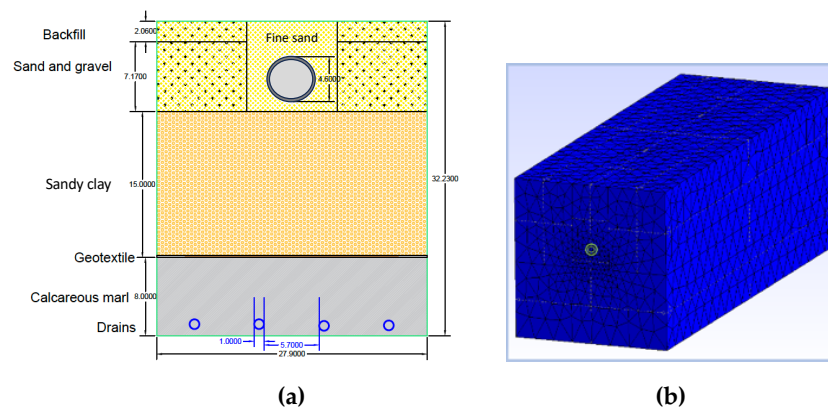
#### A. Experimental setup description

The development of this laboratory model (illustrated in Fig. 3a) was conducted in five distinct phases, detailed as follows:

- The first phase involved collecting lithological data from the municipality of Pessac in Gironde and conducting a statistical study to determine the average lithological succession as well as the thickness of each formation.
- In the second phase, the selection of physical and mechanical parameters was finalized. This phase involved monitoring the temperature and humidity of each formation as well as the deformations of the pipeline. Fifteen soil temperature and humidity sensors were installed at various depths along the study area, and fourteen strain gauges were placed at the pipeline's joints and between two consecutive joints. These sensors are connected to a data acquisition system. In addition to the strain sensors, a waveguide-based deformation measurement system is installed longitudinally along the pipeline, allowing

the propagation of millimeter waves for precise strain monitoring. Similarly, a slotted radiating cable enables the generation of a virtual radio-frequency source at any point along its length. Weather conditions are simulated for wet periods using a sprinkler system that delivers water at varying flow rates and for dry periods using heat generated by four UV lamps mounted on a support positioned above and along the length of the model.

- The third phase involved assembling the model and installing drainage systems to evacuate infiltration water during dry periods, as well as setting up piezometers to monitor the deep limestone aquifer and the shallow groundwater in alluvial sands.
- In the fourth phase, the lithological formations were established, along with the installation of temperature and humidity sensors. The PVC pipeline (with the strain sensors installed) was placed in an excavated trench within the sand and gravel layer and laid on a 2 mm-thick bedding layer of fine sand. The trench was then backfilled with fine sand.
- Finally, the fifth phase will focus on monitoring the evolution of this system by varying weather conditions.



**FIGURE 3.** Physical and numerical model: a) Front view of the physical model (measurements in cm); b) 3D finite element numerical model

### B. Climatic factors simulation

The climatic factors of temperature and humidity within the physical model are simulated as follows:

- Humidity simulation: A sprinkler system is used to simulate wet periods by distributing water at variable flow rates. This replicates rainfall or water infiltration into the soil. The water flow regulation controls the soil's humidity levels. The installed humidity sensors measure the real-time evolution of moisture in different soil layers. These sensors are placed at various depths to monitor humidity variations across lithological formations.
- Temperature simulation: Four UV lamps are used to generate heat and simulate dry periods. These lamps replicate the effect of solar radiation, emitting a light spectrum similar to sunlight, which heats the surface of the model and alters the soil temperature. Temperature sensors are installed within the same probes as the humidity sensors, positioned at different depths to monitor thermal variations in the soil.

- Combination of climatic factors: To simulate realistic climatic conditions, it is crucial to integrate both factors (temperature and humidity) using a controlled system. For instance, the UV lamps and the sprinkler system can be programmed to alternate between dry and wet periods, thereby mimicking natural climatic cycles.

### *C. Physical model validation*

A 3D finite element numerical model (virtual prototype) approximates the physical model by integrating its real input data, including material properties, geometry, and applied loads. The response of the numerical model, particularly its mechanical behavior under specific load configurations (experiments), is continuously compared with measurements from the physical model. The objective is to ensure that the numerical model's predictions align with experimental observations by calibrating key parameters identified in the model before and after numerical testing. This approach also provides an opportunity to explore tools for assessing the spatial variability of soil properties throughout the testing process. Figure 3b illustrates an example of the numerical model being developed for the soil-pipe system. Once the virtual prototype is validated, computational efficiency is further improved by constructing metamodels. These metamodels are then utilized in the final stage to assess the structural robustness and resilience of the system under extreme variations induced by external climatic factors.

## **IV. INSTRUMENTATION AND DATA COLLECTION**


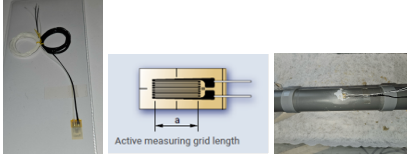
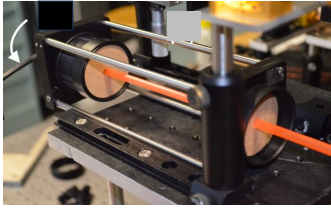
### *A. Physical operating principle of sensors*

The measurement program involves monitoring soil temperature and humidity, as well as pipe deformation. Drought and humidity cycles will be applied to the physical model, based on meteorological data from Pessac city (Gironde, France). Extreme episodes, corresponding to known or simulated events, will also be reproduced. The various types of sensors used in the physical model are described in Table 1.

### *B. Lithological layer definition in the physical model*

The lithological succession of soils in the physical model was determined using field data from 120 lithological boreholes conducted in the municipality of Pessac (Gironde, France). These data were systematically compiled and analyzed. Statistical analyses—including minimum, maximum, mean, and standard deviation values—were performed to calculate the average thickness of each layer for individual boreholes and to determine the overall average thickness of the layers across all boreholes. The following average lithological succession was established, from the surface downward: embankment; silts, sands, gravels, and pebbles; clays and sandy-gravelly clays; marls, marly limestone, and limestone. Based on these field data, the composition and thicknesses of the lithological layers in the physical model were defined, applying a 1:30 scale reduction relative to the field averages (Table 2). Using these data, the quantities of materials required for each layer were calculated, along with the force exerted by these materials on the walls of the physical model. With a flexural strength of 130 MPa, the 15 mm-thick plexiglass used in the physical model possesses the necessary structural characteristics to withstand the loads exerted by the soil.

**TABLE 1. Sensors implemented in the physical model**

Sensors	Description	Illustration
Temperature and humidity	The HTM2500LF is a specialized humidity and temperature transducer designed to interface directly with a microcontroller. This is enabled by the module's linear voltage output for humidity measurements. The sensor is engineered to deliver accurate readings across a humidity range of 10% to 95% RH. It operates effectively across a temperature measurement range of -40°C to 85°C.	
Strain	The pipe consists of 5 sections, each 20 cm in length, connected by 0.5 mm long sleeves. To monitor the pipe's deformation, HBM linear strain gages (LE11-3/350VE) were mounted on the PVC pipe. Two gages were installed on either side of each sleeve, positioned vertically at the top and bottom. Additionally, two more gages were placed between each pair of sleeves for the 3 central sections of the pipe, also positioned vertically at the top and bottom. The strain gages are designed to be resistant to moisture and chemicals, as they are fully encapsulated in a specialized plastic material on all sides.	
Millimeter-wave	The objective is to utilize a millimeter-wave radar and a dielectric waveguide to detect deformations along the guide. Any deformation alters the impedance of the waveguide, generating an echo, similar to the principle of Time Domain Reflectometry (TDR). While previous studies (Pan, et al., 2020) have focused on analyzing impedance variations at the waveguide's termination, this approach is now being extended to track changes over time through periodic measurements. The goal is to identify long-term drifts and localized pressure points affecting the waveguide.	 (Pan, et al., 2020)

**TABLE 2. Lithological layer sequence and thicknesses in the physical model**

Lithological layer	Thickness (cm)
Main backfill (sand and gravel)	2.0
Sand and gravel	7.2
Sandy clay	15.0
Calcareous marl	8.0

### C. Geotechnical tests

Geotechnical testing (Fig. 4a) primarily investigates the properties of the various soils composing the physical model—sand, clay, and limestone—by analyzing their physical and mechanical

characteristics. The behavior of these materials is expected to fluctuate with changes in moisture and temperature conditions, particularly under extreme seasonal variations. Such fluctuations are likely to influence the transverse and longitudinal support conditions of the pipeline, which are typically assumed to remain constant in both space and time during the design phase. The interaction of these factors, combined with external and internal load variations, could lead to critical configurations deviating from the intended design performance. Moreover, this analysis does not account for potential material degradation of the pipeline itself, which could further impact its long-term behavior.

#### D. Data acquisition framework

The temperature, humidity, and strain sensors are directly connected to a GL800 Graphtec data acquisition unit (Fig. 4b), which features a color graphic display and supports various analog inputs, including voltage, temperature, humidity, logic, pulse, and ToR, with 350 volts peak-to-peak isolation to prevent ground loops. Data recording is performed through direct capture onto a USB drive every 5 seconds. The voltage measurement range spans from 20 mV to 50 V.

For the millimeter-wave component, data acquisition is performed directly between the radar and a computer via a USB connection. The signal received from the Frequency Modulated Continuous Wave (FMCW) radar undergoes a Fourier transform, yielding a range measurement that maps amplitude as a function of position. A differential analysis is then applied to detect drifts and echoes, enabling the identification of deformation points within the waveguide.



**FIGURE 4.** Geotechnical tests and data acquisition framework: a) tests to determine the soil's mechanical properties; b) GL800 Graphtec data acquisition unit

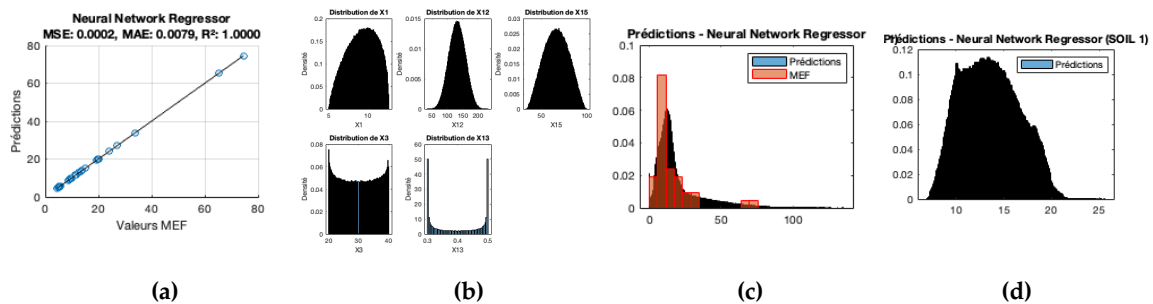
## V. ASSESSING CLIMATE IMPACTS AND ENHANCING URBAN NETWORK RESILIENCE

The following subsections outline the key steps considered for assessing the impact of extreme climatic conditions on the performance of a drinking water distribution network.

#### A. Construction of metamodels

Recent studies (Bui et al., 2025) have demonstrated that ML technologies can be effectively applied to soil-pipe systems, successfully integrating both physical and hydraulic parameters. The virtual prototype (Figure 3b) serves as the foundation for constructing metamodels aimed at predicting the mechanical performance of the pipeline. These approaches leverage predictive modeling techniques based on Machine Learning (ML) algorithms and are adaptable to a wide range of cases, utilizing diverse datasets. The construction of these metamodels begins with

identifying key variables extracted from the 3D numerical model through a global sensitivity analysis. Once these influential parameters are determined, an optimized experimental design is established using the central composite design (CCD) method. This step enables the generation of a mechanical response surface for the 3D model, providing a simplified yet accurate representation of the system's behavior. An example of this methodology is illustrated in (Bui *et al.*, 2024). The set of configurations obtained through this process allows for the development of predictive models by comparing different ML algorithms. These models are trained on the generated experimental design and subsequently used to predict critical mechanical responses of the soil-pipe system, such as maximum displacement or maximum stress within the analyzed pipe section. Figure 5a presents the predicted maximum stress in comparison to the 3D numerical model. This prediction is achieved through probabilistic sampling of the selected variables (Fig. 5b). Figure 5c presents an example of maximum stress prediction using an ML model, specifically a Neural Network Regressor. This prediction is based on an extensive and highly specific dataset tailored to a given pipe type (e.g., Bonna-type reinforced concrete pipes), as well as a broad spectrum of soil conditions and variable operational loads. Once validated, the metamodels can refine the analysis by focusing on specific pipeline configurations—for instance, considering a particular soil type, a defined pipe diameter, or other relevant parameters—to obtain precise mechanical performance predictions (Fig. 5d).



**FIGURE 5.** Predictive modeling of pipeline mechanical performance using machine learning-based metamodels: (a) developed metamodel; (b) identified key variables; (c) maximum stress prediction across various soil types; (d) maximum stress prediction for a specific soil type

### B. Structural robustness and resilience under extreme conditions

The method proposed in the previous step enables a precise and optimized assessment of the structural behavior of pipelines exposed to diverse environmental conditions, facilitating a detailed analysis of their robustness and resilience across various operational scenarios. The results obtained from the physical model will allow for the quantification of the impact of extreme climatic events on pipeline performance. The methodological approach for evaluating robustness and resilience on a linear feeder pipeline within the network will be the subject of future publications.

### C. Scaling Model Results to a Water Distribution Network

The results from the previous step are applied and integrated into an urban water distribution network to assess their relevance and effectiveness in a real-world operational context. This integration enables a comprehensive evaluation of system performance and practical implications.

## VI. CONCLUSION

The strategies presented in this study provide an accurate representation of a complex system in a controlled environment. External effects, driven by abrupt variations in highly variable environmental conditions, influence the interaction between the pipeline and its immediate surroundings, the soil. This leads to short-, medium-, and long-term changes in certain mechanical properties that were initially considered stable in a confined environment. Analyzing these changes will help assess the real impact of climate change on drinking water networks, a particularly sensitive and vulnerable infrastructure.

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