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CLIMATE-RESILIENT RAILWAY LINES: A METHODOLOGICAL FRAMEWORK FOR ESTABLISHING AN EXPERIMENTAL SYSTEM AND VALIDATING DATA USING IMAGE PROCESSING

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ABSTRACT

Aim of the study
The study focuses on assessing the impact of climate change on infrastructure. This assessment includes investigating ballast scour and degradation, establishing a systematic experimental framework, developing predictive models and early warning systems, as well as comparing structural variables.

Material and methods
The study involved the preparation of a specific experimental setup designed to investigate the behavior of railway ballast layers. The experiments were conducted under controlled laboratory conditions to simulate excessive rainfall and its impact on the infrastructure. Image processing techniques were employed as the primary method to monitor and record the movement of the ballast during these tests. The methodology was developed through an international collaboration between Akdeniz University (Turkey) and the University of Huddersfield (UK).

Results and conclusions
The main result of the study is the successful preparation of the experimental setup and the development of data acquisition procedures. It highlights the effective employment of image processing techniques to monitor ballast movement in a controlled laboratory environment. The study concludes that the described experimental methodology provides a systematic framework for assessing ballast degradation. It proposes that this setup could be used as a useful reference point for future laboratory-based research into the impact of climate change on railway infrastructure.

Keywords: railway, experimental setup, data, image processing, climate change

INTRODUCTION

The popularity of rail travel in Turkey is increasing day by day, especially as a result of rising high-speed rail investments. Due to this increase in demand, improvements to the railway infrastructure and superstructure are necessary. In recent years, flooding and unexpectedly heavy rainfall have caused significant damage to embankments and ballast layers, leading to economic problems and causing fatal accidents. For example,

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(a) Çorlu train accident, 2018 (b) Clara Hurricane, Conwy Valley line, 2020

Fig. 1. Railway lines damaged by flooding (Source: https://www.indyturk.com/node/47506/haber/25-last)

on 8/06/2018 occurred the Çorlu train accident, in which 25 people died in Turkey. The Conwy Valley line in the UK was submerged underwater due to the Clara Hurricane in 2020. Figure 1 shows the railway lines after they were damaged by flooding.

Due to climate change, an increase in such accidents is inevitable, especially in sections of pipelines that cross waterways or run parallel to waterways. This is because one of the negative effects of climate change is an increase in sudden rainfall and subsequent flooding. Numerous studies have investigated the impact of water on railway superstructure and infrastructure. Calamak (2018) investigated the safety of railway embankments during floods using SEEP/W and SLOPE/W software, carrying out seepage and slope stability analyses. This study considered 200 years of flood analyses. Aliyu et al. (2024) conducted a study to estimate the hydromechanical properties of railway embankment slopes under bidirectional water level fluctuations. To this end, they performed laboratory tests and calculations based on these tests to evaluate the impact of changes in the groundwater level on the railway embankment. In his thesis, Alrdadi (2022) modeled fluid flow in railway ballast under various flood conditions. This study placed particular emphasis on ballast gradation and ballast fouling, both of which play a significant role in ballast flow. However, no experimental studies were conducted under laboratory conditions. Modeling was performed only under theoretical conditions. Data from experimental studies were not used in the modeling studies. In their research, Alrdadi and Meylan (2023) presented a numerical simulation of water flow in railway ballast and developed a model for unsteady flow conditions. They demonstrated that the position of the free surface over time can also be used to determine steady flow conditions. The model included the effect of ballast fouling to capture the realistic behavior of railway ballast, which is critical for understanding the impact of flooding. The significant impact of ballast fouling on water flow and its potential consequences for railway infrastructure were illustrated in a simulation. The study did not include laboratory tests. Atmojo et al. (2018) determined the relationship between flood height and scour, as well as the effect of a high external containment structure on scour length. The fous of this study was the effectiveness of a downstream external containment structure in terms of reducing and damping scour length due to flooding, according to a physical model. For this purpose, the most effective structure was obtained by simulating the downstream scour containment structure with several variations in terms of type (T) and structure distance (L). This research, including the modeling of containment structure, was carried out under laboratory conditions. Ghataora and Rushton (2012) investigated ballast and sub-ballast drainage on a railroad track for a single climate scenario in the United States. Their work showed that water could be retained in the track closest to the drain for more than a week, resulting in increased deformation and consequently increased maintenance requirements. They also demonstrated that adding a high-permeability composite near the base of the sub-ballast could significantly improve track drainage. This study was prepared using simulation techniques based on a literature review of the theoretical aspects. No laboratory studies were conducted.

Rapid advances in contemporary camera technology – driven by high-resolution CMOS sensors, improved low-light capability, high frame rates and multi-modal sensing such as thermal and depth imaging – together with parallel progress in software, have expanded the use of vision systems across a wide range of domains, from industrial automation and healthcare to smart-city applications (Fossum et al., 2024). This broader trend has become particularly evident in railway transportation, where camera-based solutions have been adopted for safety, tracking and maintenance purposes. In practice, such systems are widely used to continuously monitor railway superstructure components – including rails, fasteners, sleepers, ballast, slab track, catenary and related elements supporting both condition assessment and timely intervention (Aela et al., 2024; Zheng et al., 2021).

As can be seen in the literature, studies on the impact of flooding on railway superstructure are generally based on theoretical data rather than experimental data. The aim of the project described in this paper, involving experimental systems, is to integrate a railway line infrastructure model with climate models to evaluate the effects of climate change on railway infrastructure. In this context, a channel with flow characteristics was constructed in a laboratory environment. The railway superstructure was placed on the channel and experimental studies were being carried out according to discharge data representing different climatic conditions. The project is supported by the British Council, International Science Partnerships Fund (ISPF). It is being carried out in collaboration with Akdeniz University and Huddersfield University. The project title is "Climate-Resilient Railways: Advanced Monitoring of Railway Ballast Degradation under Climate Change Influences". Additionally, this project involves obtaining data on ballast degradation using cameras. For this end, cameras have been installed in the experimental system. Data were processed using image analysis method.

MATERIALS AND METHODS

Methodological framework

This paper follows the flowchart presented in Figure 2. Each box is explained in the following paragraphs. After scaling and adjusting the pump flow, the experimental conditions in the open channel and the protocols for the experiments were presented in detail.

Digital elevation model (DEM) creates a model of the Earth using the position and height information about the Earth itself and the natural and artificial elements located on it. Geographic information system (GIS) software is used to define flow direction in drainage areas.

Flow direction: one of the keys to deriving the hydrological characteristics of a surface is the ability to determine the direction of the flow from every cell of the raster. Therefore, the flow directions on the surface of the area can be defined, as well as the way runoff converge towards rivers or water storage areas such as lakes and reservoirs.

Flow accumulation: a coefficient that calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. If no weight raster is provided, a weight of 1 is applied to each cell, and the value of each cell in the output raster represents the number of cells flowing into each cell.

Watershed delineation: watersheds can be delineated based on a DEM by computing the flow direction. Watershed boundary at any outlet point (e.g. risky point in terms of ballast degradation risk above a culvert) can be easily determined.

Precipitation analysis: provides the location of, and at least 15 years of measurement data for, all precipitation stations established by the General Directorate of Meteorology in Turkey. It automatically performs 'precipitation analysis' with the Simirnov-Kolmogorov test and suggests the most appropriate distribution type for flood discharge calculations.

Statistical downscaling: relates patterns and changes in large-scale climate to the local climate. These statistical relationships are derived from historical observations.

Hydrological analysis: based on a digital elevation model (DEM) raster data in order to create a water system model, which is used to study the hydrological characteristics, simulate the surface hydrological process, and forecast future surface hydrological situations.

Flood frequency analysis: uses a series of discharge data (e.g. from a gauging station or culvert) and evaluates the occurrence probability of a particular

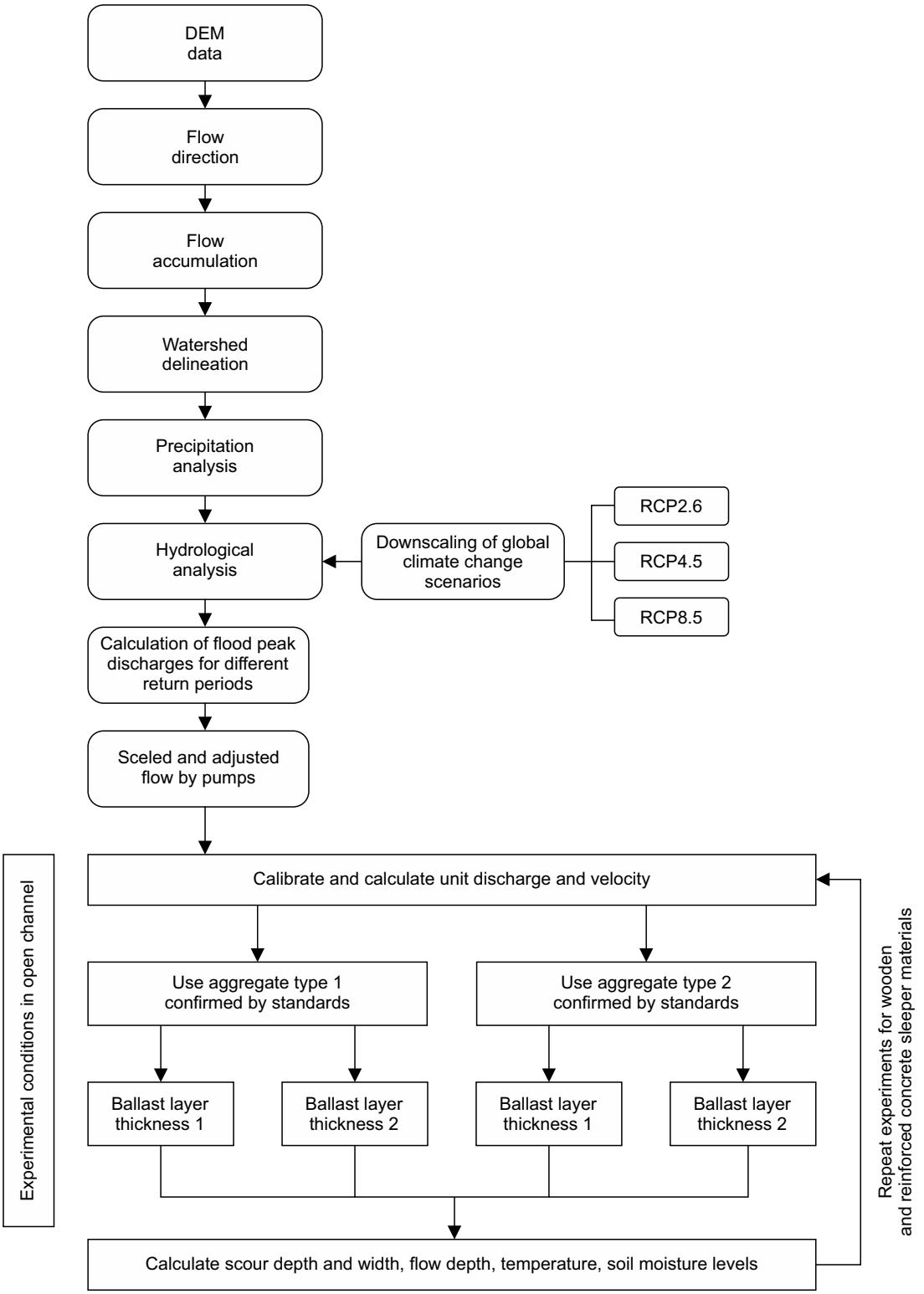

Fig. 2. The flowchart of methodological framework (Source: Authors' own elaboration)

discharge occurring. Thus, the probability of event occurrence defines the frequency of a discharge. On the other hand, there are empirical methods, such as the Mockus, SCS, DSI Synthetic, Snyder, Rational, Synthetic Unit Hydrograph methods for calculating flood peak discharges.

Physical simulation: this involves recreating a hydraulic phenomenon, such as the flow over a spillway, in a laboratory. This is called a physical model or simply a model. A prototype is a natural hydraulic phenomena, such as a spillway over a dam. Models and prototypes may have geometric, kinematic and dynamic similarities. We adopt this principle to provide the discharge in the open channel.

Water level observations: upstream and downstream sections are observed by radar and ultrasonic sensors. For the calibration procedure, ADV – Acoustic Doppler Velocity Meter instrument is used in the open channel. Then, sensors were installed to calculate unit discharge and velocity, taking into account changes in water levels.

Use the types of aggregate confirmed by the standards: types which have different granulometry are installed in ballast layer. They are confirmed by standards.

Ballast layer thicknesses: Two types of ballast layer thicknesses were tried to define the effects on ballast degradation.

Calculate scour depth and width, flow depth, temperature, soil moisture levels: The scour depths and width during ballast degradation and water temperature were observed by installed sensors in the open channel. The flow depth and soil moisture levels were observed by image processing procedures.

The samples are coded based on their configurations: 'B' for ballast, 'W/C' for sleeper material (wood or concrete), '40' for ballast thickness (40 cm), and 'GF' for gradation type F. This paper focuses on the comparison of B-W-40-GF and B-C-40-GF to evaluate the impact of sleeper material on structural integrity under identical hydraulic conditions.

Preparation of experimental system

As part of the project, an open channel measuring 1,000 cm in length, 175 cm in height and 107 cm in width was first constructed in the laboratory. This channel is shown in Figure 3. Both sides of the channel were made of tempered glass. The pump that circulates the water in the channel to represent flood flow has a flow rate capacity of 90 L/s.



Fig. 3. Open channel constructed in the laboratory (Source: Authors' own elaboration)

A railway model consisting of two sleepers and rails was constructed and placed inside the canal. The aim was to simulate the behavior of ballast in the railway superstructure under the effects of real-life flood. Two types of sleeper were used in the experimental studies: wooden and concrete (Figure 4).

Aggregates conforming to the TS 7043 EN 13450 specification for railway aggregates in Turkey were placed inside the channel. The gradation limits shown in Table 1 were used in the preparation of ballasts for high-speed and conventional lines. For ballast layer in experiments, A and F types of gradation limits were used. Ballast layer thickness were adopted as 30 cm and 40 cm.



Fig. 4. Railway models used in the experiments (Source: Authors' own elaboration)

Table 1. Ballast layer gradation limits used in the experiments

Sieves (mm)	Gradation types					
	A	B	C	D	E	F
80	100	100	100	100	100	100
63	100	97–100	95–100	97–99	95–99	93–99
50	70–99	70–90	70–99	65–99	55–99	45–70
40	30–65	30–70	25–75	30–65	25–75	15–40
31.5	1–25	1–25	1–25	1–25	1–25	0–7
22.4	0–3	0–3	0–3	0–3	0–3	0–7
31.5–50	≥ 50	≥ 50	≥ 50	–	–	–
31.5–63	–	–	–	≥ 50	≥ 50	≥ 85

Each specific experimental variant was tested in a single comprehensive run. Given the large scale of the laboratory facility and the complexity of resetting the ballast layers, the focus of repetitions was on ensuring the consistency of the measurement system rather than the physical samples. All initial conditions, including ballast compaction and hydraulic discharge rates, were strictly standardized to maintain the integrity of the comparative analysis.

Discharge data were measured by expert hydrologist for each climate change scenario. Figure 5 shows the measurement of discharge in the open channel. Different climate scenarios were defined for the experimental design.



Fig. 5. Measurement of flow rate inside the channel taken by an expert hydrologist (Source: Authors' own elaboration)

Scenarios calculated based on the climate change scenarios that are integrated with the hydrological model were created using GIS-based software. To investigate changes in the characteristics and amount of precipitation due to climate change, the following three scenarios were considered. Next, analyzed were the effects of this event on flash floods.

- SSP1-2.6: a sustainable world with low emissions, strong climate measures and warming kept below 2°C.
- SSP2-4.5: a realistic scenario with moderate development and emissions, leading to approximately 2.5–3°C of warming.
- SSP5-8.5: a fossil fuel-based, high-emission future with low climate measures, leading to 4°C or more of warming by 2100.

Regional climate models (RCMs) were used to extract peak rainfall intensities for the selected SSP scenarios in the study region. These rainfall values were taken as inputs for a GIS-based hydrological model of a representative railway catchment area to calculate peak runoff (discharge) for a 100-year return period flood. The calculated peak discharges were then scaled down to the laboratory channel dimensions (1,000 × 175 × 107 cm) using the Froude similarity principle, which ensures the ratio of inertial to gravitational forces in the laboratory matches real-world flood conditions.

Obtaining data with image analysis

To investigate the scouring behavior of the ballast layer under varying climatic conditions, image processing software was also adopted. Figure 6 shows the installed camera systems.

During the experimental phase of this study, image recordings were acquired using an Intel RealSense D435i camera in order to observe the displacement of ballast particles. As the device operates at 30 fps and simultaneously provides depth information, it enables the continuous tracking of ballast movements. The camera estimates the distance to each point in the scene by exploiting the physical separation between its two IR sensors and the corresponding pixel shift observed between the stereo image pair. The horizontal distance between the left and right cameras is referred to as the baseline (b). For a given object point, a pixel offset occurs between its projections in the left and right images. This offset is known as the disparity (d). As shown in Equation (1), disparity is computed accordingly.



Fig. 6. Cameras installed in the open channel (Source: Authors' own elaboration)

$$d = x_L - x_R \quad (1)$$

In Equation (1), x_L denotes the horizontal pixel coordinate on the left sensor, while x_R represents the corresponding horizontal pixel coordinate on the right sensor. The depth value (Z) can then be derived using the principle of similar triangles. Accordingly, as expressed in Equation (2), Z is computed as a function of the focal length (f), the baseline (b) and the disparity (d).

$$Z = \frac{f \cdot b}{d} \quad (2)$$

Accordingly, the depth information of the target observation area was obtained on a per-pixel basis, as illustrated in Figure 7.



Fig. 7. Railway model with wooden sleeper placed in the open channel (Source: Authors' own elaboration)

Since the camera generates a substantial amount of data – 30 frames per second at a resolution of 640 × 480 – the experiment was designed to focus specifically on ballast displacement. Therefore, as shown in Figure 8, the ballast region was divided into a 4 × 4 grid and a total of 16 regions of interest (ROIs) were defined to systematically observe displacement within each subarea. Instead of tracking individual ballast particles, ballast displacement was quantified at the ROI level using the temporal variation in the mean depth within each region. At the beginning of each experimental run, an initial reference depth value was recorded for each ROI and defined as the zero-offset condition.

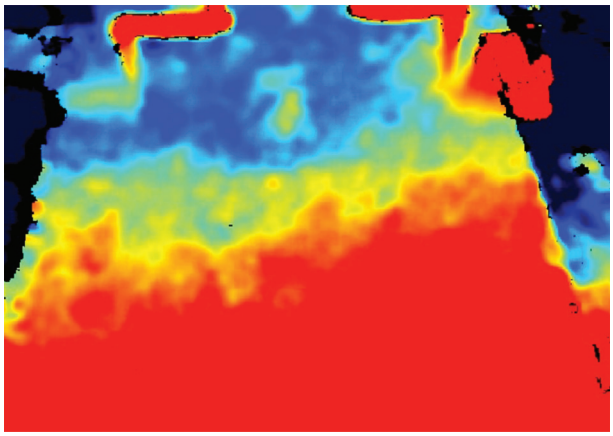

Fig. 8. Heat map visualizing the depth of ballast displacement (Source: Authors' own elaboration)

At the beginning of each experimental run, an initial reference depth value was recorded for each ROI and defined as the zero-offset condition. For each subsequent frame, the mean depth value within the corresponding ROI was calculated and compared with this

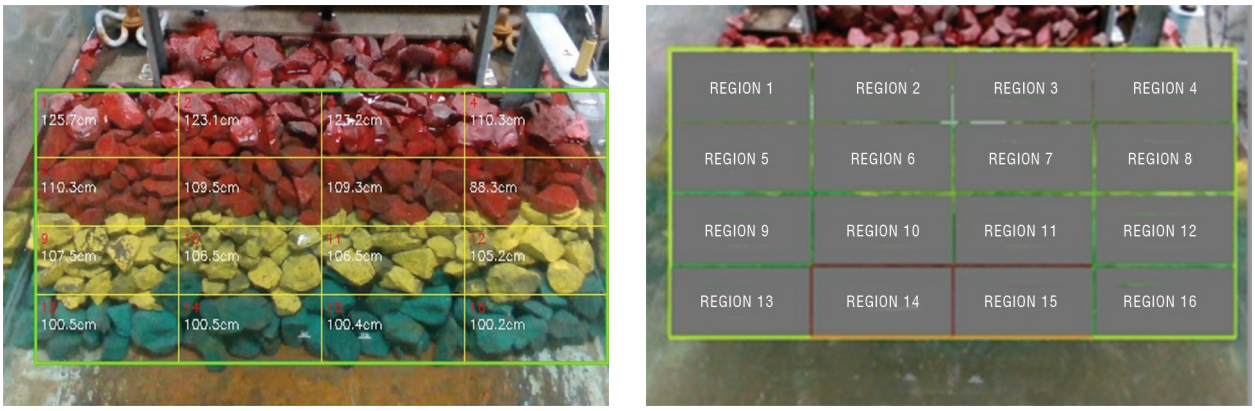

Fig. 9. (a) Camera recording view for the observation of degradation and the 16 virtual grid (b) numbering scheme of the virtual grid (Source: Authors' own elaboration)

initial reference. Accordingly, ballast displacement was characterized as the temporal variation in local ballast-surface depth relative to the initial state, rather than as the trajectory of individual ballast particles. This approach produced a separate time series for each of the 16 ROIs, enabling the continuous monitoring of the temporal evolution of local ballast-layer deformation throughout the experiment. In addition, the ROI--based analysis considerably reduced the computational and storage requirements associated with the real-time acquisition and processing of large-volume depth data. From a software perspective, the displacement signals obtained from the 16 regions were logged in real time as time-stamped datasets and exported in CSV format. Since the primary objective was to determine whether ballast movement occurred during the experiment, rather than to perform high-precision meteorological measurements, this approach offered a practical and efficient solution. Furthermore, as both the camera position and the approximate ballast surface level were known, the measurement outputs were calibrated prior to each experimental run.

During the experiment, the recorded depth signals were affected by local flow variations, water-surface fluctuations, and vibrations induced by pump activation. As illustrated in Figure 8, the raw signals acquired from the selected regions exhibited a noticeable level of noise. To obtain a more stable and interpretable representation, the signals were preprocessed in Python. First, offset correction was performed using the initial reference depth value of each ROI, such that all subsequent measurements were expressed relative to the zero-offset condition defined at the beginning of the experiment. This procedure generated a time series for each ROI representing the temporal variation in local ballast-surface depth. A Kalman filter was then applied to each ROI-based time series to reduce short-term fluctuations and suppress measurement noise caused by hydrodynamic disturbances. As a result, smoother and more analytically interpretable time-series data were obtained, enabling clearer identification of ballast displacement and other transient experimental dynamics.

From the preprocessed data, the key dynamics of the experiment could be clearly identified, including gradual water discharge, the effects of stepwise refilling, ballast displacement and other abrupt changes over time.

RESULTS AND DISCUSSION

This study constructed an experimental system under laboratory conditions. The aim was to integrate a railway line infrastructure model with climate models in order to assess the impact of climate change on railway infrastructure. By adopting a proactive strategy, the safety and reliability of railway systems can be improved while optimizing maintenance operations. Ultimately, the study supports the development of sustainable transportation and strengthens the resilience of infrastructure in the face of climate-related challenges.

While the experimental program includes multiple configurations of aggregate gradations and thicknesses, as described in the methodology section, the results presented in this paper refer specifically to two single-run experimental variants: B-W-40-GF and B-C-40-GF. These were selected to demonstrate the feasibility of the image-based monitoring system and the methodological framework.

As a result of the tests, the processes of structural integrity loss of samples coded B-W-40-GF and B-C-40-GF were examined, and notable timing differences were observed between them (Figures 10–14).

1. Speed and reaction: the concrete sleeper variant (B-C-40-GF) reached its strength threshold 13.4% faster than the wooden sleeper variant. This can be attributed to the different surface friction characteristics and weight distribution between concrete and wooden sleepers, which affects the interlocking mechanism of the ballast particles under hydrodynamic pressure.
2. Image processing role: as shown in Figure 9, the Kalman filter successfully suppressed the noise from water turbulence, allowing for a precise detection of the initial 8:36 minute movement.

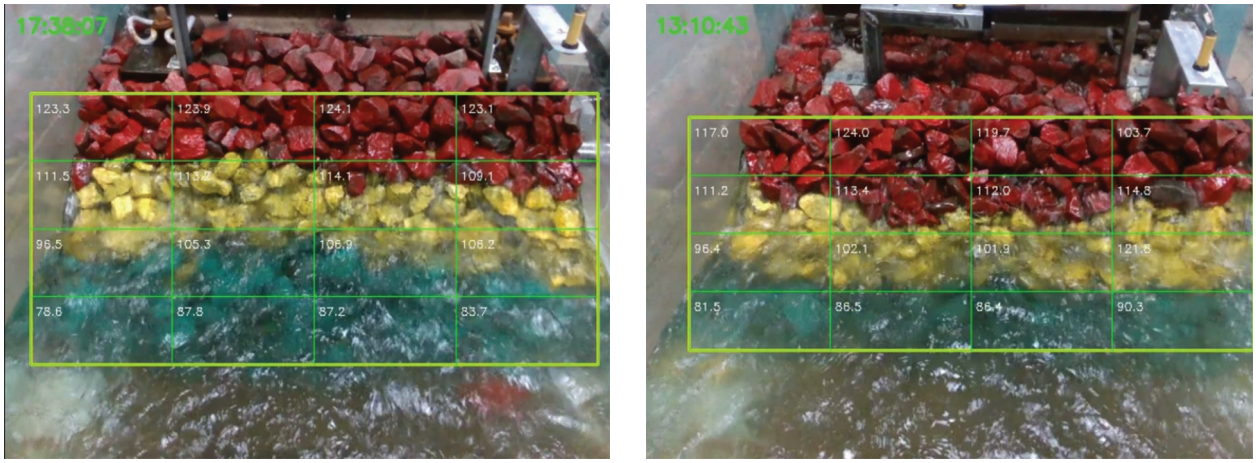

Fig. 10. (a) Scenario B-W-40-GF time 7:34 and (b) scenario B-W-40-GF time 7:25 before the start of motion in ballast layer (Source: Authors' own elaboration)

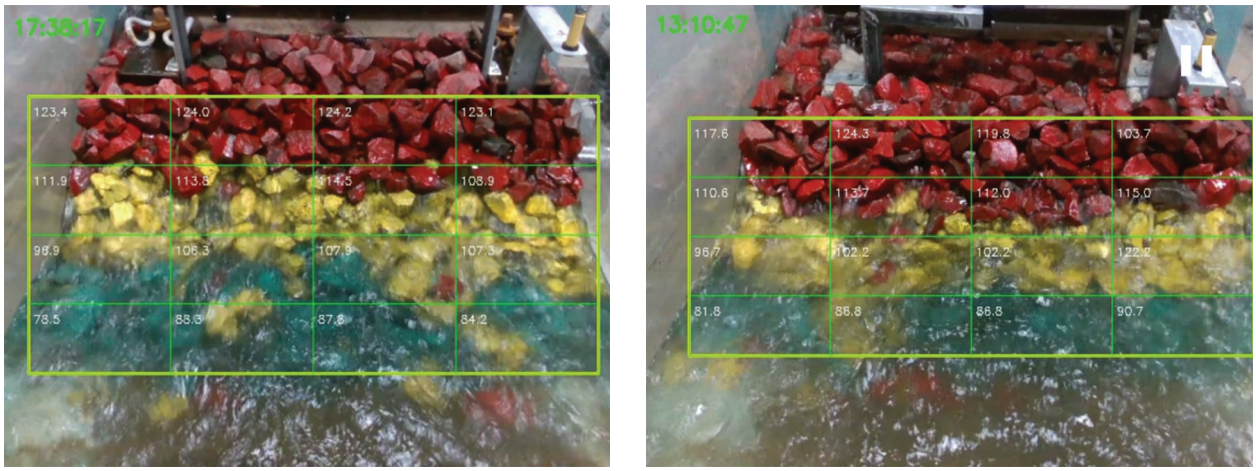

Fig. 11. (a) Scenario B-W-40-GF time 7:45 and (b) scenario B-W-40-GF time 7:28 after the start of motion in ballast layer (Source: Authors' own elaboration)

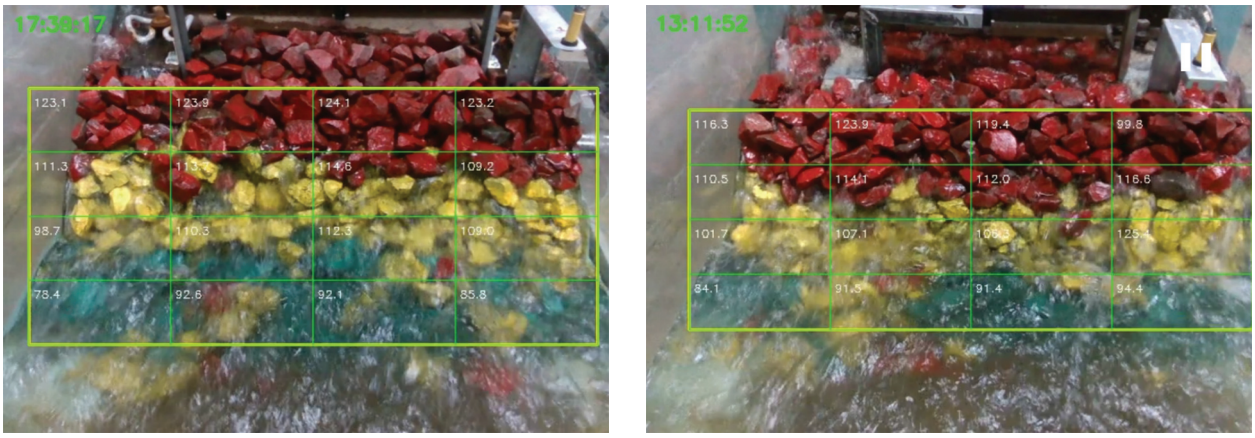

Fig. 12. (a) Scenario B-W-40-GF time 8:45 and (b) scenario B-W-40-GF time 8:33 before the start of collapse in ballast layer (Source: Authors' own elaboration

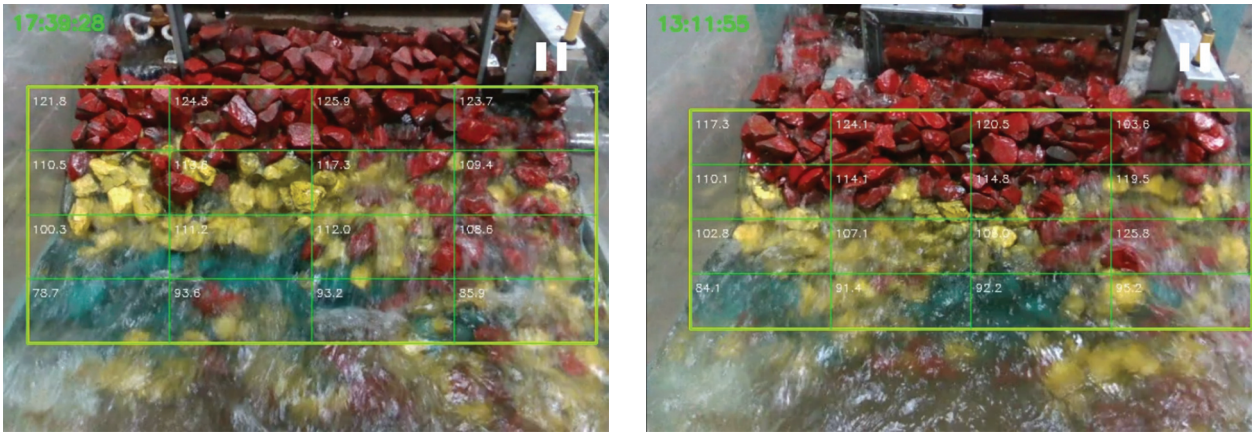

Fig. 13. (a) Scenario B-W-40-GF time 8:56 and (b) scenario B-W-40-GF time 8:36 after the start of collapse in ballast layer (Source: Authors' own elaboration)

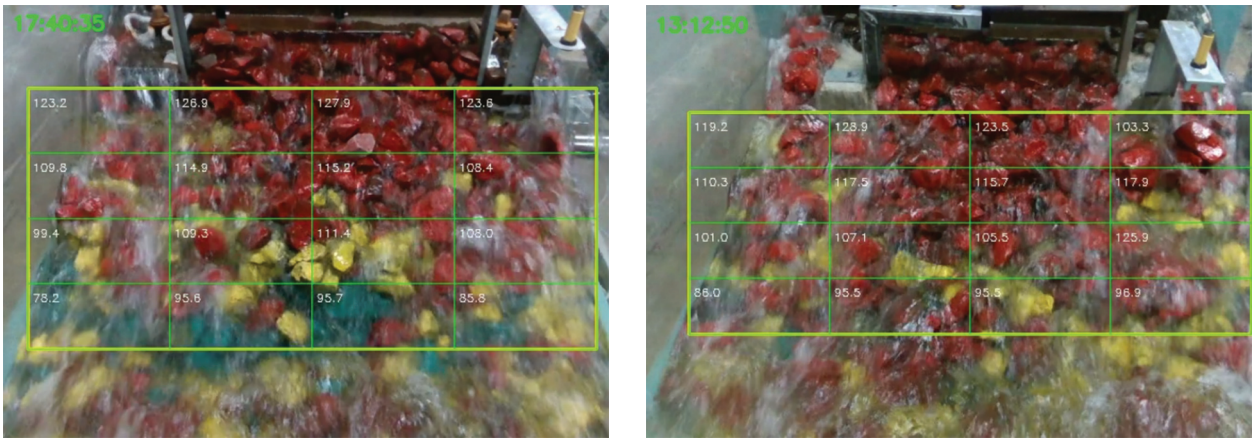

Fig. 14. (a) Scenario B-W-40-GF time 10:00 and (b) scenario B-W-40-GF time 9:28 after the final collapse in ballast layer (Source: Authors' own elaboration)

This demonstrates that the proposed image processing framework has the potential to support the future development of early warning systems by detecting sub-centimeter displacements that are invisible to the naked eye during a flood event.

3. Process completion time: while the collapse process of sample B-W-40-GF extended up to 10:00 minutes, sample B-C-40-GF completed its collapse process at 9:26 minutes. This indicates that the B-W coded sample exhibits 6–7% longer resistance to maintaining its structural form after fragmentation.

The study utilizes a combination of experimental and analytical approaches to examine the degradation of railway infrastructure. The research focused on the ballast layer, a critical component of the infrastructure. For this purpose, an experimental setup has been created using an open channel equipped with upstream and downstream reservoirs to simulate drainage and flow conditions. The aggregates forming the ballast layer were colored in three layers of different colors, enabling the infiltration curve of each layer to be drawn using image processing techniques under flood conditions. Figure 15 shows the railway model layers placed inside the channel.

Table 2. Comparative analysis of structural failure timing for wooden (B-W-40-GF) and Concrete (B-C-40-GF) sleeper variants

Observation parameter	B-W-40-GF	B-C-40-GF	Difference / Analysis
The first ballast motion	Time 8:34 (left middle up)	Time 7:26 (left middle up)	In both samples, the initial signs began in the same area. In sample B-C, the first collapse occurred 68 seconds earlier.
The start of collapse in ballast layer	Time 8:56 (right up)	Time 8:34 (right up)	Sample B-C began to degrade 18 seconds earlier than sample B-W.
Process completion	Time 10:00	Time 9:26	The degradation process in samples B and C finished much faster (34 seconds earlier).
Critical region	Left and right up	Left and right up	In both samples, the weak points are located in similar areas.

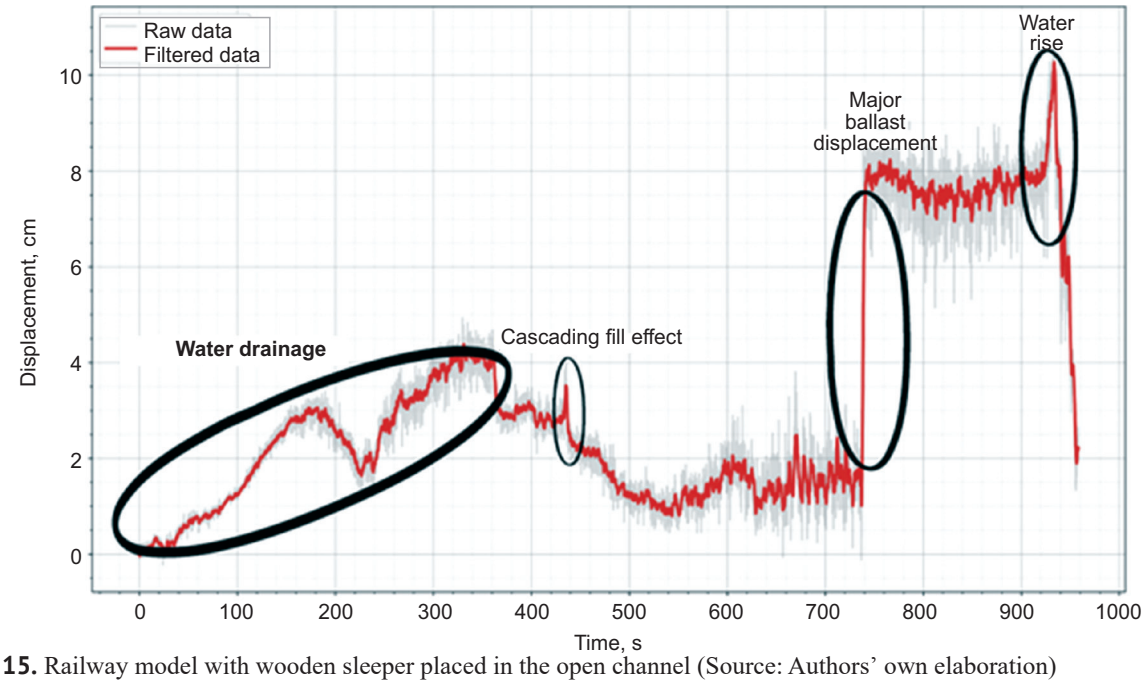

Fig. 15. Railway model with wooden sleeper placed in the open channel (Source: Authors' own elaboration)

In experimental studies, the following parameters were varied for three different climatic conditions:

- aggregate gradation,
- ballast layer thickness,
- sleeper material (wood or reinforced concrete).

It is believed that the experimental setup created under laboratory conditions facilitated the measurement of critical hydraulic parameters, such as scour depth and width, unit flow rate, velocity and flow depth, in relation to material properties and structural configurations.

The analysis of leakage mechanisms based on Darcy's law confirmed that the saturation level of the ballast substantially reduces the internal friction, leading to the abrupt collapse observed in the 'upper right' regions of both samples (Dikici and Burgan, 2025). The mathematical modeling component is based on Darcy's law and shallow water flow dynamics in order to realistically represent the flow within the ballast structure. The results obtained from the experimental phase are intended to inform the basis for the future development of machine learning models for predicting ballast degradation. Data analysis focuses on determining the effect of different experimental variables and evaluating the performance of the sensing system in detecting early signs of structural deterioration. Such models could eventually improve our ability to predict ballast failure under various environmental conditions.

CONCLUSIONS

The aim of this paper was to examine the impact of climate change events on railway infrastructure. This required integrating infrastructure models with climate models. To this end, an experimental setup has been established in laboratory conditions. Experiments were conducted under three different climate scenarios. The obtained data helps to investigate the ballast scour mechanism in railways impacted by floodings. Understanding this degradation process could lay the groundwork for the potential future development of early warning systems to prevent derailment, considering various climate scenarios. Ballast scour under flood impact is a very important and critical issue that causes accidents and requires investigation.

This research combines experimental and analytical approaches to survey the degradation of railway track substructures. The investigation focuses on ballast, a critical component of the substructure. An experimental setup has been constructed using an open channel equipped with upstream and downstream reservoirs, in order to simulate real-life drainage and flow conditions. Sensors and cameras were installed in the ballast layer and along the channel walls at both ends to monitor key seepage behaviour. Variable discharges were introduced into the ballast to simulate a range of climate change scenarios, and the resulting movement of aggregates under different flow conditions was captured using advanced sensors and cameras. The subgrade and other railway infrastructure are widely and deeply investigated in the literature within the scope of this paper. It has been determined that most academic studies are based on numerical models. However, natural ballast degradation must be validated through experimentation in a laboratory setting. This study plays an important role in this respect, investigating ballast movement under laboratory conditions.

Additionally, most of the literature has analyzed the filling part of the ballast superstructure theoretically. In laboratory conditions, in particular, tracking the movement of ballast aggregates is difficult due to their diameter. In this study, the monitoring process was successfully completed in three climate conditions using two methods (sensor and camera).

Data collected using the RealSense D435i camera suggest that the recording setup performs well in monitoring ballast displacement across varying climatic conditions. In parallel with the experiment videos, time-series measurements were obtained for the 16 virtual regions (Figure 8). Overall, the extracted signals were consistent with what was observed in the video recordings.

Future studies in this area could examine ballast scour alongside the underlying ballast material. Early warning systems capable of stopping the railway vehicle in the event of ballast separation from under the rail could be developed.

Experimental studies could identify the critical factors causing ballast degradation and future machine learning models could potentially predict track sections where ballast degradation may occur where ballast degradation may occur under different climate conditions. It should be noted that the experimental findings presented in this study are based on two single-run variants (B-W-40-GF and B-C-40-GF) used to validate the proposed methodological framework.

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LINIE KOLEJOWE PRZYSTOSOWANE DO ZMIAN KLIMATU: RAMY METODOLOGICZNE DLA UTWORZENIA SYSTEMU EKSPERYMENTALNEGO I WERYFIKACJI DANYCH ZA POMOCĄ PRZETWARZANIA OBRAZÓW

STRESZCZENIE

Cel badania

Artykuł koncentruje się na ocenie wpływu zmian klimatu na infrastrukturę. Ocena ta obejmuje analizę erozji i degradacji podsypki, opracowanie systematycznych ram doświadczalnych, stworzenie modeli prognostycznych i systemów wczesnego ostrzegania, a także porównanie zmiennych strukturalnych.

Materiały i metody
W ramach opracowania stworzono specjalny model badawczy przeznaczony do analizy zachowania warstw podsypki kolejowej. Doświadczenia przeprowadzono w kontrolowanych warunkach laboratoryjnych umożliwiających symulację intensywnych opadów deszczu oraz ich wpływu na infrastrukturę. Jako podstawową metodę monitorowania i rejestrowania przemieszczeń podsypki podczas tych badań zastosowano technologie przetwarzania obrazu. Metodologię opracowano w ramach międzynarodowej współpracy między Uniwersytetem Akdeniz (Turcja) a Uniwersytetem w Huddersfield (Wielka Brytania).

Wyniki i wnioski
Najważniejszym rezultatem badania jest pomyślne przygotowanie środowiska doświadczalnego i opracowanie procedur gromadzenia danych. Wyróżnia się w nim skuteczne wykorzystanie technologii przetwarzania obrazu do monitorowania zachowania podsypki w kontrolowanych warunkach laboratoryjnych. W badaniu stwierdzono, że opisana metodologia eksperymentalna zapewnia systematyczne ramy do oceny degradacji podsypki. Sugeruje się, że środowisko to mogłoby służyć jako pomocny punkt odniesienia dla przyszłych badań laboratoryjnych dotyczących wpływu zmian klimatu na infrastrukturę kolejową.

Słowa kluczowe: koleje, środowisko doświadczalne, dane, przetwarzanie obrazów, zmiana klimatu