CEN WORKSHOP AGREEMENT

CWA 18303

November 2025

ICS 25.040.30; 35.240.67; 91.100.30

English version

Robotic construction system for shotcrete digitization and automation through advanced perception, cognition, mobility and additive manufacturing skills

This CEN Workshop Agreement was corrected and reissued by the CEN-CENELEC Management Centre on 26 November 2025.

This CEN Workshop Agreement has been drafted and approved by a Workshop of representatives of interested parties, the constitution of which is indicated in the foreword of this Workshop Agreement.

The formal process followed by the Workshop in the development of this Workshop Agreement has been endorsed by the National Members of CEN but neither the National Members of CEN nor the CEN-CENELEC Management Centre can be held accountable for the technical content of this CEN Workshop Agreement or possible conflicts with standards or legislation.

This CEN Workshop Agreement can in no way be held as being an official standard developed by CEN and its Members.

This CEN Workshop Agreement is publicly available as a reference document from the CEN Members National Standard Bodies.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

Ref. No.:CWA 18303:2025 E

Contents

Page

Foreword

This CEN Workshop Agreement (CWA 18303:2025) has been developed in accordance with the CEN-CENELEC Guide 29 "CEN/CENELEC Workshop Agreements – A rapid way to standardization" and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by the Workshop CEN "RoBétArmé" the secretariat of which is held by UNI consisting of representatives of interested parties on 2025-07-09, the constitution of which was supported by CEN following the public call for participation made on 2025-01-27. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

The final text of this CEN Workshop Agreement was provided to CEN for publication on 2025-11-05.

Results incorporated in this CWA received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101058731 (RoBétArmé).

The following organizations and individuals developed and approved this CEN Workshop Agreement:

Fabrizio Tacca	UNI
Elena Mocchio	UNI
Federica Fugaroli	UNI
Cristina Di Maria	UNI
Giovanni Miccichè	UNI
Marco De Gregorio	UNI
Adriano Ferrara	UNI
Dimitrios Giakoumis	CERTH
Ioannis Kostavelis	CERTH
Theodora Kontodina	CERTH
Claude Jehle	Herrenknecht AG
Ricardo Carmo	COBOD
Line Steenhold	COBOD
Pedram Yosefipor	COBOD
Jonas Bentzen	Christiansen & Essenbæk A/S
Christina Buxtorf	Christiansen & Essenbæk A/S
Victor Solaz Estevan	Robotnik
Marc Bosch Jorge	Robotnik
Carlos Gascon Bononad	Robotnik
John Adamek	Arup
Marcos Sanchez	Arup
Louis Dastarac	BYCN
Bruno Lineatte	BYCN
Fernando Llano Martinez	INGENIEROS ASESORES DE CONSTRUCCIÓN SL

Ingo Martens	EFF
Gash Bhullar	EFF
Renaud Detry	KUL
Laura Tomassini	INAIL
Roberto Giacco	Roberto Giacco Engineering Firm

Attention is drawn to the possibility that some elements of this document may be subject to patent rights. CEN-CENELEC policy on patent rights is described in CEN-CENELEC Guide 8 “Guidelines for Implementation of the Common IPR Policy on Patent”. CEN shall not be held responsible for identifying any or all such patent rights.

Although the Workshop parties have made every effort to ensure the reliability and accuracy of technical and non-technical descriptions, the Workshop is not able to guarantee, explicitly or implicitly, the correctness of this document. Anyone who applies this CEN Workshop Agreement shall be aware that neither the Workshop, nor CEN, can be held liable for damages or losses of any kind whatsoever. The use of this CEN Workshop Agreement does not relieve users of their responsibility for their own actions, and they apply this document at their own risk. The CEN Workshop Agreement should not be construed as legal advice authoritatively endorsed by CEN/CENELEC.

Introduction

CEN/CENELEC Workshop Agreement is based on the results of the RoBétArmé European project (Human-robot collaborative construction system for shotcrete digitization and automation through advanced perception, cognition, mobility and additive manufacturing skills) grant agreement No 101058731.

According to the World Economic Forum, the construction industry currently accounts for about 6% of the world GDP and is expected to reach around 14.7% in 2030, which means that the construction sector plays a key role in any country's economy. At the European level, construction is a strategically important sector for the economy, involving a wide range of stakeholders and companies, providing 18 million jobs.

The importance of construction automation has grown rapidly worldwide, aiming to deliver new machinery for the automation of roads, tunnels, bridges, buildings and earthwork construction and this transformation has been called as Construction 4.0. This need is mainly driven by the shortage and rising costs of skilled workers, the tremendous increased needs for new infrastructures to serve the daily activities and the immense demand for maintenance of ageing infrastructure.

One might reasonably think that Construction 4.0 could bring equivalent benefits to construction domain, by automating traditionally manual, laborious, repetitive, and unhealthy for human workers construction activities.

According to construction market needs, the increase in mining activities around the world, the increase in tunnel construction due to rapid urbanization in emerging economies, and the growth in construction repairs in developed countries demand excessive automation of concrete placement. Shotcrete (sprayed concrete) is increasingly becoming popular among contractors and builders, as its application is extremely economical and flexible.

Shotcrete is a typical example in the construction domain, where even though a highly mechanized procedure (nozzles, pumping machines, mortar-mixers, telescopic reach tractors, etc.), the quality of sprayed concrete application heavily depends on the operators' skills:

— the compliance of the sprayed concrete thickness with the design requirements (CAD) is not known until after a survey is completed. The survey is manual and relies on expertise of workers to identify areas of over spray or under spray;

— to control the quality of application, nozzlemen use depth pins or string lines as guidance to allow them to (visually) gauge the approximate depth of concrete placement, which is a time consuming and labor-intensive task;

— to reduce the amount of underspray sections and prevent rework, nozzlemen place more shotcrete than required, wasting significant amounts of material and water.

The rebound phenomenon during shotcrete produces large amount of dust containing quick-setting agents, which inhaled by workers may cause great harm to the health (e.g. pneumoconiosis, cancer, etc.).

RoBétArmé aims towards a step change in the Construction 4.0 by automating particularly laborious construction tasks in all phases of shotcrete application.

The proposed CWA will be backed by existing relevant standards in each specific domain, which are the main references for the development of these applications. The CWA is aimed indeed at providing a description of new technologies regarding collaborative construction mobile manipulators, consisting of:

— an Inspection-Reconnaissance mobile manipulator (IRR) to address fast, high precision modelling and rebar reinforcement through metal additive manufacturing in the preparatory phase and

— a Shotcrete and Finishing mobile manipulator (SFR) to address autonomous shotcrete application and surface finishing during the construction and finishing phase, respectively.

1 Scope

This document is applicable to the following cognitive robot platforms that address the complete chain of shotcrete application for autonomous construction, maintenance and monitoring activities of infrastructures:

a) an inspection and reconnaissance mobile manipulator (IRR) with cognitive perception capabilities that fuse multimodal sensors or the high precision modelling of the construction site endorsed with a metal additive manufacturing (AM) manipulator to perform reinforcement of metallic rebar;

b) a shotcrete and finishing mobile manipulator (SFR) to perform wet shotcrete through concrete spay-casting, relied on visual guided robotic manipulation.

This CEN Workshop Agreement, concerning the mobile manipulators:

– provides terms and definitions and describes the characteristics of mobile manipulators and their components;

– specifies requirements and evaluation methods for the performance of mobile manipulators;

– specifies requirements for cement mix and materials;

concerning the construction site:

– defines uses cases: construction of ground support walls, repair of piles or beams, inspection and monitoring of bridge post-tensioned boxes and construction of culverts or service tunnels;

– provides guidelines for mapping and navigation strategies;

– sensor deployment per construction site;

concerning the digitization, deals with:

– autonomous decision making;

– interaction with BIM;

– digital twin and methods to transmit and collect data;

– IoT Integration with other subsystems.

This CEN Workshop Agreement does not apply to safety requirements for mobile manipulators.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 196-1, *Methods of testing cement — Part 1: Determination of strength*

EN 1015-6, *Methods of test for mortar for masonry — Part 6: Determination of bulk density of fresh mortar*

EN 1015-7, *Methods of test for mortar for masonry — Part 7: Determination of air content of fresh mortar*

EN 12190, *Products and systems for the protection and repair of concrete structures — Test methods — Determination of compressive strength of repair mortar*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp/

— IEC Electropedia: available at http://www.electropedia.org/

3.1
robot
an automatically controlled, reprogrammable manipulator, programmable in three or more axes, which may be either fixed in place or mobile for use in personal service applications

[SOURCE: EN ISO 13482:2014, definition 3.2, modified]

3.2
mobile robot, mobile base or mobile platform
robot able to travel under its own control

[SOURCE: EN ISO 13482:2014, definition 3.5]

3.3
mobile manipulator
robot mounted on a mobile robot

3.4
mobile base/platform IRR
wheeled closed chassis robot

3.5
IRR robotic manipulator
off the shelf 6 degree of freedom robotic manipulator

3.6
mobile base/platform SFR
wheeled open chassis robot

3.7
SFR robotic manipulator
custom made 6 degrees of freedom robotic manipulator

4 Mobile manipulators

4.1 Characteristics of mobile platforms and their components

Mobile platforms used in industrial and construction environments shall meet specific characteristics to ensure efficiency, safety, and adaptability. These characteristics define their capabilities and integration with various components.

Mobility is a fundamental aspect. The kinematic configuration determines how the platform navigates its environment. Steering mechanisms, including systems with steerable and non-steerable wheels, influence manoeuvrability and path planning. Speed and acceleration shall be adjusted to ensure safe and efficient movement.

Structural and mechanical properties affect reliability. The platform shall support the required payload, including sensors, manipulators, and tools. Durability ensures operation in challenging conditions such as dust, humidity, or uneven terrain. Size and form factor should allow movement through confined spaces while maintaining stability.

Power and energy management sustain operations over time. Battery autonomy shall align with operational needs to minimize downtime. Efficient power distribution ensures all onboard systems function properly without affecting performance.

Sensing and perception enable interaction with the environment. Localization and navigation rely on LiDAR, cameras, and IMUs for accurate positioning and obstacle detection. Environmental awareness supports adaptive path planning and collision avoidance, allowing safe operation in dynamic surroundings.

Control and communication systems define autonomy and operational flexibility. Platforms can be teleoperated, semi-autonomous, or fully autonomous. Real-time control mechanisms manage motion planning, safety protocols, and precision tasks. Reliable connectivity, through wired or wireless protocols, ensures seamless integration with external systems.

These characteristics define the functionality of mobile platforms, ensuring they meet the demands of industrial and collaborative applications.

4.2 Characteristics of shotcrete manipulators and their components

The SFR robotic manipulator is a custom-made 6 DOF machine with modular joints, that has a specific kinematics chain, in order to fulfil the required task of shotcreting and scrape the surface afterwards/surface finish it.

The manipulator itself has 6 degrees of freedom (DOF), in a specific orientation, optimized for shotcreting planar and curves surfaces, based on the learnings from the simulation environment.

Though the shotcreting part of the combined tool is static, a different version can be used – taking advantage of the modular design –, namely an actuated one. The scraper/surface finish part of the combined tool is already actuated with one motor, allowing for both static scraping (with a plain scraper) and rotational scraping, with a circular tool, as the latter has been shown to yield better results in research.

The SFR manipulator allows for both velocity and torque-based control, respectively more suitable for shotcreting and surface finishing tasks. The controllers are further described below.

The focus was to establish a robust, reactive control structures suitable for shotcrete and surface finishing tasks. A bio-inspired control approaches to robotic shotcrete was explored, aiming to replicate the dynamic motions of expert nozzlemen. By modelling these expert motion patterns through a mathematical encoding using dynamical systems (DS-s)—a set of ordinary differential equations—we facilitate the generation of reference velocities for the robot's controller. DS systems not only ensure the real-time reactivity of the control structure but also produce inherently robust motion plans that are critical in dynamic and uncertain environments such as construction sites. These systems can also ease human-robot interaction, enabling a shared control strategy where the robot operates under the supervisory guidance of a human operator located in a safe, remote location. The operator can compensate for any gaps in automatic perception and assess the quality of the shotcrete in real-time, guiding the robot to areas requiring further attention. Our goal is to develop robotic solutions that exhibit expert-level shotcrete skills, thus reducing the need for human operators to possess specialized shotcrete expertise. This approach aims to expand the application of robotic shotcrete to a broader range of end-users and address the shortage of skilled workers in the construction industry.

Further were developed means of autonomously guiding the shotcrete manipulator to achieve a prescribed concrete thickness through a given surface, based on visual feedback obtained from a camera. The key challenge that we face is that visibility is severely impaired by dust and occlusions. Our team has developed a method for guiding the trajectory of the shotcrete nozzle using data-driven approaches that can handle noisy and incomplete observations from cameras. By leveraging techniques like deep reinforcement learning and uncertainty-aware algorithms, the precision of the robot's movements was enhanced, ensuring accurate concrete spraying even in difficult conditions. A key aspect of our work is managing the uncertainty that arises from these noisy inputs. Machine learning models was used, such as variational inference combined with reinforcement learning, to estimate the most likely state of the environment despite missing or unclear data. This allows us to make more informed decisions about how to apply the shotcrete efficiently, improving material conservation and reducing waste. A robust, adaptive system that can handle the unpredictable nature of construction sites while maintaining high-quality outcomes for both new construction and repair projects was designed.

4.3 Characteristics of metal additive manufacturing manipulators and their components

A motion library for metal additive manufacturing tasks was created. This library is specifically designed for the RoBétArmé robot (Inspection Mobile Manipulator, IRR) to facilitate safe and high-precision rebar reinforcement during the preparatory phase. The task requirements and industry standards and guidelines were analyzed, with a focus on safety measures. This analysis informed the development of a path planner and control systems which can be used for both the printing and welding applications. A modular, general state machine as a high-level monitoring mechanism to ensure safety, reliability, and maintainable code structure was developed. Our approach involves detailed planning of feasible paths for the robotic arm to perform welding and printing tasks, including obstacle avoidance strategies—addressing both self-collisions and potential collisions with external objects like workstations. A critical aspect of this work is evaluating the feasibility of the generated paths and ensuring the system can effectively manage challenges such as singularities and infeasible paths. Additionally, integrating vision data and incorporating welding and printing machines into the IRR robot was focused. To validate the performance of the developed control system, tests in both a realistic simulation environment and a mock-up setup simulating real-world conditions were conducted. These evaluations considered task requirements and safety protocols, with performance metrics assessed using a six-degrees-of-freedom robotic arm.

4.4 Requirements and evaluation methods for the performance of mobile manipulators

Following the description from clause 4.1, the following requirements and specifications were set for the mobile platforms of the robots developed in RoBétArmé. Evaluation methods can be categorized as functional tests, non-functional tests, automated tests, and subjective evaluations:

- **Functional tests** verify core operations, including emergency stop responses, remote control operation, navigation, and execution of perception, mapping, and manipulation algorithms.

- **Non-functional tests** assess performance and environmental resilience, such as water resistance, operation in nominal conditions, network bandwidth, and power efficiency.

- **Automated tests** cover sensor data processing, emergency stops, remote control responsiveness, odometry, and mechanical brake activation, relying on measurable parameters.

- **Subjective evaluations** involve aspects like platform cleanliness and outrigger stability, which require human judgment.

This classification ensures both objective performance metrics and qualitative assessments are addressed.

Table 1 — Evaluation criteria

Mobile base shape, size and weight	Robot operates in the testing areas
Emergency stop	- All components (mobile base, manipulator, end effectors) are stopped when the e-stop button is pressed - Operation is restarted only once the e-stop button is reset
Remote control	The mobile robot can be controlled using a remote control from a nominal distance
Ingress protection	- Water does not enter during the cleaning process - Platform can be cleaned
Refrigeration/Ventilation	Platform can operate in the nominal environment conditions
Mounting of sensors	Sensor data can be used by perception algorithms
Sensors for localization and mapping	Mapping and localization algorithms work with the required precision
Sensors for perception	Sensor data can be used by the perception module
Wireless transmission	All data is transmitted to external components
Internal network to connect computers, sensors and actuators	The internal network has enough bandwidth to transmit the data
IRR Mobile Base payload capacity (shape, size and weight)	The mobile base moves with the payload during the testing in the nominal floor and obstacle conditions
Mobile Base Traction system	- The mobile base is equipped with the selected traction system - Mobile base can move with all the equipment with the selected traction system - Mobile base operates at nominal speed and overcomes nominal obstacles - Odometry and controllability meet expected values
Mechanical brakes for traction system	- Mechanical brakes are activated when the e-stop button is pressed - Mechanical brakes are activated when the system runs out of battery - The platform does not move when standing on a slope and the mechanical brakes are activated - The platform comes to a safe stop depending on the floor condition when the mechanical brakes are activated while the platform is moving

Battery capacity	Mean current and peak current are not exceeded during the operation of the system
Battery recharging method	The battery is recharged at the expected rate
Computers for processing and storing data on board	All required on-board processing and data storing is done

In addition, the combined SFR system is to be evaluated based on requirements and performance metrics set together with end users back at the early stage of the project.

In terms of performance metrics, the system needs to be evaluated to be fully integrated, including the orchestrator, tasks planners, trajectory planners and controllers. For the SFR, this means that communication needs to be robust, and that the HMI represents the current status of the machinery in the field – in terms of high-level steps, but also in terms of activation/de-activation and lower-level states of the planners. The material delivery system (read pump/mixer) needs to be coordinated with the SFR, and both the latter need to have a close to real-time communication line to the workstation. Within the SFR itself, the SFR robotic manipulator needs to have communication with the mobile platform, the camera's needs to be able to stream data to the workstation and the information from the later also needs to be used to eventually guide any corrections required on the trajectory planner.

Overall, the camera's information and the cross-referencing of that information with the BIM need to be used to update the status of the system, as a whole, and that high-level state needs to be used to further coordinate actions in lower-level planners – like adjusting the positioning of the mobile platform or the trajectories of the manipulator. Shotcreting and surface finish tasks need to be evaluated based on the same criteria as nozzlemen are currently evaluated on, in terms of quality assurance.

4.5 Requirements for cement mix and materials

The development of the shotcrete mix design was carried out to align with the requirements set by the end users. These specifications, summarized in Table 2, encompass critical parameters aimed at ensuring optimal performance under varied operational conditions. The design process prioritized achieving the desired rheological properties, durability, and early-age strength essential for shotcrete applications, particularly in demanding underground environments.

Key considerations included the selection of lower CO_2 cementitious materials, fine tuning of aggregates size, and the integration of advanced chemical admixtures. Admixtures, such as high-performance superplasticizers, set accelerators, air entrainment agents were evaluated for their role in enhancing flowability and ensuring rapid strength development. The design process incorporated extensive laboratory testing to validate compliance with performance benchmarks, in order to be evaluated on-site to robotic system deployment.

Table 2 — Shotcrete mix requirements

Requirements	End user A	End user B	End user C
w/c	0,4	0,45 – 0,60	0,35 – 0,50
Density hardened concrete (EN 12190) [kg/m^3]	2 240 ± 100	2 200 – 2 500	2 300 ± 100
Max grain size (due to the choice of pump)	4 mm	Thickness dependent: 20 ≤ d ≤ 60 mm: D ≤ 4mm 30 ≤ d ≤ 60 mm: D > 4mm Min. 1/15. max. 1/3	4 - 16 mm
Air content (EN 1015-7)	5 %	3 – 5 %	3 %
Density wet concrete (EN 1015-6) [Kg/m^3]	2 240	2 200 – 2 500	2 300 ± 50
Compressive strength 1 day (EN 196-1, 4x4x16 cm prism)	25 MPa	30 MPa	11 MPa
Compressive 28 day strength (EN 196-1, 4x4x16 cm prism)	C40/50	50 MPa	C40/50
Slump Test	150 mm	115 mm	200 mm
Setting time	4 h	2 – 4 h	3 – 4 h (20°C)
Carbonation	(The thickness of concrete cover depending on the anticipated exposure classes)		
Cl Ingress [m^2/s]	Depends on the cement used	D < 8 x 10^{12}	Depends on the cement used

5 Construction site

5.1 Guidelines for a plan for the construction site and for the relationship between manipulators and people

To develop and implement a safety plan for construction sites, in which there are interventions on tunnels, shafts, retaining walls, piles and beams, and the use of shotcrete manipulators and/or metal additive manufacturing manipulators, see Annex A.

5.2 Use cases

5.2.1 General

The RobétArmé use cases, i.e. the user-oriented scenarios that drive the project's research and development activities, are described and expressed as a sequence of steps involving the autonomous solution of RobétArmé considering the prioritized requirements expressed by end users.

The shotcrete application can be validated through demonstrations in four diverse real-world construction sites that cover all aspects of inspection, monitoring, maintenance and shotcreting. Each use case follows three major operational phases:

a) the inspection & preparatory phase;

b) the construction/repair shotcrete application phase; and

c) the surface finishing phase.

These phases ensure a comprehensive evaluation of the system's performance across the entire shotcrete workflow. The selected construction sites represent distinct technical challenges related to variable environmental conditions, terrain complexity, confined spaces, and accessibility constraints. The targeted use cases involve the construction of ground support walls, the repair of piles or beams, the inspection and monitoring of bridge post-tensioned boxes, and the construction of culverts or service tunnels. Each use case is designed to assess robotic precision, material application efficiency, and compliance with construction standards while addressing site-specific limitations. The robotic system must navigate in varying illumination conditions, operate effectively in GPS-denied environments, and ensure controlled shotcrete deposition through real-time monitoring and adaptive control mechanisms. By addressing these challenges, the shotcreting system contributes to the advancement of robotic automation in construction, enhancing safety, operational efficiency, and quality in infrastructure maintenance and development.

5.2.2 Construction of ground support walls

Ground support walls are critical for stabilizing excavations, tunnels, and slopes, requiring uniform and precise shotcrete application. Shotcrete is widely used in the construction of ground support (retaining) walls, which are rigid structures designed to support soil in various construction applications. The system is validated using the wet-mix shotcrete process. The specific challenges imposed in such construction sites include variable illumination conditions, such as direct sunlight, necessitating a robust multimodal vision system for surface modeling and shotcrete quality assessment. The terrain is typically rough and uneven, requiring adaptive navigation and stability control for precise robotic positioning. During the inspection and preparatory phase, the IRR robot performs detailed site scanning and 3D reconstruction, using multimodal sensors. It also executes metal additive manufacturing (AM) to reinforce metal rebars, improving adhesion and structural performance. The SFR robot is deployed in the construction phase, capable of adapting to various spatial constraints and ensuring controlled shotcrete deposition. The integration of digitalization tools enables real-time process monitoring and predictive optimization, improving construction efficiency, material usage, and structural durability.

5.2.3 Repair of piles or beams

Piles and beams serve as primary load-bearing elements in buildings and infrastructure, often requiring reinforcement due to aging, environmental exposure, structural degradation, or damage from external factors such as earthquakes or fires. The system is validated, utilizing the wet-mix shotcrete process. The repair process is particularly complex in indoor or restricted environments where GPS signals are unavailable, necessitating advanced localization techniques. Precision is essential, especially since piles and beams often have small cross-sectional dimensions, requiring high-accuracy shotcrete application to prevent material overspray beyond designated areas.

The IRR robot is employed in the preparatory phase to support high-resolution scanning and reinforcement enhancement through metal extrusion. During the repair phase, the SFR robot ensures accurate shotcrete deposition and seamless adaptation to spatial constraints. Additionally, it integrates automated material removal and reapplication capabilities, ensuring smooth surface finishing. A tool-changing mechanism enables the system to adjust between scraping and re-shotcreting, enhancing adhesion and repair consistency. Integrated digitalization tools, the system supports real-time adjustments and process monitoring optimize material application, improve efficiency, and support sustainable infrastructure maintenance.

5.2.4 Inspection of bridge post-tensioned boxes

Bridge post-tensioned boxes require continuous inspection and maintenance to ensure structural integrity and prevent long-term deterioration. These enclosed structures pose significant accessibility challenges, making robotic solutions necessary for precise assessments. The system is validated using the wet-mix shotcrete process. The inspection process is particularly challenging due to low-light conditions, requiring the integration of artificial illumination and advanced vision systems for accurate surface analysis and defect detection. Navigation within the post-tensioned boxes is constrained by narrow passages and sloped surfaces, necessitating high-maneuverability robotic platforms capable of maintaining operational stability in complex geometries. The robotic vision system is engineered to identify structural anomalies, such as cracks, corrosion, or exposed rebar, enabling precise shotcrete reinforcement in critical areas. The perception system is optimized to compensate for dust accumulation, and limited ventilation, ensuring reliable operation throughout extended inspection activities.

5.3 Construction of culverts or service tunnel

Culverts and tunnels require structural reinforcement to ensure long-term stability, particularly in underground environments with confined spaces and complex geometries. The system is validated using the wet-mix shotcrete process, with full-scale validation trials. Tunnels and culverts present unique challenges, including occlusions and restricted maneuverability, requiring a complementary perception system that enables robots to generate high-precision 3D reconstructions of the environment. The robotic shotcreting system is designed to operate while in motion, ensuring continuous coverage and adaptation to tunnel curvature. Excessive rebound, particularly in culverts, generates dust, necessitating advanced perception systems to maintain visibility and operational efficiency. Featureless tunnel environments hinder localization, requiring sensor fusion techniques to enhance positioning accuracy. The robotic system is configured to handle large-diameter hoses, ensuring optimal shotcrete application for underground construction. Autonomous perception and navigation technologies allow real-time adaptation of movement and spraying patterns, improving process efficiency and shotcrete quality while ensuring structural durability and long-term performance.

5.4 Guidelines for mapping and navigation strategies

Mapping and navigation are essential for robotic autonomy in construction sites, enabling precise localization and controlled movement in complex and dynamic environments. The proposed shotcreting system employs a multi-sensor Simultaneous Localization and Mapping (SLAM) framework, integrating Light Detection and Ranging (LiDAR), Red-Green-Blue (RGB) cameras, and Inertial Measurement Unit (IMU) data to enhance positioning accuracy in Global Positioning System (GPS)-denied areas. These methods allow robots to construct high-precision environmental maps while optimizing path planning for shotcrete application. The navigation system combines global and local planning to ensure efficient movement and task execution. Global planning determines optimal routes within the construction site, while local planning dynamically adjusts the robot's trajectory based on real-time sensor feedback. Different kinematic models are considered to accommodate diverse mobile platforms, ensuring flexibility across various construction scenarios. A localizability-aware navigation strategy can enable robots to optimize their movement while maintaining accurate position estimation. All mapping and navigation modules are integrated within a Robot Operating System (ROS)-based architecture, ensuring adaptability, interoperability, and deployment across robotic platforms. These advancements enhance robotic precision, improve construction efficiency, and support safe and reliable automated operations.

5.5 Sensor deployment per construction site

Sensor deployment in construction sites is critical for monitoring structural conditions, environmental parameters, and robotic operations. The RoBétArmé project employs a network of IoT-enabled sensors for real-time data collection, ensuring accurate process control and adaptive decision-making. Sensors are strategically placed to measure parameters such as humidity, temperature, structural vibrations, and shotcrete layer thickness, providing essential input for quality control and predictive maintenance. Data fusion techniques integrate multiple sensor inputs, enhancing situational awareness and enabling automated alerts for potential anomalies. Sensor placement is optimized to minimize interference with robotic operations while ensuring full coverage of critical areas. The collected data is transmitted to the Digital Twin (DT) platform, allowing real-time visualization and process optimization. Interoperability with BIM ensures that sensor-generated insights support construction planning, execution, and post-construction monitoring. This approach enhances safety, efficiency, and the accuracy of robotic shotcrete application in dynamic construction environments.

6 Digitalization

6.1 General

Digitalization in the shotcreting approach transforms construction and repair automation by integrating Building Information Modelling (BIM), Digital Twin (DT), Internet of Things (IoT), Human-Machine Interaction (HMI) interfaces to optimize robotic shotcrete applications. These tools facilitate real-time monitoring, process orchestration, and data-driven decision-making, ensuring efficient and precise execution across all construction/repair phases. The DT platform and simulation environment allow for lifelong monitoring of constructed and repaired sites, utilizing smart, low-energy IoT sensors for real-time diagnostics. These tools support process visualization, 4D planning, shotcrete simulation, and robot accessibility analysis, ensuring adaptive control and predictive maintenance. The DT framework provides a real-time 3D representation of construction progress, enabling as-planned vs. as-built tracking and enhancing workflow optimization. HMI interfaces, including Augmented Reality (AR)-enabled tools, facilitate operator interaction with robotic systems, supporting supervision, safety monitoring, and process adaptation. The simulation environment ensures that robotic workflows are tested and refined virtually before deployment, minimizing risks and improving efficiency. These digital solutions enhance productivity, reduce material waste, and enable scalable automation in construction and repair processes.

6.2 Autonomous task planning in construction site

Autonomous task planning is essential for optimizing robotic operations in complex and dynamic construction environments. The system integrates cognitive robotic functionalities to enhance situational awareness, task execution, and decision-making, ensuring adaptable and safe operations. A structured task orchestration framework enables robots to assess construction progress, interpret environmental constraints, and coordinate tasks accordingly. The Behaviour Trees (BT) method is employed for task planning, providing a modular and scalable approach to managing robotic actions. This method ensures structured decision-making for navigation, shotcreting, and material handling, enabling flexibility in response to real-world conditions. Initial validation in simulation environments has demonstrated the effectiveness of BTs, with refinements planned for deployment in construction sites. Task execution considers material properties, workspace constraints, and real-time safety requirements, ensuring human-aware navigation and hazard avoidance. An Augmented Reality (AR)-based interface enhances collaboration between human operators and robotic systems, improving task monitoring and coordination. All planning modules follow a standardized and repeatable approach, ensuring interoperability with existing construction automation frameworks. These strategies support safe, efficient, and scalable robotic workflows, contributing to the advancement of autonomous construction methodologies.

6.3 Integration of BIM with human machine interaction interface

The integration of Building Information Modelling (BIM) with Human-Machine Interaction (HMI) interfaces enhances real-time monitoring, control, and collaboration in robotic shotcrete applications. The system ensures seamless interoperability between BIM models and robotic systems, enabling dynamic adjustments based on site conditions and construction progress. Augmented Reality (AR) tools provide an interactive and immersive interface, allowing operators to engage with real-time BIM data for remote supervision, visualization, and adaptive workflow modifications. These tools improve robot navigation, shotcrete application, and reinforcement placement monitoring, ensuring safe and efficient human-robot collaboration. HMI interfaces support adaptive control mechanisms, enabling operators to intervene, refine robotic execution, and ensure process accuracy. This seamless integration between digital models and real-world construction activities enhances situational awareness, precision, and automation in construction and repair workflows

6.4 Digital twin and methods to transmit and collect data

The Digital Twin (DT) framework provides a real-time, virtual representation of construction and repair processes, integrating data from sensors, robotic systems, and environmental monitoring tools. This synchronization of real-world operations with digital models enhances process control, quality assurance, and predictive maintenance throughout the construction lifecycle.

Data transmission is supported by edge computing and cloud-based infrastructures, enabling low-latency processing, remote access, and secure data storage. High-frequency data from on-site sensors—such as those monitoring structural responses or environmental parameters—is wirelessly transmitted to centralized cloud servers. Each data point is timestamped, facilitating Structural Health Monitoring (SHM) and historical analysis.

The DT framework aggregates, structures, and visualizes this data to inform construction planning and adaptive robotic execution. Seamless communication between robotic platforms, monitoring systems, and remote operators is ensured through standardized wireless protocols. This allows for real-time decision-making, anomaly detection, and efficient coordination across all subsystems. These methods enable robust digital integration for resilient and efficient construction site automation.

6.5 IoT integration with other subsystems

The integration of Internet of Things (IoT) technologies supports automation and data-driven decision-making in construction environments by enabling continuous monitoring and real-time analysis. IoT sensors are deployed across construction sites to capture environmental data, structural responses, equipment status, and material curing conditions. These sensors facilitate predictive maintenance, safety monitoring, and quality assurance processes.

All IoT components are designed for seamless interoperability with other digital systems, including robotic platforms, Building Information Modelling (BIM), and Digital Twin (DT) frameworks. This ensures synchronized operation, efficient task coordination, and centralized oversight of construction workflows.

IoT sensors are configured to transmit raw data directly to a shared cloud-based database. Each recorded parameter includes a unique timestamp, enabling structural health monitoring (SHM) and temporal analysis. The shared database architecture allows subsystems to access and post-process the stored data using dedicated algorithms, including statistical or predictive models for assessing future structural behaviour.

Wireless communication protocols ensure low-latency data transmission and integration across distributed systems. The modular setup supports scalability and cross-platform compatibility, enabling standardized IoT implementation in various construction contexts while maintaining system flexibility and robustness.

Annex A
(informative)

List of main potential risks for a safety plan tailored to the construction environment in the context of the project

A.1 General

This annex provides guidelines potentially relevant to the development and implementation of a safety plan for construction sites where the machinery covered by this CWA is expected to operate (tunnels, shafts, retaining walls, piles and beams), considering the presence of such machinery.

In particular, the annex:

- identifies the main safety risks associated with environments for the construction of tunnels, shafts, retaining walls, piles and beams;
- provides guidelines potentially relevant to the development and implementation of the safety plan relating to the construction, maintenance and monitoring of infrastructure.

As for the areas of intervention, analyses are carried out on hypothetical areas, as no specific worksite has been identified.

In construction projects, intervention areas are typically defined using the Work Breakdown Structure (WBS). This approach allows project activities to be broken down into smaller, manageable components, enabling a more detailed analysis of the individual operations corresponding to each WBS element.

A.2 Identification of the safety risk associated with construction environments

A.2.1 General

Before analysing the individual WBS elements, it is necessary to assess the risks associated with a common area that affects all WBS elements: the external area, including access roads and logistical yards.

The analysis should therefore proceed according to the following structure:

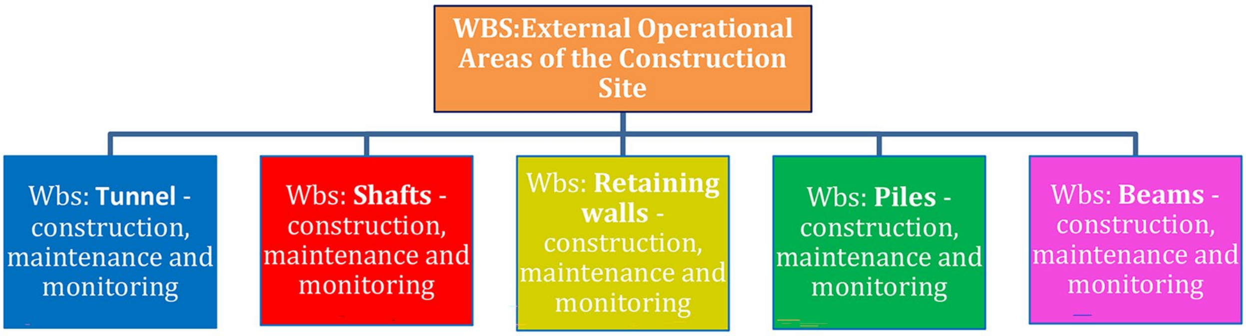

Figure A.1 — WBS elements analysis

A.2.2 WBS elements

A.2.2.1 External Operational Areas of the Construction site

The external zones of the construction site include areas designated for the storage of machinery and equipment, material stockpiles, excavated soil and rock deposits, logistical yards, administrative offices (e.g., site management, project supervision), and support facilities such as locker rooms, sanitary units, canteens, and, where applicable, dormitories — all serving the operational needs of the project under construction.

It is important to highlight that, particularly in the context of large-scale infrastructure projects, the setup of the construction site is not static but continuously evolves in accordance with the progress of the work.

The design and management of the construction site area must comply with the provisions of Directive 89/391/EEC, as well as the specific regulations applicable in the location where the intervention is carried out. A clear example of this is the site fencing, which, under the aforementioned Directive, must be designed to effectively prevent unauthorized access to work areas. However, local municipal regulations may further define the permissible types of fencing that can be used.

A.2.2.2 Tunnels

The construction of a large-scale infrastructure such as a tunnel involves numerous activities, starting from the stabilization of the tunnel portal to the consolidation and support works of the excavation walls, water drainage, appropriate inspections and monitoring for the presence of gases, asbestos, etc. Excavation operations can be carried out using explosives, mechanical equipment such as excavators, hydraulic breakers or milling machines, or by means of TBM (Tunnel Boring Machine), a mechanized cutterhead that excavates rock while simultaneously installing the lining of the future tunnel.

Tunnel excavation follows a sequence of operations, including pre-consolidation of the face; rock demolition; loading and transportation of excavated material; face scaling (i.e., face stabilization and removal of loose rock); and primary lining of the excavated section. In this context, beyond the intrinsic hazards associated with the nature of the structure itself, numerous additional risks arise from the simultaneous execution of multiple activities. This also applies to subsequent phases such as the excavation of the invert, construction of side walls, installation of the final lining, and construction of the tunnel crown.

As can be inferred, the tunnel face area is the zone with the highest risk of injury, and it is precisely in this area that supervision and control activities by field personnel (e.g., foremen, site managers) and designers are most heavily concentrated, through work scheduling and planning, often represented via Gantt and/or PERT charts.

Another critical element requiring detailed attention by the designer to ensure the safe construction of tunnels is spatial organization: signage, separation between pedestrian and vehicular areas, lighting, fire suppression systems, emergency containers, communication systems, air quality management, and alarm systems. Once these elements are designed and implemented, they shall be continuously maintained in efficient condition through periodic inspections.

Equally important is the use of high-visibility clothing in accordance with EN ISO 20471. Similarly, the safe operation and proper maintenance of vehicles is vital. To enhance visibility, machinery is equipped with rotating beacons, reverse acoustic alarms, cameras, and monitors to provide the operator with improved visibility of lateral and rear areas.

Another key factor in ensuring safety during tunnel works is mental health and work-related stress. It is evident that working underground entails discomfort, exacerbated by environmental conditions such as lack of natural light, dust, and noise.

Of particular interest is the issue of an “ageing workforce”, identified among the key social developments by EU-OSHA in its new Occupational Safety and Health strategy for 2025–2035. Among the identified social transitions—digital transformation, green transition, and workforce ageing—EU-OSHA plans to address occupational health and safety challenges through three strategic approaches: providing knowledge for policymaking, developing tools to prevent risks, and raising awareness to foster a prevention culture, while remaining environmentally and socially sustainable (Source: EU-OSHA).

Safety does not only pertain to tunnel structures and systems but also encompasses operations and maintenance.

Among the most common causes of degradation in concrete tunnels are freeze–thaw cycles and reinforcement corrosion. Evidence of such deterioration typically manifests as concrete cracking and disintegration. Maintenance activities require a preliminary assessment to define the structural condition, evaluate the extent of damage, and determine the most appropriate solutions for infrastructure restoration. In-situ and laboratory tests are generally conducted to determine the mechanical properties of the structure and the state of internal stress.

To assess the thickness of concrete structures, ground-penetrating radar (GPR) can be used, which operates by emitting electromagnetic pulses that propagate through the material at a velocity dependent on the material's dielectric constant. Cracks can be evaluated using a "doorstopper" method, which involves measuring the deformation at the base of a core hole following stress release induced by overcoring around it. It is critically important to determine whether the observed cracks are actively propagating or have stabilized. To assess this, crack gauges (fissurometers) are used to detect any structural movement. For a more detailed analysis of crack progression, it is essential to record temperature variations to determine whether crack development is due to thermal effects rather than structural deterioration.

Once all the necessary investigations have been completed, a recovery intervention is defined. This may include structural reinforcement using steel plates and linings, or—depending on the size of the cracks—sealing through injection of special resins. For small cracks (typically between 1mm and 1.5 mm), a more targeted intervention may involve cutting along the crack line, pressure washing, and application of specially formulated cementitious mortars.

Based on the analysis of construction, monitoring, and maintenance operations in tunnels, it becomes evident that the primary field of application for both IRR (Internal Reinforcement Robot) and SFR (Shotcrete Finishing Robot) lies in maintenance activities: specifically, the restoration of metal reinforcement segments using the IRR and the application of shotcrete using the SFR.

A.2.2.3 Utility tunnels

Utility tunnels are engineered structures designed for the conveyance of wastewater, stormwater, solid waste, and urban effluents, as well as for the routing and protection of underground utility infrastructure.

The construction of utility tunnels involves excavation and earthworks to clear the area, followed by the installation of a reinforced concrete foundation in accordance with project specifications. Subsequently, modular precast elements are positioned, which may be made of concrete, glass-fiber-reinforced plastic (GFRP), or other materials.

The precast elements may have a U-shaped cross-section with a cover slab or may be fully enclosed. These precast concrete utility tunnels shall comply with the requirements of EN 14844.

With regard to monitoring and maintenance activities in utility tunnels, these primarily concern the equipment and systems housed within the tunnels themselves.

As for the structural components of the tunnels, maintenance interventions typically involve inspection of the walls and ceiling, detection of potential cracks and/or fissures, and the subsequent planning of repair operations. These can include cutting along the crack line, surface cleaning, treatment of any exposed reinforcement steel, and the application of appropriate cementitious mortars.

The use of the two robotic systems—IRR (for welding operations) and SFR (for shotcrete application)—within tunnels represents a significant opportunity to improve occupational health and safety conditions.

This is particularly relevant because tunnels are typically categorized as "confined spaces": enclosed or partially enclosed spaces with restricted or limited means of access or egress, poor natural ventilation, and the potential presence of hazardous agents (e.g., gases, vapours, dust, explosive atmospheres, biological agents, electrical hazards, etc.). These conditions, in combination with oxygen deficiency or impaired evacuation and communication, can lead to serious or fatal injuries.

Personnel access is permitted only after confirming the absence of life-threatening conditions and verifying that safety measures are in place.

Additional dimensional and anthropometric considerations should also be evaluated in accordance with the following standards: EN 547-1, EN 547-2 EN 547-3, EN ISO 15537:2022 and EN ISO 15535.

Of particular interest is the classification of confined spaces according to risk factors, as provided by NIOSH in document 80-106. For procedural guidelines and worker training, an additional authoritative reference is OSHA Standard 1926.1207 (United States), which specifically addresses procedures and training for entry into confined spaces in the construction industry.

Within this framework, the deployment of robotic systems may fully replace human intervention under suitable conditions. However, the use of robots may not always be feasible—due to dimensional limitations of tunnel access, or the potential presence of explosive substances that could be ignited by the robots themselves.

A.2.2.4 Retaining walls

Retaining walls are used to hold back soil and prevent the collapse of slopes. There are various types of retaining walls, including those made of stone, metal gabions, and reinforced concrete.

Reinforced concrete retaining walls are constructed following an excavation phase, the creation of a foundation through a reinforced concrete pour, the placement of steel reinforcements, formwork installation, and the final concrete pour. In most cases, the retaining wall is built using precast concrete elements.

The physical and mechanical characteristics of the IRR and SFR robots do not allow their use for the construction and/or maintenance of retaining walls such as of particular height and dimension. However, the SFR robot can be employed for the construction and maintenance of retaining walls such as of low height, both for the foundation pour alone (in cases where precast elements are used to build the wall) and for the foundation and the retaining wall pour (in cases where both the foundation and the wall are cast in place). The IRR robot can be applicable for maintenance activities related to the wall's steel reinforcement.

A.2.2.5 Piles

Concrete piles are primarily employed to improve the geotechnical characteristics of the soil and/or to support the load of buildings or infrastructure to be constructed above.

In essence, the main applications of piles include the construction of foundations for new structures, the underpinning of existing structures, the development of retaining systems to allow for excavation (e.g., Berlin-type walls with micropiles), and the stabilization of slopes and embankments.

Piles can be broadly classified into two main categories based on their construction method: precast piles and cast-in-place piles. For the purpose of our study, particular attention is given to cast-in-place piles, which are constructed by drilling into the ground, inserting a reinforcement cage, and then casting concrete in situ.

A brief analysis of the potential applications of the SFR and IRR robots reveals that their wheeled mobility represents a significant limitation in this specific working environment, which is typically characterized by the presence of mud and water. Track-based mobility would substantially enhance their operational effectiveness.

Regarding operational tasks, the SFR robot could be employed in cementitious mortar casting activities.

Conversely, the IRR robot should find suitable application in the repair or reinforcement of steel rebar prior to its placement within the excavation.

A.2.2.6 Beams

Reinforced concrete beams are structural elements constructed following the installation of steel reinforcement and the placement of appropriate formwork. The reinforcement phase involves the manual assembly of steel bars (rebars) and stirrups by workers, using tie wire to secure the components. The subsequent phase—formwork assembly—entails creating a mould or containment structure for the reinforced concrete element. Concrete casting operations, depending on the dimensions involved, can be carried out manually or with the aid of a truck-mounted concrete pump, which uses an articulated boom to place the concrete within the designated formwork. A simultaneous operation during casting is concrete vibration, which is performed using dedicated equipment (mechanical vibrators) to ensure proper compaction and eliminate air pockets. Once the required curing time has elapsed—which varies according to the type of structure—the formwork is removed (a process known as stripping or formwork removal).

Of particular interest to this research are both localized castings, used for the construction or repair of individual reinforced concrete components, and large-scale castings that involve not only individual beams but also combined casting of beams and slabs. An example from residential construction includes floor systems composed of precast joists (made of prestressed reinforced concrete, clay-concrete composite, etc.) and hollow clay blocks (e.g., “pignatte” or similar), over which a cast-in-place concrete layer is poured to complete the slab. In contrast, floor systems for large-scale infrastructure works are often executed as solid slabs made entirely of steel reinforcement and cast-in-place concrete.

Another highly relevant example is the casting of large-scale structures such as multi-level parking facilities.

This category of structures typically includes reinforced concrete beams and columns, as well as large-span slabs, often executed as solid slabs composed of reinforcement steel and cast-in-place concrete.

An analysis of the potential applications of the SFR and IRR robots indicates that the use of wheeled mobility constitutes a significant operational limitation within the specific working environments typical of residential and industrial construction, which are frequently characterized by the presence of significant amounts of mud and water. Wheeled systems should be more effectively utilized during monitoring and/or maintenance phases, rather than during the primary construction operations. In the specific context of constructing and maintaining multi-level parking facilities, where access ramps often have steep gradients, it is advisable to equip both robots with a dedicated servo brake system to ensure safe manoeuvrability.

With regard to specific tasks, the SFR robot could be employed in cementitious mortar casting operations. The IRR robot, on the other hand, can find suitable application in the repair or augmentation of reinforcement steel elements.

A.2.3 Identification of the safety risks associated with construction environments

Risk	External Operational Areas	Tunnels	Utility tunnels	Retaining walls	Piles	Beams
Unexploded Ordnance	The risk must always be assessed based on historiographic analysis, Ministry of Defense sources, bibliographic references on local history, State Archives, or through instrumental surveys.	The risk must always be assessed based on historiographic analysis, Ministry of Defense sources, local historical literature, State Archives, or through instrumental investigations.	The risk must always be assessed through historiographic analysis, Ministry of Defense sources, local historical archives, or instrumental investigation.	The risk must always be assessed through historiographic analysis, sources from the Ministry of Defense, bibliographic references on local history, State Archives, or via instrumental investigations.	The risk must always be assessed through historiographic analysis, sources from the Ministry of Defense, bibliographic references on local history, State Archives, or via instrumental investigations.	The risk must always be assessed based on historiographic analyses, sources from the Ministry of Defence, bibliographic references on local history, State Archives, or through instrumental investigation methods.
Interference risks	Between site traffic and public roads/areas, the risk is present in all construction site areas where access from public roads is required.	The risk is related to interference between workers and machinery, operational vehicles, and temporary equipment within tunnel work zones.	These concern the interference between vehicles, machinery, and workers in the external area during culvert construction. This risk is also present during maintenance due to multiple workers being inside the culvert.	The risk is related to interference between workers and machinery, operational vehicles, and temporary equipment within the retaining wall work zones.	This risk is related to the interference between workers, machinery, operational vehicles, and temporary equipment within pile construction areas.	The risk is associated with the interference between workers and machinery, operational equipment, and temporary structures within the work areas dedicated to the casting of the beam.

Overturning of Equipment/vehicle					This refers to the potential overturning of the drilling machine due to unstable soil conditions or unsuitable routes with steep gradients. It also considers the presence of underground utilities in positioning and transit areas.	The risk refers to the potential overturning of the concrete pump, which may result from inadequate support of the stabilizers or the presence of underground utilities.
Blows, impacts, compressions, punctures, cuts, and abrasions	The risk refers to possible interactions with machinery, equipment, materials, tools, and temporary structures.	The risk is linked to interaction with tunnel support systems such as compressed air, water, electrical systems, etc.	These arise from worker interaction with machinery (earth-moving machines, concrete pumps, mobile cranes, etc.), tools (cutters, screwdrivers, hammers, etc.), and equipment used in culvert construction. The risk is also present during maintenance due to interaction with internal systems and equipment.	The risks associated with the retaining wall area are examined, specifically those related to interaction with service systems such as compressed air, water supply, electrical installations, and the use of equipment	These risks relate to interaction with equipment and systems used in pile installation, such as drilling rigs, compressors, cement grout silos, electrical systems, diesel tanks, and water systems.	The risks present in the beam construction area are examined, particularly those related to interaction with service systems such as concrete casting pipelines, water supply, electrical installations, rebar bending

				such as grass trimmers and circular saws.		machines, and circular saws. The risk is also associated with the presence of materials susceptible to rolling.
Slips and trips	The risk refers to the potential for workers to fall within the construction site due to uneven ground levels, rough or depressed terrain, embankments, muddy areas, or even over piles of materials and equipment placed on the ground. It also includes situations where steel reinforcement is laid directly on the ground without designated walkways.	The risk refers to the potential for workers to fall within tunnel areas due to uneven ground levels, rough or depressed terrain, embankments, muddy surfaces, or even over piles of materials and equipment placed on the ground. It also includes situations where steel reinforcement—such as that for the invert arch—is laid directly on the ground without	The risk refers to the potential for workers to fall within the area where utility tunnels are constructed, due to uneven ground levels, rough or depressed terrain, embankments, muddy surfaces, or even over piles of materials and equipment placed on the ground. The risk is also present during maintenance activities and relates to the potential for workers to fall or slip inside the tunnels, where the presence of water is frequently observed.	The risk refers to the potential for workers to fall within the areas surrounding the retaining wall, due to uneven ground levels, irregular or depressed terrain, embankments, muddy surfaces, or even over piles of materials and equipment placed on the ground. It also includes situations where reinforcement bars—such as those for	The risk refers to the potential for workers to fall within the pile installation areas due to uneven ground levels, rough or depressed terrain, embankments, muddy surfaces, or even over piles of material, equipment left on the ground, the presence of piping, or stakes and rebar used for layout marking.	The risk refers to the potential fall of workers in the areas involved in beam casting, due to uneven ground levels, irregular or depressed terrain, embankments, muddy surfaces, or even over piles of materials and equipment left on the ground. It also includes cases where reinforcement bars are laid on the ground (or on the slab level involved in the activity)

		designated walkways.		foundations—are laid directly on the ground without designated walkways.		without designated walkways.
Falls from height	The risk is present in cases involving access to temporary works, self-propelled equipment, or elevated structures with respect to ground level. It also includes situations where workers climb onto, lean over, or tamper with guardrails associated with elevated structures (such as pedestrian walkways, work platforms, etc.). The risk is likewise present when approaching excavation edges or embankments that are not protected against fall hazards. Finally, this risk also applies to the	The risk is present in cases involving access to temporary works, self-propelled equipment, or elevated structures with respect to ground level. It also includes situations where workers climb onto, lean over, or tamper with guardrails associated with elevated structures (such as pedestrian walkways, work platforms, etc.). The risk is likewise present when approaching excavation	The risk is present when approaching excavation edges or embankments that are not protected against fall hazards. Finally, this risk also applies to the operation of vehicles, particularly when manoeuvring near excavation edges and embankments.	The risk is present when accessing temporary works (such as metal scaffolding), self-propelled equipment, or elevated structures relative to ground level (e.g., elevating platforms, formwork systems, etc.). It also includes situations where workers climb inclined surfaces to carry out various tasks, such as the placement of nonwoven geotextile	The risk is present when accessing temporary works (such as metal scaffolding or mobile towers), self-propelled equipment, or elevated structures with respect to ground level (e.g., elevating platforms, etc.). It also includes the potential fall of workers during the assembly and/or maintenance of the drilling rig, or due to incorrect refueling operations	The risk is present in cases of access to temporary works (such as mobile scaffolding and metal scaffolds), self-propelled equipment, or elevated structures relative to ground level (e.g., elevating platforms, formwork systems, etc.). The risk also includes situations where workers climb onto the ties of columns to perform various tasks, such as

	operation of vehicles, particularly when manoeuvring near excavation edges or embankments.	edges or embankments that are not protected against fall hazards. Finally, this risk also applies to the operation of vehicles, particularly when manoeuvring near excavation edges or embankments.		fabric on the backfill area behind the retaining wall under construction. Furthermore, the risk encompasses cases where workers climb onto, lean over, or tamper with guardrails serving elevated structures (e.g., elevating platforms, formwork systems). The risk is also present when approaching unprotected excavation edges or embankments. Finally, this risk applies to vehicle operation in proximity to excavation	when the operator stands on the tracked undercarriage. The risk further considers situations where workers climb onto, lean over, or tamper with guardrails installed on elevated structures (such as elevating platforms, mobile scaffolding, etc.). It is also present when approaching excavation areas related to drilling, or excavation edges and embankments that are not protected against fall hazards. Finally, this risk also applies to	stripping the formwork. Additionally, it applies to workers who climb onto, lean over, or tamper with guardrails installed on elevated structures (such as elevating platforms and formwork) or on temporary works (e.g., scaffolding or mobile towers). Fall-from-height risk is also present during cleaning or maintenance of the concrete pump arm, particularly when operators climb onto the arm itself instead of using appropriate equipment (such as

				edges and embankments.	vehicle operation, particularly when approaching edges and embankments.	elevating platforms). The risk further extends to proximity to unprotected excavation edges or embankments. Finally, this risk is relevant during vehicle operation, especially when driving near excavation edges and embankments.
Falling objects/material from above	The risk refers to the proximity of workers to construction vehicles. It also includes the hazard associated with passing beneath suspended loads (such as those lifted by cranes, mobile cranes, etc.).	The risk refers to workers' proximity to construction vehicles. It also concerns passage beneath suspended loads (such as mobile cranes, the conveyor belt of the marine excavation system, overhead equipment extensions,	Risk due to worker proximity to vehicles, suspended loads (e.g., prefabricated culvert elements lifted by cranes), and collapse of excavation edges or trench walls.	The risk refers to workers' proximity to construction vehicles. It also concerns movement beneath suspended loads (such as those lifted by mobile cranes), as well as passage under work equipment including	The risk refers to workers' proximity to construction vehicles. It also concerns the passage beneath suspended loads and work equipment such as drilling rigs, elevating platforms, mobile scaffolding, fixed	The risk refers to workers' proximity to construction vehicles. It also includes the hazard of passing beneath suspended loads (such as mobile cranes or the boom of a concrete pump), as well as moving underneath

		reinforcement bars for the tunnel crown, etc.) as well as movement beneath work equipment such as elevating platforms, formwork systems, waterproofing gantries, and similar structures. The risk is also present in all activities involving movement beneath unlined rock masses—for example, during excavation operations, installation of steel ribs, application of shotcrete, and similar phases.		elevating platforms and formwork systems. The risk is present in all activities involving transit beneath slopes that are still unstable and subject to ongoing operations.	scaffolding systems etc.	work equipment or temporary structures (such as elevating platforms, mobile scaffolding, fixed scaffolds, etc.).
Collision risk	This risk involves workers coming close to operational machinery on site	This risk refers to workers' proximity to operational	This risk refers to workers' proximity to operational construction equipment	This risk refers to workers' proximity to operational	This risk refers to workers' proximity to operational	This risk concerns the proximity of workers to

	(excavators, concrete pumps, trucks, etc.). It also relates to the proper use of vehicles by drivers, necessary inspections, and compliance with operational limits.	construction equipment (such as excavators, concrete pumps, trucks, etc.). It also concerns the proper use of such machinery by operators, including the required inspections, adherence to operational limits, and compliance with safety protocols.	(such as earthmoving machinery, excavators, concrete pumps, trucks, etc.). It also pertains to the proper use of such equipment by operators, including the necessary inspections, adherence to operating limits, and compliance with relevant safety procedures.	construction equipment (such as excavators, concrete pumps, trucks, etc.). It also pertains to the correct operation of such equipment by drivers, including the required inspections, adherence to operational limits, and compliance with applicable safety procedures.	construction equipment (such as drilling rigs, excavators, trucks, etc.). It also pertains to the proper use of such equipment by operators, including the required inspections, adherence to operational limits, and compliance with relevant safety procedures.	construction equipment (such as excavators, concrete pumps, trucks, etc.). It also pertains to the correct use of such equipment by operators, the necessary inspections to be carried out on the machinery, compliance with operating limits, and related safety requirements.
Shearing and crushing hazards	The risk relates to worker interactions with machinery, equipment, various tools, and temporary structures. It includes scenarios such as proximity to machines handling suspended loads or machines equipped with rotating	The risk refers to potential interaction between workers and machinery, equipment, materials, various tools, and temporary structures. This includes	The risk refers to potential interaction between workers and machinery, equipment, materials, various tools, and temporary structures. This includes proximity to machines handling suspended loads or those equipped with rotating	The risk refers to potential interaction between workers and machinery, equipment, materials, various tools, and temporary structures. This includes	The risk refers to the potential interaction between workers and machinery, equipment, materials, various tools, and temporary structures. This includes	The risk refers to the potential interaction between workers and machinery, equipment, materials, various tools, and temporary structures. This includes

	components (e.g., drilling rigs, concrete mixers, etc.).	proximity to machines handling suspended loads, equipment moved along rails (such as crown formwork systems), or machines with rotating components (e.g., drilling rigs, concrete mixers, etc.).	components (such as concrete mixer trucks).	proximity to machines handling suspended loads, machines with rotating components (such as drilling rigs, concrete mixers, etc.), as well as the use of equipment like rebar bending machines, grass trimmers, and circular saws.	proximity to machines handling suspended loads, machines with rotating components such as drilling rigs, and the use of equipment like rebar bending machines. The primary risk arises during the loading and unloading phases of drilling rods, casings, reinforcement cages, and related components, where direct worker interaction with the machine is required.	proximity to machines handling suspended loads, machines with rotating components (such as concrete mixers), as well as the use of rebar bending machines or circular saws.
Burial risk	The risk refers to the potential falling of materials from the edges of the	The risk is associated with falling material from excavation	Involves falling material or trench wall collapse during culvert construction.	The risk refers to the falling of material from the slope		The risk refers to the falling of material from the edge of the

	excavation and/or the collapse of the excavation walls themselves.	edges or collapse of tunnel walls, and also during work under unlined rocky outcrops (e.g., excavation, support installation, shotcrete application, etc.).		affected by ongoing activities and/or from the edges of the excavation, as well as the potential collapse of the excavation walls themselves.		excavation and/or the collapse of the excavation walls themselves.
Electrocution risk	This risk involves the correct installation and use of the construction site's electrical system, and possible contact with other existing systems (within structures, underground, aerial), including indirect contact via machinery or tools.	This risk pertains to proper installation and use of the tunnel's electrical system and electric-powered operational equipment (e.g., drills, shotcrete pumps, etc.).	This risk concerns both the proper installation and use of the construction site's electrical system and the potential contact of workers with other existing systems on site (whether underground or overhead), including indirect contact through machinery, equipment, or tools. The risk of electrocution is also present during maintenance activities within the tunnels, arising from the same factors—namely, the proper installation and operation of the electrical system on site,	This risk concerns both the proper installation and use of the construction site's electrical system and the potential for workers to come into contact with other electrical installations on site (whether underground or overhead), including indirect contact through machinery,	This risk concerns both the proper installation and use of the construction site's electrical system and the potential contact by workers with other electrical installations present on site (whether underground or overhead), including indirect contact through machinery,	This risk concerns both the correct installation and use of the construction site's electrical system, and workers' contact with other electrical installations present on site (including within any structures involved in the works, underground or overhead), as well as indirect contact through

			as well as the potential presence of electrical installations inside the tunnel itself.	equipment, or tools.	equipment, or tools.	machinery, equipment, or tools.
Biological risk	The risk is present in site areas located in unremediated, desolate, unhealthy zones, or where wastewater is present.	The risk stems from the presence of pathogens, bacteria, fungi, and viruses in tunnel water, construction materials, or due to insects, parasites, or dust containing pathogens.	The risk is due to the presence of pathogenic agents—bacteria, fungi, viruses—found in water within the tunnels, in the construction materials used, or resulting from the presence of insects, other pests, or dust containing harmful biological agents.	The risk is due to the presence of pathogenic agents—bacteria, fungi, and viruses—contained in construction materials or resulting from the presence of insects or other pests.	The risk is due to the presence of pathogenic agents—bacteria, fungi, and viruses—either contained in construction materials or resulting from the presence of insects or other pests.	The risk is due to the presence of pathogenic agents, including bacteria, fungi, and viruses, which may be found in construction materials or result from the presence of insects or other pests.
Dust and pollutants	The risk arises in external areas where various types of material storage are established (e.g., demolition debris, excavated rock, soil, etc.), or in large construction sites where new internal roadways are constructed using bitumen, asphalt, and similar materials.	This risk is always present in tunnels under construction due to demolition dust and construction materials (e.g., shotcrete).		Present in retaining wall construction activities, caused by demolition and excavation dust and the use of construction materials (e.g., concrete casting).	The risk is present during pile construction activities and is due both to the presence of dust generated by excavation, demolition, and earthworks, and to the use of construction materials (such as during concrete	The risk is present during beam construction activities and arises both from the possible presence of dust generated by demolition and excavation, and from the use of construction materials (such

	It is also present in cases where release agents (formwork oils) are used.				casting operations).	as during concrete casting operations).
Material splashes, sprays, and projections	The risk refers to site cleaning activities, vegetation clearing, concrete casting operations, as well as the demolition of existing structures within the construction site area, or ground consolidation works within the designated site zone.	The risk is present in all activities involving material projections (e.g., concrete casting, shotcrete, compressed air, drilling, excavation, and muck removal).	The risk is present in all activities that may involve material projections, such as concrete casting, operations using compressed air, and drilling activities performed with demolition hammers.	Present in all activities involving possible material splashes, such as concrete casting, excavation, and grass cutting.	The risk is present in all activities that may involve material projections, such as drilling and concrete casting.	The risk is present in all activities that may involve material projections, such as concrete casting or the use of form-release oil.
Chemical risk	Present in all activities involving chemical substances, such as paints, adhesives, solvents, insulating materials, bituminous products, cement dust, etc.	Present in all activities involving chemical substances such as cementitious mortars, adhesives, solvents, insulating materials, etc.				
Asbestos risk	Present in activities involving remediation of asbestos-containing materials					

	(corrugated roofing sheets, pipes, flues, floors, coatings, gaskets, etc.) or excavation in asbestos-bearing rock masses or mountains.					
Asphyxiation			The risk is present in utility tunnels with poor air exchange or where the presence of certain substances leads to oxygen depletion—such as combustion processes releasing carbon dioxide or ammonia, the presence of water (e.g., carbonated water) that absorbs oxygen, or controlled fermentations (e.g., wine, beer, vinegar) and uncontrolled fermentations (e.g., decaying vegetation, waste, etc.).			
Poisoning			Within utility tunnels, there is a risk of poisoning through inhalation and/or dermal contact. This may result from the presence of harmful or			

			toxic gases, fumes, or vapours that are either normally present (e.g., residues in gas storage or transport containers) or may infiltrate from surrounding environments (e.g., carbon monoxide emissions). The risk may also arise from the evaporation of liquids or sublimation of solids that are typically present or that may suddenly release gases when agitated or displaced (e.g., sulfuric acid, hydrochloric acid, solid sulfur). Another contributing factor may be the maceration and/or decomposition of organic matter, leading to the release of biogas.			
Exposure to artificial optical radiation	This risk is linked to welding activities and topographic surveys using laser equipment.	The risk is related to welding operations and laser-based topographic surveying.	The risk refers to welding activities and topographic surveying operations involving laser beams.	Related to welding activities and topographic surveying using laser beams.		The risk refers to welding activities and topographic surveying operations involving the use of laser beams.

Fire risk	The risk is present throughout the site and is exacerbated by the presence of flammable materials and gas cylinder storage.	This risk is always present in tunnels, exacerbated by flammable materials (e.g., timber, waterproofing membranes, PVC piping) and gas cylinder storage.	The risk is consistently present during the construction phase of utility tunnels and is significantly heightened by the presence on site of flammable materials (such as timber, waterproofing membranes, and PVC piping) as well as storage of gas cylinders. During maintenance operations, the risk of fire and explosion is associated with the presence of: • Flammable gases and vapours (e.g., methane, acetylene, propane/butane, xylene, benzene); • Flammable liquids (e.g., gasoline and hydrocarbon-based solvents); • Airborne dust in high concentrations (e.g., flour,	The risk is constantly present and is particularly exacerbated by the presence on site of flammable materials (such as timber, waterproofing membranes, PVC piping, etc.).	The risk is constantly present and is particularly exacerbated by the presence on site of flammable materials such as timber, diesel fuel, and similar substances.	The risk is always present and is particularly exacerbated by the presence on site of flammable materials (such as timber, waterproofing membranes, PVC piping, etc.).
Explosion risk		The risk is inherently present in tunnel environments due to the constant presence of explosive substances, such as combustible dust from construction materials, or the potential presence of natural gas or other flammable substances in gaseous, liquid,				

		or solid form. Another scenario to be considered is that of tunnels where excavation is carried out using explosives.	carbon black, sawdust); • Excess oxygen or other oxidizing agents (e.g., resulting from violent oxidation of greasy/oily substances, or from ammonium nitrate in contact with straw or wood shavings); • Maceration and/or decomposition of organic substances leading to self-heating of the mass up to autoignition temperature; • Ignition sources (as outlined in EN 1127-1:2019)			
Drowning and flooding risk	The risk exists in construction sites located near or within riverbeds, or where dewatering basins and water	The risk exists near or within riverbeds or areas with dewatering basins and				

	treatment systems are installed (e.g., underground/tunnel works).	water treatment systems.				
Vibration	The risk results from the use of vehicles and tools (e.g., vibrators, screwdrivers).	The risk results from the use of vehicles and equipment (e.g. vibrators, screwdrivers)	Caused by the use of vehicles and tools such as vibrators and screwdrivers.	The risk arises from the use of vehicles and equipment (such as concrete vibrators, screwdrivers, concrete pumps, grass trimmers, etc.).	The risk arises from the use of vehicles and equipment (such as concrete vibrators, etc.).	The risk arises from the use of vehicles and equipment, such as concrete vibrators, screwdrivers, drills, concrete pumps, and similar machinery.
Work-related stress	The risk is present in all activities due to tight work schedules, physically demanding conditions, and exposure to chemical agents, vibrations, and noise.	This risk exists in all activities due to tight schedules, physically demanding environments, lack of natural light, dust, chemical agents, vibration, and noise exposure.	The risk is present across all activities due to tight work schedules, physically demanding working conditions, absence of natural light, lack or deficiency of oxygen, and exposure to dust, toxic substances, and biological agents.	The risk is present across all construction activities due to tight work schedules, physically demanding working conditions, and exposure to dust, vibrations, noise, and all other factors typical of the construction sector.	The risk is present across all construction activities due to tight work schedules, physically demanding working conditions, exposure to dust, vibrations, noise, and all other factors typically associated with the	The risk is present in all construction activities due to tight work schedules, physically demanding working conditions, exposure to dust, vibrations, noise, and all other factors typically associated with the

					construction sector.	construction sector.
Noise	Present in all areas where machinery and/or equipment is used.	The risk is present in all areas where machinery and/or equipment is used.	The risk is particularly present during excavation and the installation of prefabricated tunnel elements, especially when earthmoving machinery and lifting equipment are used. However, it is also present during the use of power tools such as drills, screwdrivers, and similar equipment. In general, the risk is present in all areas where machinery and/or equipment is in operation. It may also be present during maintenance activities, depending on the tools and equipment used.	The risk is present during excavation activities and the installation of any prefabricated elements or in-situ concrete casting of the retaining wall; that is, whenever earthmoving machinery, concrete pumps, lifting equipment, etc., are used. It also remains present during the use of equipment such as drills, screwdrivers, grass trimmers, and similar tools.	The risk is present in activities involving the use of the drilling rig (such as drilling, reinforcement insertion, casing removal, etc.), the possible use of compressors, and in concrete casting operations. More generally, it is present in all areas where machinery and/or equipment is used.	The risk is present during beam construction activities, as they involve the use of earthmoving machinery, concrete pumps, lifting equipment, etc. It is also present during the use of equipment such as drills, screwdrivers, concrete mixers, and more generally in all areas where machinery and/or equipment are in operation.

A.2.4 Identification of the safety risks associated with the presence of robots (IRR, SFR) on site

EN_Risk Assessment Sheet for Robot Use.xlsx

Bibliography

[1] EN 547-1, *Safety of machinery — Human body measurements — Part 1: Principles for determining the dimensions required for openings for whole body access into machinery*

[2] EN 547-2, *Safety of machinery — Human body measurements — Part 2: Principles for determining the dimensions required for access openings*

[3] EN 547-3, *Safety of machinery — Human body measurements — Part 3: Anthropometric data*

[4] EN 14844, *Precast concrete products — Box culverts*

[5] EN ISO 15535, *General requirements for establishing anthropometric databases*

[6] EN ISO 15537, *Principles for selecting and using test persons for testing anthropometric aspects of industrial products and designs*

[7] EN ISO 10218-1, *Robotics — Safety requirements — Part 1: Industrial robots*

[8] EN ISO 10218-2, *Robotics — Safety requirements — Part 2: Industrial robot applications and robot cells*

[9] EN ISO 20471, *High visibility clothing — Test methods and requirements*

[10] ISO/TS 15066, *Robots and robotic devices — Collaborative robots*

[11] ISO/PAS 5672, *Robotics — Collaborative applications — Test methods for measuring forces and pressures in human-robot contacts*

[12] NIOSH NO 80-106, *Working in confined spaces*

[13] OSHA Standard 1926.1207, *Safety and Health Regulations for Construction — Confined Spaces in Construction — Training*

[14] EN 1127-1:2019, *Explosive atmospheres — Explosion prevention and protection — Part 1: Basic concepts and methodology*