Master Of Science Program In Civil Engineering
Collegio di Ingegneria Civile

Thesis Title

BIM And GIS In Predictive Maintenance of Tunnel

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July 2025

“Thanks to the guidance of my professors and the tools I’ve learned to use, I can now approach complex problems in integrating BIM and GIS with confidence, which is exactly what an innovative engineer should strive for”

Mohamad KARZOUN

Acknowledgement

First, I would like to express my heartfelt gratitude to my supervisors, Prof. Anna OSELLO and Eng. Nicola RIMELLA, for their invaluable guidance, encouragement, and support throughout this thesis. Their expertise and feedback have been instrumental in shaping my work and keeping me on track.

I am also deeply thankful to the faculty of the Department of Structural, Geotechnical, and Building Engineering (DISEG) for their academic guidance and insightful input, which greatly enriched this research. Additionally, I extend my sincere appreciation to TECNE company for providing the case study of the tunnel and the necessary data, which were crucial for completing this thesis.

To my family my mother, my father, Lina, Firas, Bashar, and my relatives thank you for your unconditional love and encouragement. You were my strength during moments of doubt, always reminding me to keep going. I hope this accomplishment makes you proud.

Special thanks to my friends and colleagues for their constant support, advice, and motivating discussions. Your encouragement has been a source of inspiration and positivity throughout this journey.

Finally, I am grateful to everyone who contributed in any way to this project. Your support has been invaluable, and this achievement is as much yours as it is mine.

Abstract

BIM and GIS are powerful tools in modern engineering, particularly when applied to predictive maintenance of infrastructure. This thesis explores the integration of these technologies to enhance the management and upkeep of linear infrastructure, with a focus on a case study involving an Italian tunnel.

Starting from a detailed BIM model, we evaluated its compatibility with a range of GIS and BIM platforms including InfraWorks, Blender, Cesium Ion, and ArcGIS Pro. Each platform contributed distinct features that enabled the extraction and visualization of precise, high-resolution data regarding the tunnel structure and its surrounding terrain. The integration of geospatial data with GeoBIM highlights the potential of combining geographic information with building information models to support predictive maintenance planning. This approach enables a more informed and proactive asset management strategy by embedding real world spatial context into infrastructure monitoring and decision-making processes. A key technical challenge addressed in this study was georeferencing ensuring that data from various sources align within the same coordinate system. To manage this, the IFC format was used to standardize data exchange and promote interoperability across platforms.

ArcGIS Pro was employed to produce essential geological representations, including slope, hillshade, and aspect maps, which enriched our understanding of the tunnel's environmental setting. To further enhance the analysis, we developed a 3D geological model of the area surrounding the tunnel. This model enabled a preliminary classification of soil types and allowed us to spatially correlate geotechnical properties with tunnel design data. By merging geological data with the GeoBIM, we were able to assess the attention or risk classification of individual tunnel segments, laying the groundwork for a more targeted and informed predictive maintenance strategy.

This work underscores the potential of BIM-GIS integration in tunnel infrastructure, not only by demonstrating practical benefits but also by identifying current limitations. Through this approach, we aim to support more intelligent, efficient, and data-driven decision-making in the future of infrastructure management.

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List of Acronyms

Acronyms	Definition
BIM	Building Information Modelling
GIS	Geographic Information System
IFC	Industrial foundation Class
RVT	Autodesk Revit file format
DEM	Digital Elevation Model
AEC	Architecture, Engineering, and Construction
SHP	Shapefile
DAE	Digital Assest Exchange
CdA	Attention Class
BoD	Degree of Danger
CCR	Curvature Change Rate
IRI	International Roughness Index
IBM	International Business Machines
ATMs	Automated Teller Machines
PdM	Predictive Maintenance
MVD	Model View Deinition
VGI	Volunteered Geographic Information
IOT	Internet of things

1. Introduction

One of the key technologies in the architectural, engineering, and construction sectors is building information modeling, or BIM. BIM was first presented as a digital tool to enhance the precision and coherence of design documentation, but it has undergone substantial development over time. BIM has evolved from its inception as a technique to lower construction drawing errors to become a powerful platform for overseeing the lifecycle of infrastructure projects. Advanced applications including risk analysis, resource management, and sustainability planning are now supported. BIM's capacity to centralize data and promote cooperation among interdisciplinary teams has proved crucial in increasing productivity and cutting expenses in large-scale infrastructure projects, such as tunnels (Eastman et al., 2008) .

GIS has also experienced amazing evolution. GIS was first created as a tool for digitizing conventional maps, but it has since grown into a flexible technology that combines analytical tools with spatial data. GIS has developed throughout time to manage large datasets, allowing for intricate terrain modeling, spatial analysis, and visualization. Its uses in tunnels and other infrastructure projects are priceless because they offer vital information on geotechnical hazards, terrain variability, and environmental conditions (Hedayatzadeh et al., 2020).

Infrastructure management has advanced significantly with the combination of BIM and GIS, which provides a single platform that blends spatial intelligence and comprehensive asset data. In tunnel projects, where exact spatial alignment and thorough data management are essential, this integration is especially crucial. Throughout a tunnel's lifecycle, BIM and GIS integration enables better planning accuracy, real-time monitoring, and more informed decision-making by utilizing the advantages of both systems.

In this work we focus on BIM GIS can use for. Over time, tunnels may experience wear and tear due to a range of loads, such as environmental factors and geological pressures. Infrastructure managers can use data-driven insights to identify possible problems via predictive maintenance, which integrates BIM and GIS. The operating life of tunnel structures is increased, critical breakdowns are avoided, and maintenance tasks are optimized thanks to this proactive approach.

The first step in successfully integrating BIM and GIS into tunnel projects involves acquiring data. The initial phase in this process is creating a 3D BIM model, which forms the project's core dataset. Several platforms and tools with a focus on BIM and GIS are needed to create the model. To find the best tools for organizing and evaluating the data, these platforms must be tested once it has been gathered. This guarantees the reliability and efficiency of the integration process.

According to (buildingSMART, 2024) the application of IFC is a crucial step in this integration process. To facilitate the smooth movement of BIM models between platforms without sacrificing important data, IFC was created as an open standard. By offering a common protocol for data exchange, it guarantees compatibility and enables the integration of BIM models into GIS operations. In this procedure, MVDs are crucial because they specify the precise subsets of IFC data needed for certain use cases, guaranteeing that only pertinent data is exchanged.

Another essential data for tunnel projects is a geological map. For the safe and effective building of tunnels, these maps offer comprehensive information on subsurface features such as fault lines, rock forms, and groundwater levels. Geological maps help engineers better comprehend terrain characteristics and foresee difficulties during excavation and building by adding information like as slope, hillshade, and aspect.

With a focus on a real tunnel case study, the major goal of this thesis is to examine how BIM and GIS might be integrated for predictive maintenance in infrastructure projects. The goal of this study is to address problems including data conversion, georeferencing, and interoperability across different BIM and GIS software platforms. The research guarantees that all crucial parameters are maintained throughout data sharing by employing the IFC standard, facilitating smooth cooperation and precise geographical representation. Additionally, tunnel segments are categorized into attention classes ranging from low to high risk using a risk analysis approach customized to Italian maintenance rules. GIS software is used to depict these classifications to give maintenance planning decision-makers a spatial context. The goal of this effort is to create a thorough framework that improves predictive maintenance processes and infrastructure management tactics by utilizing BIM and GIS technologies.

In addition to that, the scope involves providing Autodesk Revit 3D BIM model of the Tunnel and combining it with several GIS programs, including InfraWorks, Cesium Ion, ArcGIS pro, and Blender. Key technical issues like georeferencing and preserving data integrity during software changes are the focus of the integration process. Slope, hillshade, and aspect maps are examples of geological maps that are created to facilitate future tunnel construction and offer insights into the surrounding environment. In the thesis, danger levels are also categorized using a risk analysis methodology that complies with Italian maintenance criteria. These classifications are then visualized in GIS platforms to aid in spatial decision-making.

The oversight of tunnel infrastructure can be revolutionized by combining BIM, GIS, and geological mapping. This thesis offers a dependable and effective framework for handling the complexity of contemporary tunnel projects by adhering to a systematic procedure of data collecting, platform evaluation, and utilizing open standards like IFC. This thorough approach improves long-term infrastructure sustainability, optimizes maintenance procedures, and guarantees safe and effective tunnel construction.

2. Literature Review

2.1. Predictive Maintenance Definition

PdM is a proactive strategy that leverages data analytics, machine learning, and real-time monitoring to anticipate equipment failures before they occur. Unlike traditional maintenance methods such as reactive maintenance, which only responds after failure, or preventive maintenance, which relies on scheduled interventions regardless of asset condition, PdM ensures that maintenance activities are performed precisely when needed. This targeted approach enhances operational efficiency, optimizes resource utilization, and extends the lifespan of infrastructure assets (IBM, 2023).

A successful PdM program depends on the continuous monitoring of key performance indicators that reflect asset health, including electrical signals, lubricant quality, acoustic emissions, temperature fluctuations, and vibration patterns. Systematic tracking of these parameters allows maintenance teams to establish performance baselines and quickly identify deviations that suggest emerging issues, thereby enabling timely and focused interventions that prevent costly downtime and improve system reliability (Molęda, 2023).

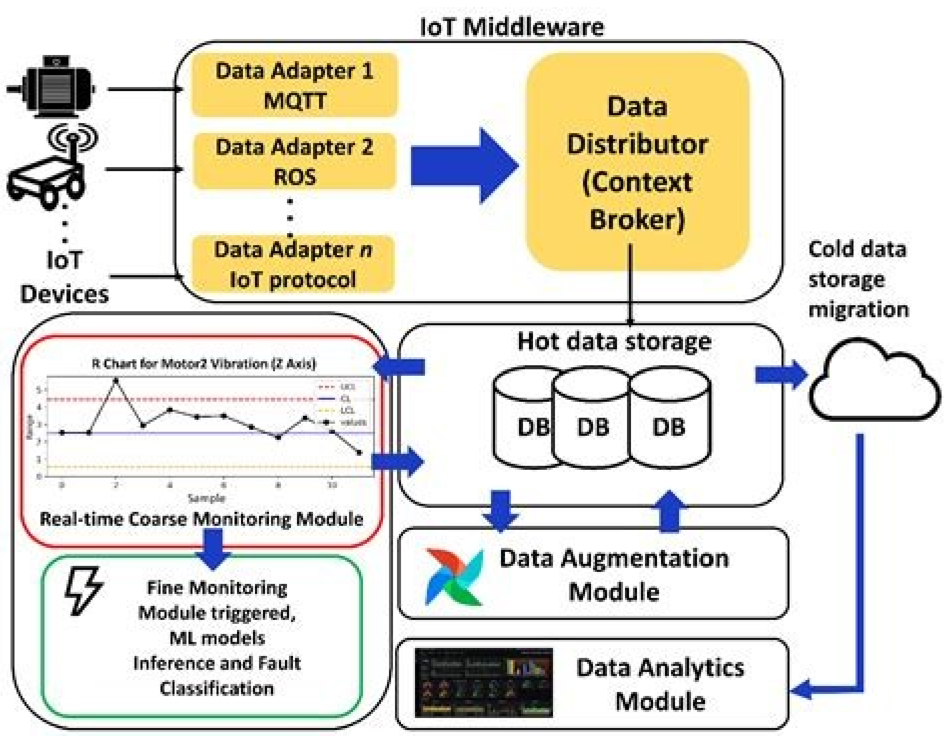

Figure 1. Example dashboard displaying monitored KPIs such as vibration and lubricant temperature (Molęda, 2023)

Figure 1 below highlights the progression from unprocessed sensor data to intelligent fault classification in a tiered IoT-based predictive maintenance system. A central data distributor receives data from a variety of IoT devices connected by different protocols. This makes it possible to combine disparate devices into a single monitoring system with ease. A real-time coarse monitoring module (as seen in the embedded R chart example) continuously scans for abnormalities such unusual vibrations after data is first stored in hot databases for real-time access. More sophisticated machine learning models for fault classification are activated by a fine monitoring module once it is triggered. This structure is especially important for vital tunnel or bridge parts, such as expansion joints or ventilation motors, where ongoing observation is required to identify departures from the norm. To improve scalability and operational efficiency, the system also has analytics and data augmentation modules for managing long-term performance data through cold storage migration and improving forecast accuracy.

As a condition-based methodology, PdM uses predictive analytics to determine the optimal time for service, based on asset behavior rather than arbitrary schedules. (Małysiak-Mrozek , 2023) highlights that it combines historical performance data with real-time sensor feedback to forecast failures and refine maintenance planning, ultimately reducing both planned and unplanned outages. Figure 2 shows the data flow for predictive maintenance in its entirety, starting with real-time data collecting from industrial sensors and progressing through analytics, storage, and visualization. Technical workers are then warned by the system through regular notifications and emergency alerts. This modular flow emphasizes how crucial it is to combine automatic alert systems and condition monitoring, which is particularly pertinent for managing vital infrastructure like bridges and tunnels. For example, before they approach safety thresholds, abnormal strain gauge deformation readings or fan motor vibration signals may automatically initiate maintenance interventions. The graphic illustrates how PdM improves reactivity and resilience across asset management workflows by fusing responsive alerting systems with live data management.

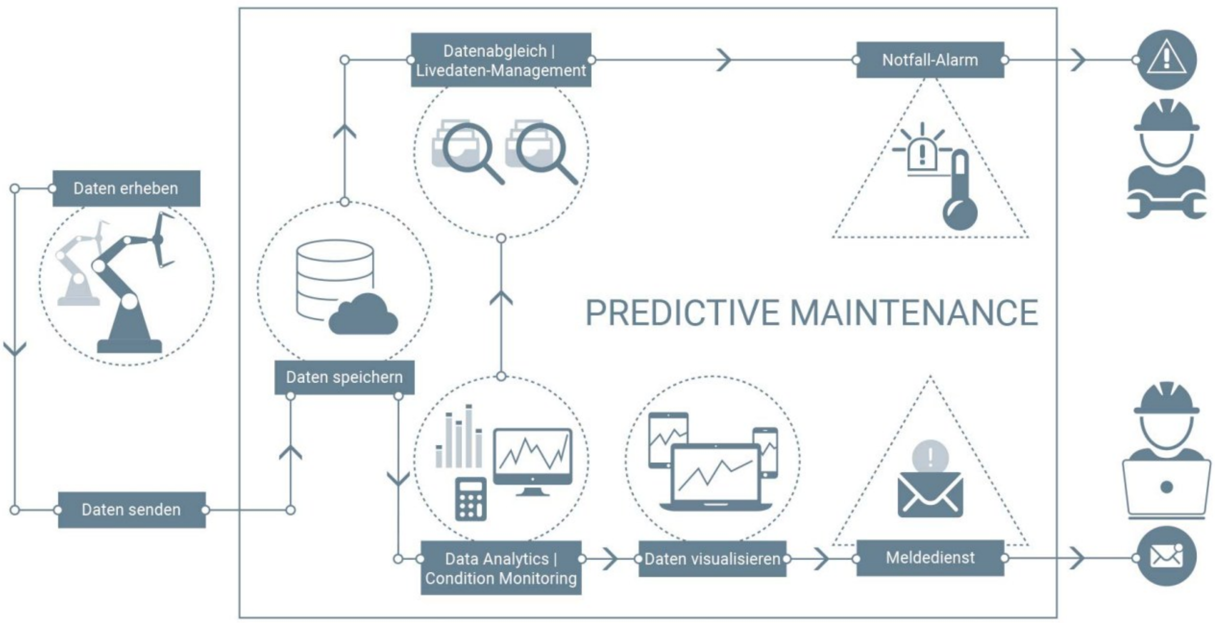

Figure 2. Real-time data acquisition and decision-making architecture (Małysiak-Mrozek , 2023)

Similarly described PdM as a risk-based framework that identifies failure patterns, such as in gas distribution networks, to support proactive repair and replacement strategies before service disruptions occur. In the context of large-scale infrastructure, this predictive approach significantly enhances operational dependability and reduces interruptions. Beyond traditional applications, PdM is also critical in facility management, where it helps prevent costly breakdowns through early detection techniques (Betz et al. , 2022).

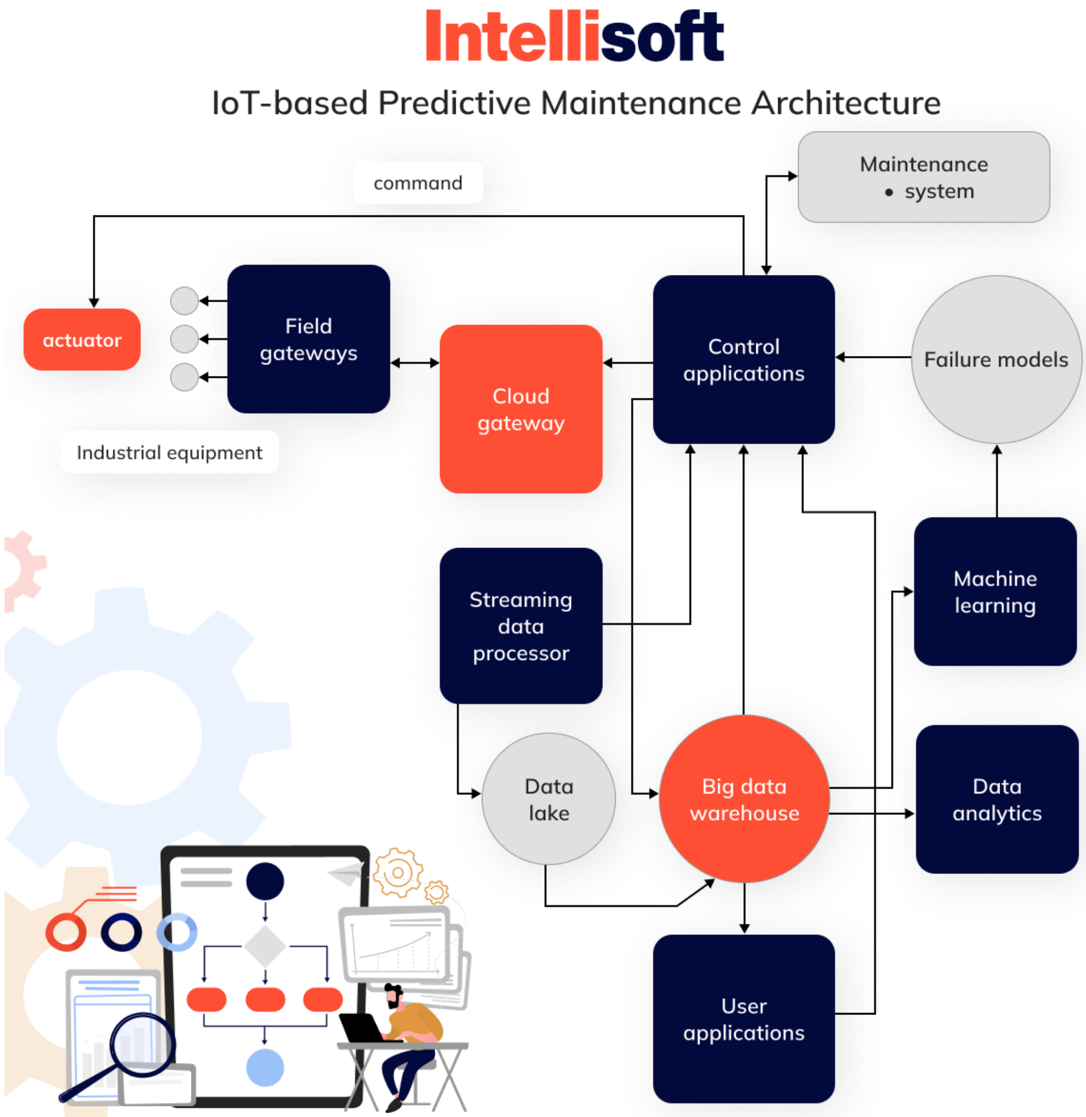

Figure 3. PdM architecture using machine learning and risk modeling for infrastructure systems (Betz et al. , 2022)

Figure 3 shows the data flow from industrial equipment to actionable insights via a full IoT-based predictive maintenance infrastructure. Raw sensor data is sent to a large data warehouse via a streaming processor and data lake, beginning with field gateways and cloud gateways. Control applications then work with failure prediction algorithms and machine learning models to provide condition-based commands that are fed back into the maintenance system. This graphic illustrates how PdM systems transform unprocessed asset data into predictive diagnostics by combining IoT, real-time analytics, and AI. Because high-frequency data (such as vibration, temperature, and deformation) may be systematically processed to prevent failures and improve intervention time, such systems are particularly pertinent to tunnel and bridge infrastructure.

However, PdM enables facility managers to leverage real-time sensor data to anticipate infrastructure failures and take preemptive action, thereby increasing resilience and minimizing operational disruptions (Robertson, 2023). this perspective reinforces by describing PdM as a combination of sensor-driven monitoring and predictive algorithms that improve the efficiency of both planned and emergency maintenance (Decaix et al., 2021). With ongoing advancements in artificial intelligence and machine learning, PdM is becoming increasingly intelligent and adaptive define PdM as an AI-powered suite of tools that enhances system reliability, reduces maintenance costs, and mitigates safety risks through sophisticated failure prediction and asset condition forecasting, ensuring higher uptime and extending the operational life of critical infrastructure. (Cummins et al. , 2024).

2.2. IOT Definition

A network of physically connected objects with sensors, software, and communication technologies that allow them to gather, send, and share data in real time is known as the Internet of Things. These gadgets, which may all monitor characteristics like temperature, vibration, pressure, or humidity, range in complexity from basic sensors to sophisticated industrial gear.

IoT is revolutionary in predictive maintenance since it continuously monitors the state of infrastructure and assets. IoT systems provide early detection of anomalies or wear indicators through real-time data gathering and transmission, allowing maintenance teams to act before breakdowns arise. This prolongs the life of vital infrastructure elements while also increasing operational effectiveness and decreasing downtime.

IoT further improves the spatial awareness of maintenance methods when combined with technologies like GeoBIM and geospatial analytics. To provide more accurate and timely maintenance interventions, sensor data can be mapped and examined within the structural and spatial context of a building or infrastructure asset.

2.3. Historical Data in Predictive Maintenance

Predictive maintenance plays a crucial role in the sustainability and operational efficiency of tunnel infrastructure. A key component of this approach is the analysis of historical data, which provides insights into asset performance, failure trends, and maintenance requirements. By systematically reviewing past operations logs, engineers can anticipate potential failures, optimize maintenance schedules, and enhance the reliability of tunnel structures and systems. Historical data analysis has been widely recognized as a fundamental strategy in infrastructure management. Importance of reviewing tunnel operation logs to extract valuable information that supports predictive maintenance planning, highlighting how analyzing previous maintenance records enables engineers to foresee future issues and develop more efficient maintenance strategies (Tichý et al. , 2021). Similarly, that failure data is essential for optimizing maintenance schedules, as each maintenance activity produces large volumes of raw data that can be leveraged to improve the reliability of engineering assets. This integration of historical data is particularly beneficial in tunnel infrastructure, where proactive strategies help reduce disruptions and extend asset lifespan (Endrenyi et al. , 2001).

This by analyzing three tunnels in Ilam Province, showing how lifecycle data including defect records, repair history, and maintenance actions can inform strategic rehabilitation plans. Their findings demonstrate that identifying recurring failure points allows for timely interventions, lowering long-term costs and enhancing durability (Moradi et al. , 2021). Figure 4 illustrates a deterioration-cost modeling technique that creates optimal maintenance plans by combining past inspection data, repair schedules, and financial limitations. Infrastructure component condition evaluation and indexing are the first steps in the process. These data are then entered into a degradation model to project future repair requirements and related expenses. The system assesses many strategies (A, B, and C) and models their results over time based on several goals, such as reducing injuries, maximizing funds, or prioritizing evacuation routes.

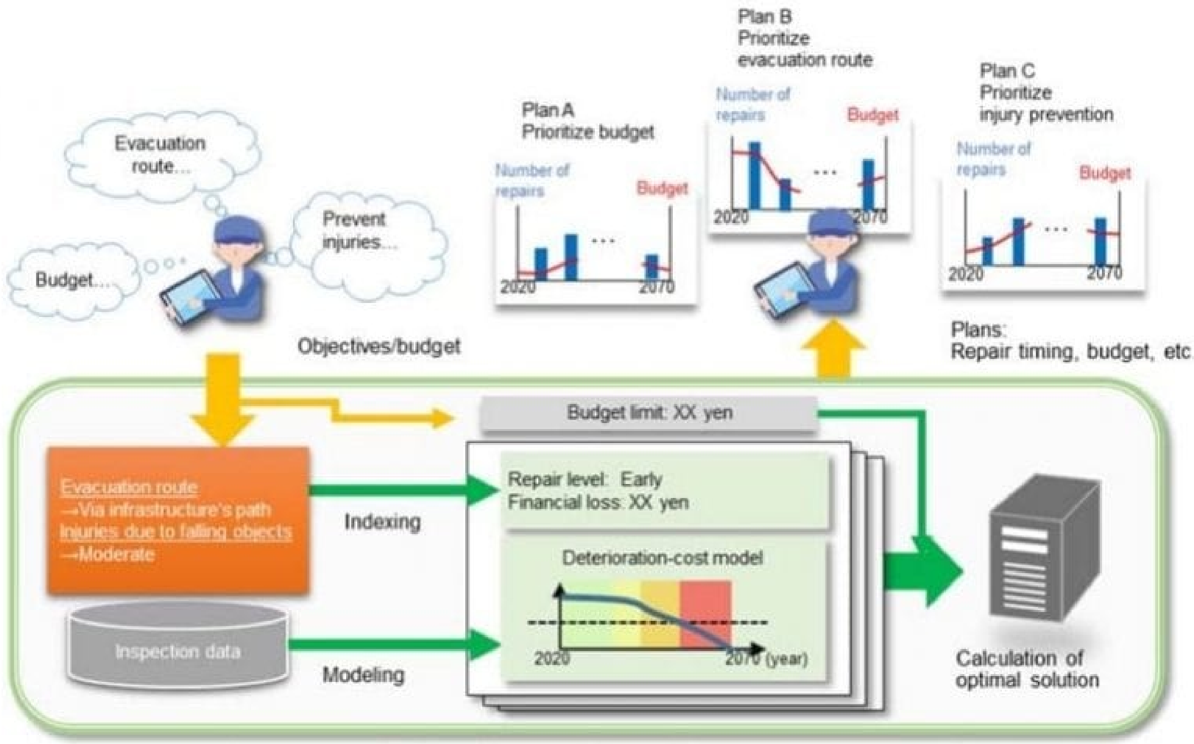

Figure 4. Lifecycle mapping of recurring tunnel defects used to schedule proactive maintenance interventions (Moradi et al. , 2021)

A more specialized application of predictive maintenance in tunnel systems is evident in ventilation management. Decade of maintenance data from Stockholm's highway tunnels to optimize fan replacement schedules, identifying patterns in repair costs and failure frequencies to develop a cost-effective maintenance plan that reduces service interruptions while maintaining safety . Their work also extended to structural monitoring in railroad tunnels, using an image-based method to document deformations and compare them with historical geometric data. Their results reveal that even slight deviations from baseline measurements can act as early indicators of structural deterioration, enabling timely maintenance actions that enhance safety and prolong the lifespan of tunnel infrastructure. The value of historical data in predictive maintenance also extends beyond tunnel systems. Figure 5 shows how a variety of sensor data, including vibration, temperature, pressure, and acoustic signals, are gathered and sent in real time to an analytics dashboard as part of predictive maintenance. The ongoing evaluation of asset health made possible by this integration makes it possible to make prompt and well-informed maintenance decisions. The graphic highlights the conversion of unprocessed information into comprehensible performance indicators, which is consistent with the condition-based maintenance techniques covered in this section (Hassan et al. , 2020).

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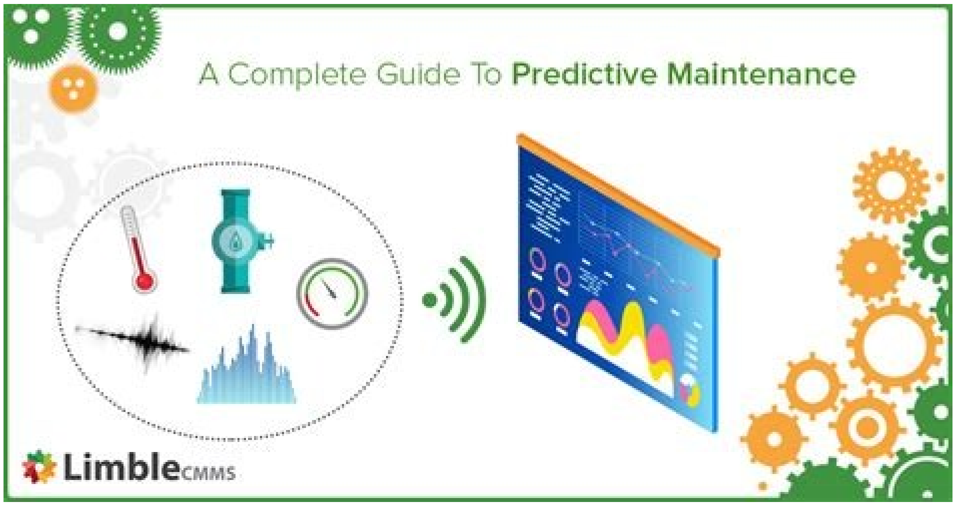


Figure 5, Predictive maintenance analysis for tunnel ventilation fans—correlating failure frequency with cost to define optimal replacement timing (Hassan et al. , 2020)

A study conducted using event logs from a fleet of 156 ATMs, developing a predictive maintenance strategy in environments where sensor data was unavailable. Although the context differs, the methodology underscores the broader applicability of historical data analysis as a powerful tool for anticipating failures and preventing equipment breakdowns across various infrastructure sectors (Guillaume et al. , 2020).

2.4. Definition of BIM

BIM is a digital approach to designing, constructing, and managing infrastructure and buildings. It enables the creation of a comprehensive virtual model that integrates geometric, spatial, and attribute data, facilitating collaboration across different disciplines in the AEC industry. BIM as a highly advanced technique for digitally simulating architectural and environmental systems while incorporating extensive data on their characteristics and behavior. Unlike traditional 2D drafting, BIM encodes each building component with parametric rules and data properties, effectively functioning as a centralized database for efficient project management (Tardif, 2009).

One of the foundational works on BIM was conducted, who explored its significance as a transformative tool in the AEC industry. Their research laid the groundwork for BIM adoption in large-scale projects, demonstrating how it enhances collaboration, reduces design errors, and improves construction efficiency (Eastman et al., 2008).

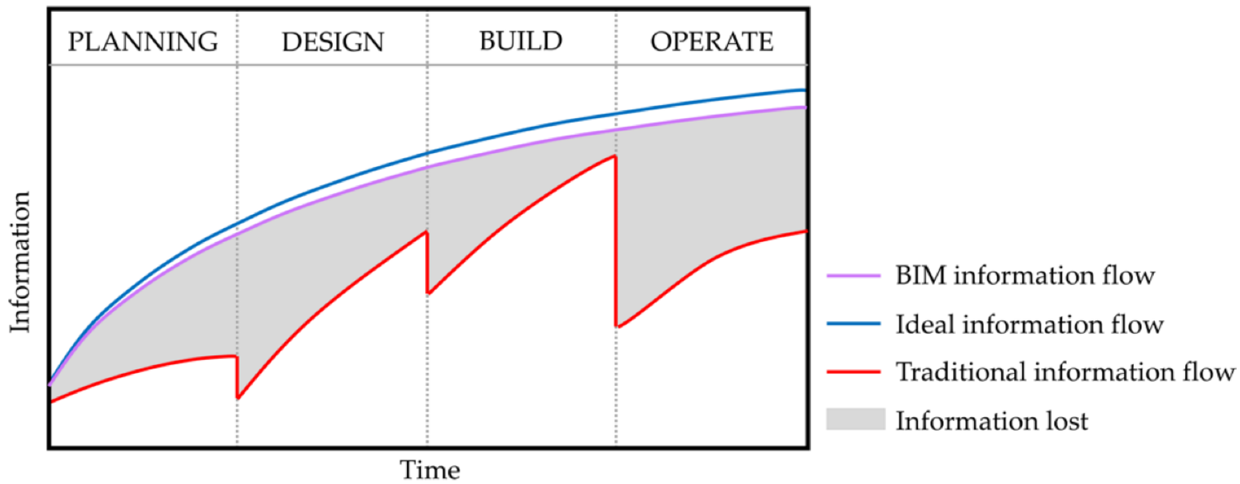


Figure 6. information loss and flow in traditional vs. BIM-based workflows (Eastman et al., 2008)

The previous illustration figure 6 shows how information flows and loss vary between traditional workflows and BIM during a project. introduced this idea in the BIM Handbook, pointing out that conventional project delivery techniques frequently lose data during phase changes. The shaded grey area on the red line symbolizes the conventional information flow, which is frequently fractured and results in severe data loss. The BIM-enabled information flow, on the other hand, is represented by the purple line. This information flow ensures data integrity and continuity throughout the planning, design, construction, and operation phases. A perfect, continuous data flow is depicted by the blue line. The importance of BIM in reducing loss of information, fostering teamwork, and increasing lifecycle efficiency is highlighted in this graphic (Eastman et al., 2008).

The integration of BIM has since evolved beyond design documentation, extending into lifecycle management and infrastructure maintenance. For instance, examined BIM's application in existing buildings and identified its potential for facility refurbishment and lifecycle management. Their study highlighted that BIM can efficiently store and manage

as-built data, making it a valuable tool for projects requiring frequent maintenance and upgrades (Volk, Stengel, and Schultmann , 2014).
Furthermore, the adoption of BIM varies across organizations, in his BIM maturity model. This model defines the stages of BIM implementation within organizations, ranging from initial awareness to full integration into business processes. The model is widely used to assess an organization's readiness to implement BIM, particularly in complex projects where interoperability and data integration are critical (Succar , 2009).
In infrastructure projects, BIM's ability to incorporate both structural and environmental data makes it an essential tool for sustainability and risk management. BIM's role analyzed in infrastructure development, emphasizing its effectiveness in evaluating environmental influences on tunnels and other structures over time. Their study demonstrates how BIM can be used for predictive analysis, assessing potential geotechnical hazards, and ensuring long-term structural stability (Liu et al. , 2017).
Beyond its technical capabilities, BIM also plays a crucial role in decision-making across the project lifecycle. The primary objective of BIM is to generate actionable data that aids in informed decision-making and optimizes facility management. By offering tailored insights to different stakeholders whether to assess design alternatives, evaluating constructability, estimating costs, or enhancing facility operations, BIM fosters a collaborative decision-making environment that improves overall project performance (Mills , 2023).
BIM has emerged as a transformative tool in the AEC industry, addressing long-standing challenges such as miscommunication among stakeholders, inefficient workflows, and escalating project costs. By centralizing project data and integrating 3D parametric models, BIM facilitates seamless coordination and information sharing among architects, engineers, contractors, and facility managers.

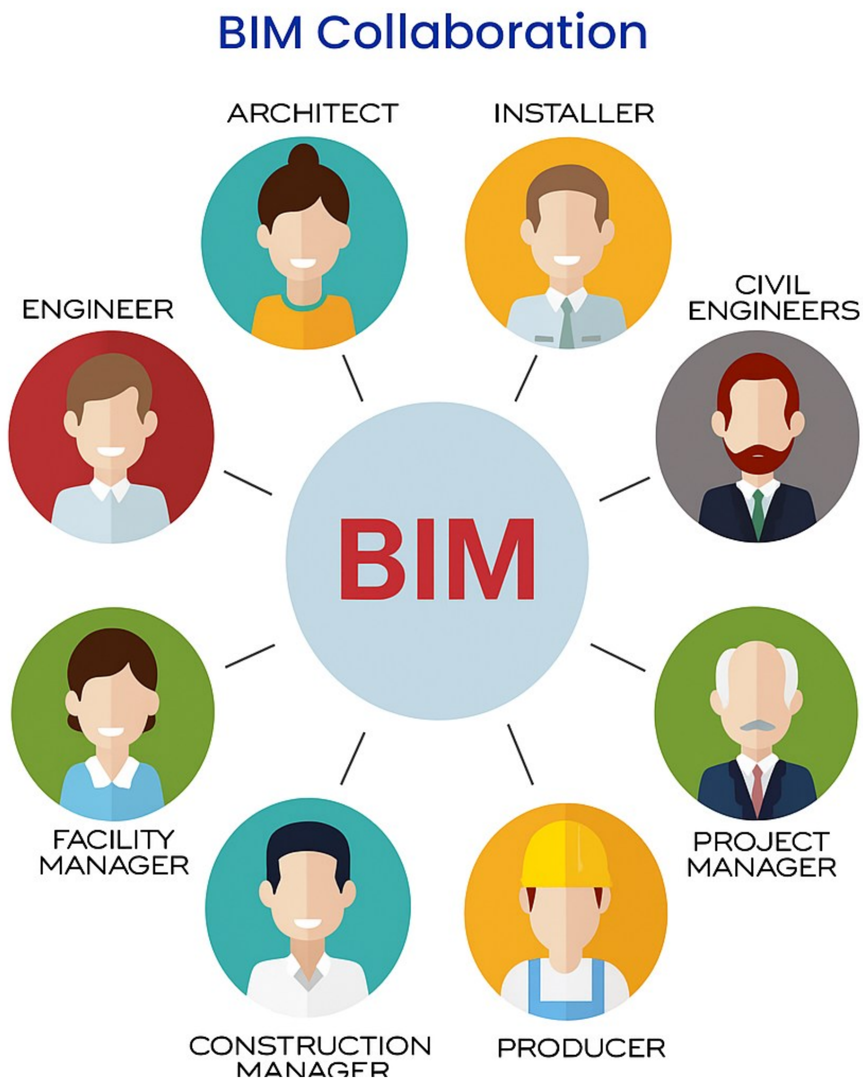


Figure 7. AEC Collaborators (Lu, Zhang, & Rowlinson, , 2013)

This collaborative approach shown in figure 7 enhances decision-making processes, reduces errors, and fosters synergy between project participants, ultimately streamlining construction workflows and improving overall project outcomes (Lu, Zhang, & Rowlinson, , 2013)..

Over the past decade, BIM has gained widespread recognition for its potential to optimize construction processes and drive industry-wide innovation highlights how BIM transforms conventional construction methods by minimizing errors and increasing operational efficiency. As a result, the AEC sector has increasingly adopted BIM, recognizing its ability to streamline project execution and improve cost management.

Beyond efficiency, BIM plays a crucial role in risk reduction and productivity enhancement (Azhar, 2011). BIM not only enhances collaboration but also mitigates construction risks and improves productivity. Their study underscores BIM's potential to revolutionize the construction industry, even as challenges such as high implementation costs and resistance to change continue to pose obstacles to widespread adoption. (Olatunji, Sher, and Gu , 2010).

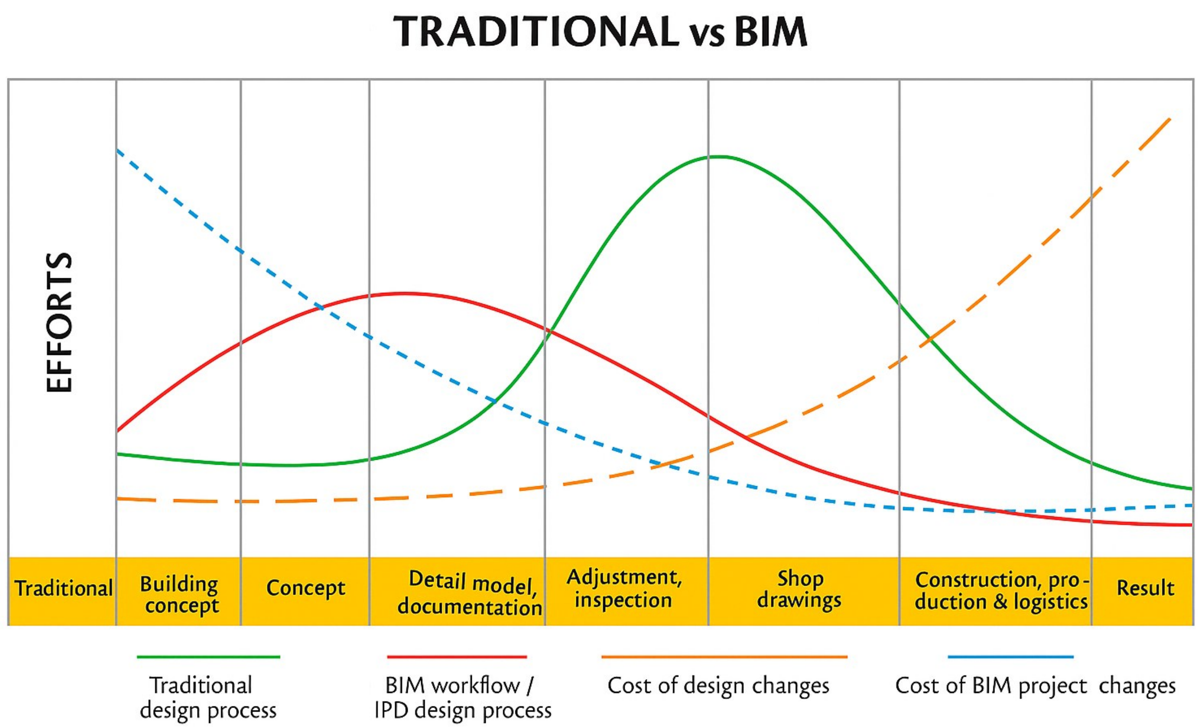


Figure 8. traditional versus BIM-based workflows across a project timeline (Olatunji, Sher, and Gu , 2010)

The figure above shows how, in contrast to the traditional approach, where most of the effort and risk accumulates during construction, BIM frontloads design effort early in the project, avoiding the need for expensive revisions later. While the green line (conventional) climbs during later stages, the red line (BIM) indicates early investment in modeling and coordination. The dashed lines demonstrate that design modifications in BIM are less expensive over the course of the project, confirming the efficiency and risk-reduction advantages of BIM as reported by (Olatunji, Sher, and Gu , 2010).

As BIM adoption continues to grow, it is increasingly being recognized as a strategic asset that facilitates data-driven decision-making, improves project coordination, and enhances construction efficiency. While challenges remain, its ability to transform traditional construction methodologies into more integrated and streamlined processes makes it an indispensable tool for the future of the built environment.

2.5. Definition of GIS

GIS has undergone significant evolution due to advancements in science and technology, transforming from a simple mapping tool into a multidisciplinary field known as GIScience. Emphasizing the role of GIS in processing, storing, managing, and analyzing geographical data. Over time, GIScience has expanded beyond traditional cartography and spatial analysis to encompass a broad range of applications in public health, environmental management, urban planning, and disaster response. This evolution underscores the growing importance of GIS in solving complex spatial challenges across diverse fields (Goodchild , 1992).

The foundational understanding of GIS as a spatial analytical technology was further highlighted its significance in handling and interpreting geographic data. Their work laid the groundwork for GIS applications across multiple sectors, demonstrating their versatility in managing and analyzing spatial datasets (Fotheringham and Rogerson , 1994)

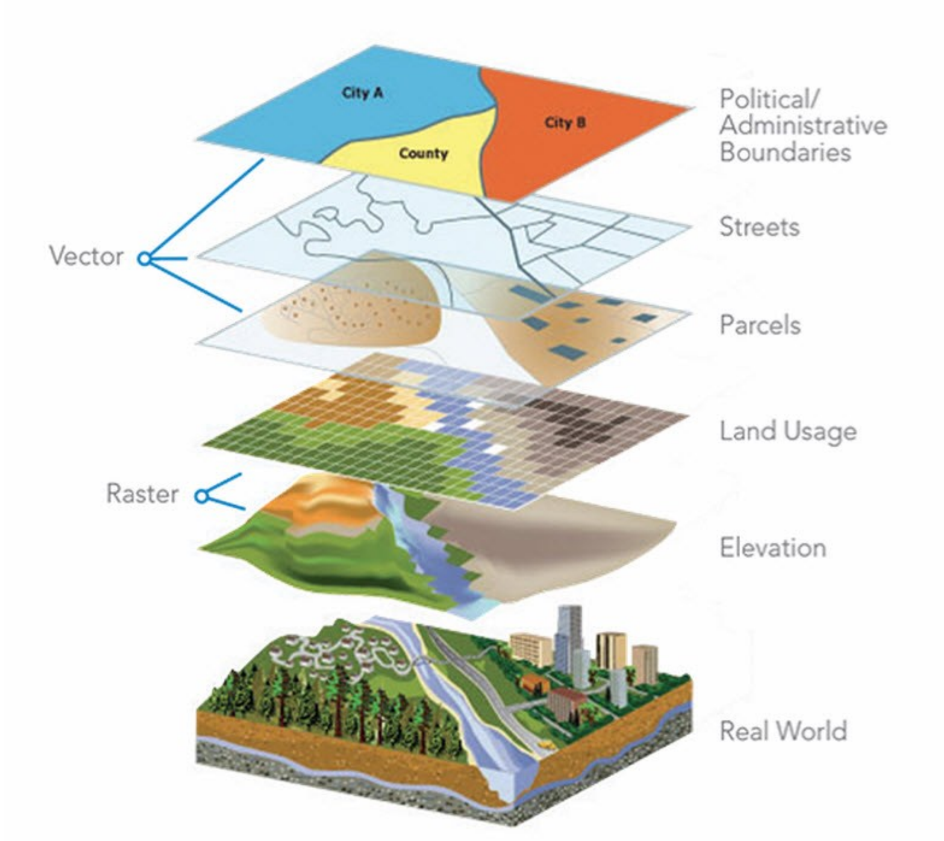


Figure 9. Conceptual structure of GIS (Fotheringham and Rogerson , 1994)

Figure 9 illustrates the core conceptual model of how GIS organize spatial data into thematic layers, each representing different aspects of the real world. It visually aligns with the ideas presented by (Fotheringham and Rogerson , 1994) in Spatial Analysis *and GIS*, who emphasized GIS as a framework for managing and analyzing spatial data in structured, interpretable forms.

Breakdown of Each Layer:

1. Political/Administrative Boundaries

   Represents city or county borders using vector data (points, lines, polygons).

2. Streets

   Linear features used for network analysis (e.g., routing, traffic flow).

3. Parcels

   Represents property boundaries or land parcels, fundamental in land-use planning, taxation, and urban analysis.

4. Land Usage

   Shows land classification (e.g., agriculture, residential, industrial) via pixelated raster data.

5. Elevation

   Represents terrain data in a continuous raster grid (e.g., DEMs—digital elevation models).

6. Real World

   The bottom layer anchors all the abstracted spatial representations to actual geography—what's physically observable.

Similarly, the integration of GIS in public health, showcasing its capability to visualize and analyze spatial trends related to disease outbreaks, healthcare accessibility, and epidemiological patterns. Their research demonstrated the adaptability of GIS and its potential for cross-disciplinary integration with emerging technologies, (Nykiforuk and Flaman , 2011).

Despite its advancements, GIS faces challenges in data quality and reliability, particularly with the rise of VGI. emphasizing the importance of ensuring accuracy and dependability in geographical datasets, which is especially critical for infrastructure projects and decision-making in spatial planning. Their study provided strategies for improving data validation techniques, ensuring that GIS applications maintain high standards of precision and reliability (Fonte et al. , 2019).

Figure 10. Geographic Information System components (CARMATEC, 2023)

The diagram represents in Figure 10 the five key components of GIS, which work together to enable efficient collection, analysis, management, and presentation of spatial data. Each component plays a vital role in the functionality and success of GIS applications (CARMATEC, 2023)**.**

- **Hardware**: The physical equipment needed to interpret spatial data and execute GIS software is referred to as hardware. Computers, servers, GPS units, and other accessories like plotters and scanners fall under this category. GIS users may effectively manage massive datasets, carry out intricate studies, and visualize spatial information in 2D and 3D environments thanks to advanced hardware.

- **Software:** Any GIS system's foundation is its software, which offers capabilities for data input, storage, analysis, and display. Platforms such as ArcGIS, QGIS, and MapInfo are a few examples. GIS software enables users to make maps, simulate real-world situations, and conduct spatial analysis. It is essential for disaster response, environmental management, and urban planning since it combines data from various sources to produce insightful conclusions.

- **Data:** is the backbone of GIS, consisting of spatial (geographic locations) and non-spatial (attributes) information. Spatial data includes coordinates, boundaries, and shapes, while non-spatial data provides context, such as population statistics or land use types. The quality and accuracy of data significantly affect the reliability of GIS outputs. Sources of GIS data include satellite imagery, aerial photographs, surveys, and governmental databases.
- **People:** GIS systems are operated by people, who are also the experts and users who interpret data and use insights to solve issues. These include environmental scientists, urban planners, cartographers, and GIS analysts. Accurate data entry, appropriate analysis, and efficient use of GIS tools to solve real-world problems depend on skilled staff. GIS outputs are also used by decision-makers to inform their planning and policy decisions.
- **Methods:** The workflows and procedures that direct the usage of GIS data and technologies are referred to as methods. These include methods for gathering, storing, and analyzing data as well as creating models and algorithms to address spatial issues. Repeatable and precise analyses are made possible by standardized procedures, which provide consistency and dependability in GIS outputs.

GIS plays a crucial role in the management and analysis of geospatial data, also referred to as geodata. This data encompasses various elements such as water systems, vegetation coverage, elevation levels, land use patterns, and transportation networks. By integrating and visualizing these datasets, GIS enables users to analyze spatial relationships, optimize decision-making, and facilitate global accessibility of geographic information (Bishr, 1998). However, despite its widespread use, a significant challenge arises when geodata is stored in non-machine-readable formats, such as local data catalogs, manuals, or proprietary file structures. This lack of standardization creates compatibility issues, making it difficult to share and integrate geospatial information across different GIS platforms.

To address these challenges, the concept of semantic interoperability has been developed. Semantic interoperability ensures that GIS platforms can communicate effectively, allowing for the seamless exchange of geospatial data across different systems while preserving its meaning and usability. By standardizing geospatial terminology, metadata structures, and encoding formats, this approach facilitates data integration and enhances GIS functionality in multidisciplinary applications (Bishr, 1998).

The importance of semantic interoperability in overcoming barriers to GIS data exchange. Their research highlights that by enabling automated and meaningful communication between GIS platforms, semantic interoperability significantly enhances the usability and applicability of geospatial data. This development is particularly valuable in fields such as urban planning, environmental management, disaster response, and infrastructure development, where real-time geospatial data sharing is critical for informed decision-making (Harvey et al. , 1999).

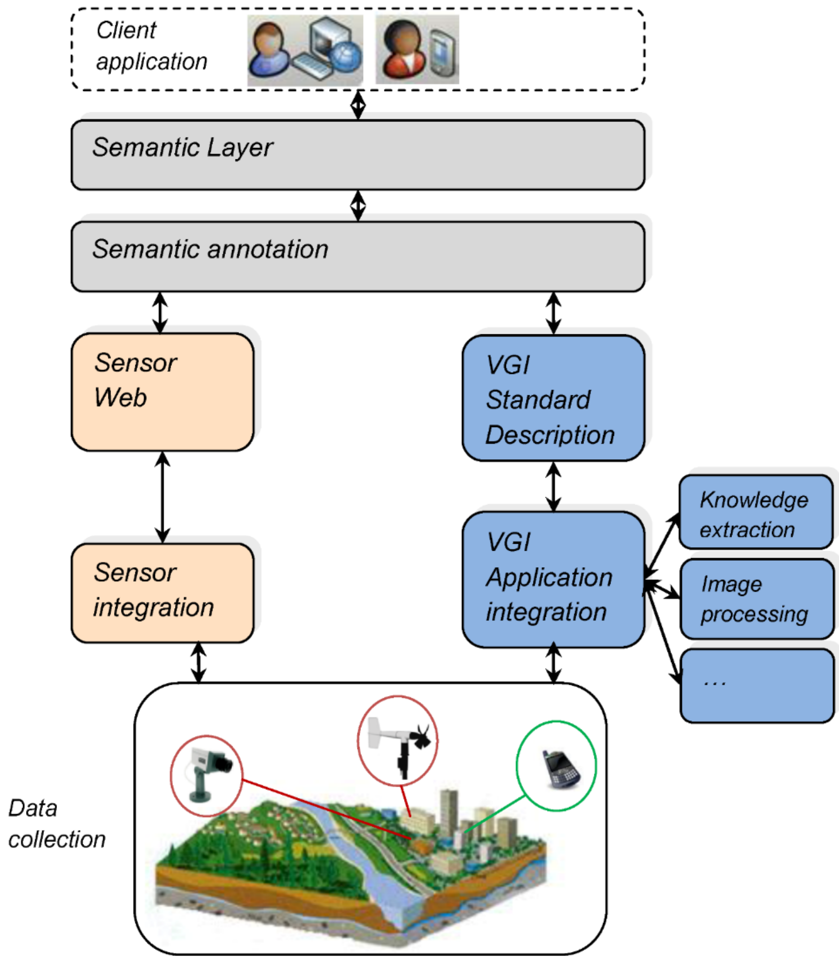


Figure 11. Semantic Interoperability Architecture (Bishr, 1998) , (Harvey et al. , 1999)

Figure 11 outlines a multi-tier framework for harmonizing heterogeneous geospatial data, a central theme in the foundational research of (Harvey et al. , 1999) and (Bishr, 1998):

1. Data Collection Layer
   - Combines data from diverse sources: sensor networks, VGI, and traditional GIS layers.
2. Integration & Annotation Layer
   - Applies semantic annotation, mapping raw data to a common ontology and vocabulary.
   - Ensures that terms from different data origins are consistently interpreted and aligned.
3. Semantic Layer
   - Performs reasoning over annotated data.

- Supports query translation and interoperability enabling systems to "understand" each other semantically, not just syntactically.

4. Application Layer
    - Presents a unified interface for end-users or systems to access semantically integrated geospatial data, without having to resolve internal heterogeneities.

2.6. Integration between BIM and GIS

For GIS and BIM to work shared, information flow between BIM, CAD, and geographic data must be optimized. Globally, the AEC industry is quickly approaching a standard where design and spatial data are easily combined. Common BIM and CAD file formats, which are utilized in a range of planning, construction, operations, inspection, and maintenance procedures, are being supported by ArcGIS BIM at a quick pace. There is more to using BIM data in ArcGIS than just incorporating BIM content from many disciplines, sources, and applications into a few asset lifecycle processes. An attractive alternative for managing projects and infrastructure in a spatial real-world setting is provided to AEC companies by the ArcGIS GeoBIM platform, which is the result of the integration of GIS and BIM (Tejjy Inc., n.d.).

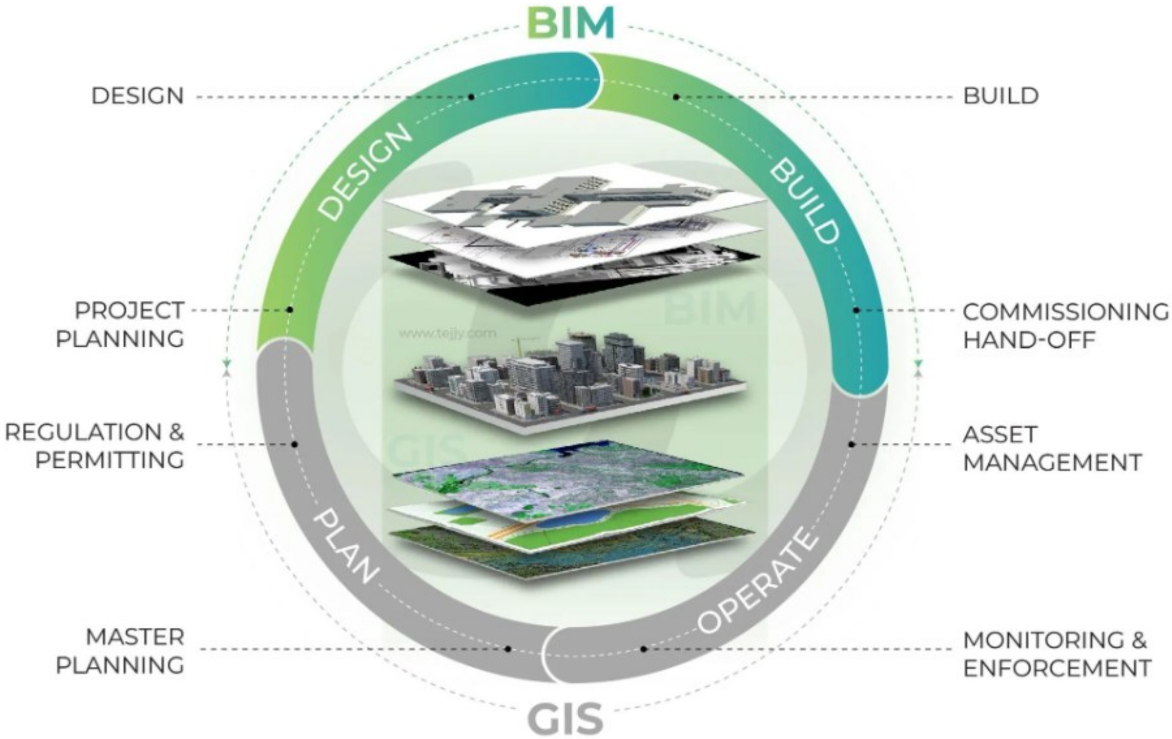


Figure 12. synergistic integration of BIM and GIS across the project lifecycle (Tejjy Inc., n.d.)

A lifecycle integration model that shows how BIM and GIS collaborate to enhance infrastructure design, execution, and management is shown in figure 12. While BIM oversees the design and build stages by providing comprehensive 3D models and construction coordination, GIS assists with the early planning stages through master planning, permitting, and spatial analysis. BIM offers asset-level data during the commissioning and operation stages, whereas GIS permits spatial oversight and real-time monitoring. When combined, they provide a digital ecosystem that connects large-scale spatial context with precise building information, improving lifecycle asset management, efficiency, and decision-making (Tejjy Inc., n.d.).

In recent years, the integration of BIM and GIS has emerged as a transformative approach to improving infrastructure management, maintenance planning, and risk assessment. While BIM provides detailed asset information, including structural details, architectural elements, mechanical, electrical, and plumbing (MEP) systems, GIS focuses on spatial analysis and visualization of geographic data, such as terrain models, environmental features, and urban landscapes (Ying & Li, , 2017). The combination of these two historically distinct fields enhances the accuracy of infrastructure management by bridging the gap between detailed building-specific information and broader spatial contexts.

One of the key applications of BIM-GIS integration lies in urban infrastructure maintenance. Merging BIM's asset-level details with GIS's spatial analysis capabilities enables urban planners and engineers to predict maintenance needs more accurately, particularly in densely populated areas where space constraints present challenges (Biljecki et al. , 2015). This integration allows for more efficient allocation of resources and helps minimize disruptions to urban infrastructure operations. Similarly, proposed a unified platform that combines BIM and GIS for managing underground utility networks, emphasizing how spatial data from GIS enhances the detailed asset information stored in BIM models. Their study highlighted how accurate maintenance predictions and improved decision-making in underground system management could be achieved through this integration (Amirebrahimi et al. , 2016).

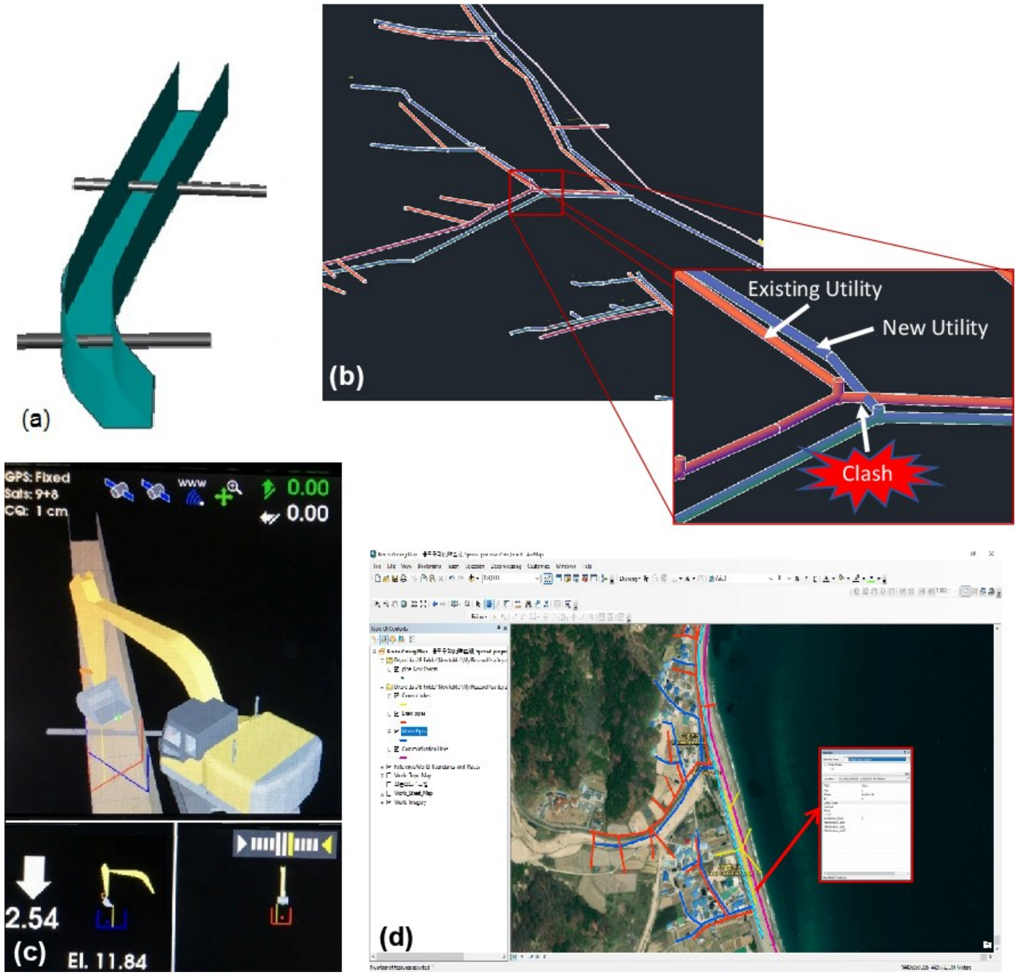


Figure 13. These visual captures the application of a BIM–GIS platform for underground utilities management (Amirebrahimi et al. , 2016)

Figure 13 clearly depicts the real-world application of a BIM–GIS integrated platform for subterranean utility network management. This multi-part picture illustrates how different phases of utility maintenance and construction can be supported by integrating spatial data from GIS with comprehensive BIM models. A 3D model of the pipeline network created with BIM software like Autodesk Revit is shown in Subfigure (a). Engineers can comprehend the physical arrangement of subterranean infrastructure thanks to this visual representation, which offers accurate geometric and semantic data for every utility component. The technology identifies possible conflicts between newly designed utilities and existing infrastructure by performing clash detection, as shown in subfigure (b). This capacity is essential for preventing expensive mistakes during construction, especially in crowded metropolitan settings.

The machine guidance interface, which converts design data into real-time feedback for excavator operators, is depicted in subfigure (c). This interface, which is based on the integrated BIM–GIS model, improves construction safety and accuracy by visually guiding machinery during excavation. Lastly, a GIS-based map overlay with utility data superimposed on high-resolution satellite imagery is shown in subfigure (d). Better coordination and decision-making are made possible by this integration, which enables stakeholders to see the infrastructure in a larger geographic context. The picture is a useful resource for contemporary infrastructure management techniques since it encapsulates the main advantages of BIM–GIS integration, which include improving real-time construction support, minimizing spatial conflicts, and enabling correct design validation.

Beyond maintenance, BIM-GIS integration has also been explored for risk classification and disaster resilience planning. Merging structural data from BIM with spatial data from GIS allows for a more precise identification of high-risk areas in urban environments. This approach enhances risk assessment, particularly in disaster-prone regions, by improving the classification of vulnerable structures and infrastructure (Isikdag et al. , 2014). Additionally BIM's detailed information on individual assets can be mapped onto a geographic scale using GIS. For example, linking a tunnel's structural attributes with real-time GIS weather data enables facility managers to predict deterioration due to environmental exposure, ultimately enhancing maintenance strategies (Liu et al. , 2017).

IFC plays a crucial role as the fundamental data structure for BIM and serves as a key enabler for its integration with GIS. As a widely accepted open standard, IFC provides a semantic data model that captures a broad range of building-related information, facilitating seamless data exchange across multiple platforms (Noardo et al., , 2020). The latest advancements in IFC have expanded its capabilities, allowing for more sophisticated representation and management of complex building data. This ongoing development underscores the importance of IFC in ensuring interoperability between BIM and GIS, ultimately enhancing collaboration in multidisciplinary infrastructure projects.

Beyond serving as a data exchange standard, IFC also plays a vital role in georeferencing BIM models for GIS applications. The necessity of open data standards like IFC to support the automatic georeferencing of BIM models. Their research emphasizes that by embedding georeferencing information directly into BIM datasets, interoperability between BIM and GIS can be significantly improved, reducing errors in positioning and ensuring precise spatial alignment. This advancement is particularly critical for projects that require accurate geographic positioning, such as urban infrastructure management, transportation planning, and environmental analysis (Berlo and Bomhof , 2014).

Despite its potential, the integration of BIM and GIS presents technical challenges, particularly concerning data compatibility and coordinate systems. Among the first to identify georeferencing issues, noting that BIM tools, such as Autodesk Revit, typically operate on a local coordinate system, which is not directly compatible with the global reference systems used in GIS (Isikdag and Zlatanova, 2009). Their study underscored the importance of georeferencing BIM models to ensure consistent alignment with GIS data. Addressing these challenges is crucial for achieving seamless BIM-GIS integration and maximizing its potential benefits.

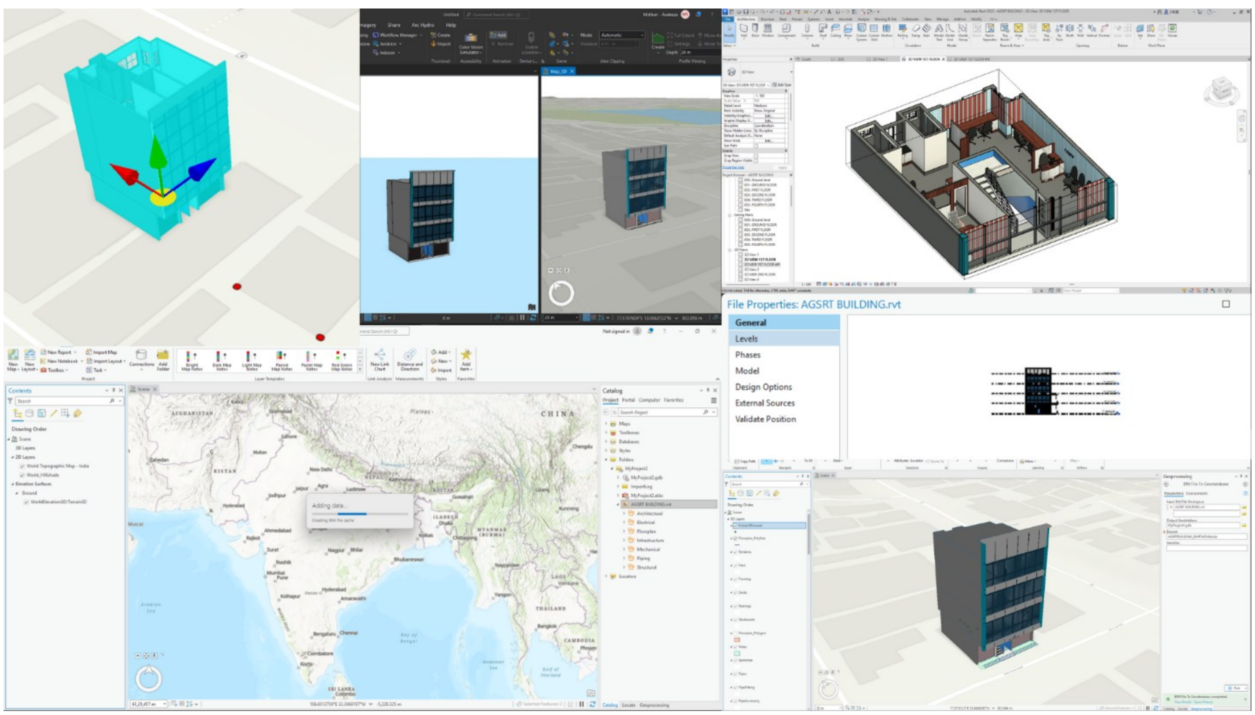


Figure 14. BIM–GIS integration visualization in Revit and ArcGIS Pro, illustrating georeferencing workflow (Kuehne, D. , 2019)

Figure 14 shows a BIM model from Autodesk Revit is integrated into ArcGIS Pro to demonstrate the georeferencing process and 3D visualization amongst several software programs. While the center and lower parts use ArcGIS Pro to precisely put the building into a geographic context, the top and right panels illustrate the underlying structure and geometry of the Revit model. This configuration enables location-aware asset management and urban analysis by highlighting the alignment of local BIM coordinates with global spatial reference systems. The figure exemplifies the fundamentals of BIM–GIS integration, especially in terms of promoting spatial accuracy, semantic interoperability, and enhanced context for infrastructure operations and planning.

The integration of BIM and GIS is typically classified based on multiple criteria, including data flow directionality, platform type, and integration level (Ying & Li, , 2017). Semantic integration focuses on ensuring data consistency and compatibility by aligning the meaning and interpretation of data objects in BIM and GIS. This approach is crucial for maintaining uniformity across different disciplines, enabling more accurate data interpretation and decision-making. On the other hand, geometric integration aims to harmonize spatial representations between BIM and GIS, enabling precise spatial analysis and visualization. By bridging the gap between semantic and geometric data, BIM-GIS integration allows for enhanced spatial analysis, improved asset management, and more efficient urban planning.

2.7. Industrial Foundation Class (IFC)

2.7.1. What is IFC?

Figure 15.Industrial Foundation Class (buildingSMART International)

IFC was developed by buildingSMART International as an open standard to facilitate seamless data exchange in BIM. By providing a neutral and standardized data model, IFC ensures interoperability across multiple software platforms, allowing professionals in AEC to collaborate effectively. As a structured framework, IFC defines relationships, properties, and digital representations of building components, establishing a consistent approach to handling digital building information. Over time, IFC has become a critical tool for ensuring data consistency, improving project workflows, and integrating diverse digital platforms (Noardo et al., 2020).

To address the increasing complexity of BIM data management and interoperability, IFC has undergone several revisions since its initial release as IFC 1.0 in 1997. The IFC 2x3 version became widely adopted due to its improved data architecture and object definitions, enabling more efficient data handling. Later iterations, such as IFC 4 and IFC 4.3, introduced enhanced property sets, improved infrastructure project support, and better georeferencing capabilities (Zhu et al., 2024). IFC 4.3 is gaining prominence for smart cities and major infrastructure projects as it supports complex urban environments, transportation networks, and underground utilities, making it essential for large-scale digital urban planning.

Beyond its role in BIM, IFC also plays a key role in GIS integration for geospatial applications. By enabling precise georeferencing of building models, IFC ensures accurate alignment of digital structures with real-world locations. This functionality is particularly valuable for large-scale construction projects, facility management, and infrastructure planning, where seamless communication between architectural and spatial data is essential. IFC serves as a fundamental tool for digital construction and intelligent urban planning, facilitating data standardization, supporting the development of digital twins, and enhancing long-term asset management. These advancements highlight the growing significance of IFC in integrating BIM with GIS, fostering a more connected and data-driven built environment (Slongo et al. , 2022).

Figure 16. distinction between information exchange in a traditional context and by using IFC (Esri, 2023)

A BIM model is exported as an IFC file and then integrated into GIS software, as shown in Figure 16, which depicts the BIM and GIS integration procedure. The integration strategies outline on their official website, where they talk about how BIM and GIS work together to close the gap between the design and geographic realms. This integration facilitates better decision-making, improved project coordination, and lifecycle management in both the built and natural settings by allowing the smooth transfer of data between building models and geospatial contexts.

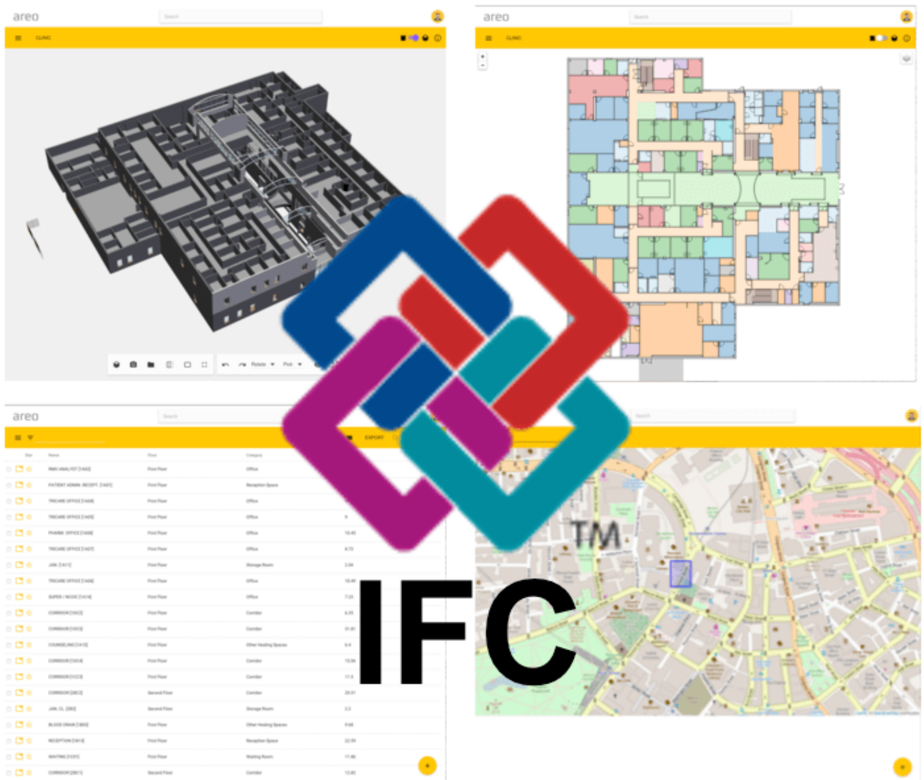


Figure 17. Composite screenshot illustrating IFC-based workflows—3D model, 2D floor plans, assets list, and mapping views with the IFC logo overlay (artofit.org, n.d.)

The ability of the standard to provide data integration across different BIM domains is graphically illustrated in this figure 17. Interoperability is represented by the sizable IFC logo in the middle, which links several perspectives:

- Top left: A thorough 3D BIM model that displays a facility's mechanical and architectural configuration.
- Top right: A 2D floor plan with color coding to indicate different sorts of rooms or areas for use.
- A structured data table with space attributes like names, categories, and dimensions is shown at the bottom left.
- Bottom right: A GIS map view that shows the facility's geolocation within a city.

One of the main benefits of IFC is highlighted by this integration: it serves as a common language that unites design, construction, operation, and geographic context. Throughout the construction lifecycle, the IFC standard allows for the meaningful movement of information between various programs (such as Revit and GIS platforms), guaranteeing consistency, minimizing rework, and facilitating better informed decision-making.

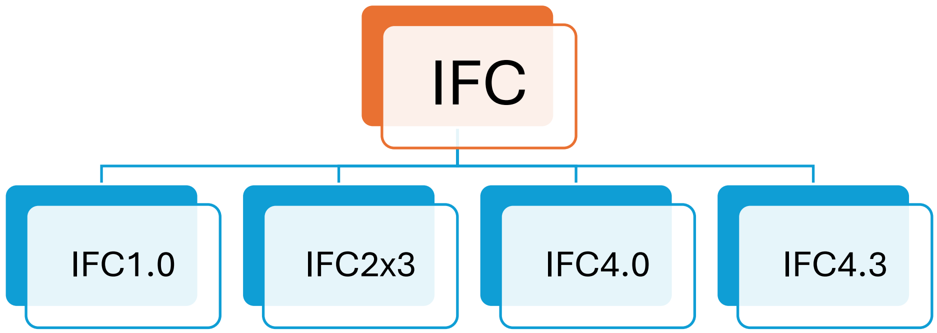


Figure 18.Industrial Foundation Class Evolution

Figure 18 presents the major versions of IFC, highlighting their progressive improvements over time:

IFC 1.0 (1996): IFC 1.0, which was released as the first edition, established a consistent data model and made it easier for AEC professionals to share fundamental information.

IFC 2x3 (2006): This version gained popularity because it provided better object definitions and data organization, which facilitated interoperability across different BIM applications.

IFC 4.0 (2013): marked a substantial advancement in the standard's capabilities by introducing sophisticated property sets, improved support for infrastructure projects, and improved geometric representation.

IFC 4.3 (2021): expanded to include infrastructure sectors including highways, ports, rivers, and railroads, enabling thorough data interchange in intricate projects.

Each iteration of IFC has progressively addressed the industry's need for a robust, open standard, ensuring seamless data exchange and collaboration across diverse platforms and disciplines.

With the release of IFC4, the IFC standard has improved its georeferencing capabilities (Mitchell et al., 2020) due of the restricted georeferencing in IFC2x3, workarounds such creating bespoke property sets to include geographical reference information were frequently necessary (Tauscher et al., , 2023). Because this method was not standardized, it can result in discrepancies between various software systems (Jaud et al., 2019). IFC4 addressed these issues by introducing explicit entities such as IfcMapConversion and IfcCoordinateReferenceSystem, which allowed for accurate and consistent georeferencing in BIM models (Mitchell et al., 2020)**.** To improve integration with Geographic Information Systems (GIS) and facilitate intricate infrastructure projects, these entities enable precise mapping of local coordinate systems to global reference systems (Tauscher et al., , 2023). Using IFC4 for georeferencing guarantees uniformity, compatibility, and enhanced data sharing between apps using GIS and BIM (Jaud et al., 2019).

2.8. Importance of BIM and GIS in Tunnel Maintenance

For underground transportation networks to remain safe, functional, and long-lasting, tunnel maintenance is an essential component of infrastructure management. Whether for roads, railroads, or utilities, tunnels are vulnerable to environmental effects, structural aging, and tear and damage. To avoid degradation and failures, consistent maintenance measures are necessary. To ensure ongoing and secure operation, proper maintenance helps reduce risks including water infiltration, structural deterioration, fire hazards, and ventilation problems.

2.8.1. BIM in Tunnel Maintenance

As illustrated in Figure 10, BIM offers several critical advantages, enhancing project management, operational efficiency, and sustainability in construction and infrastructure projects. The figure highlights four key aspects of BIM's importance: Predictive Maintenance, 3D Visualization, Improved Decision-Making, and Digital Management.

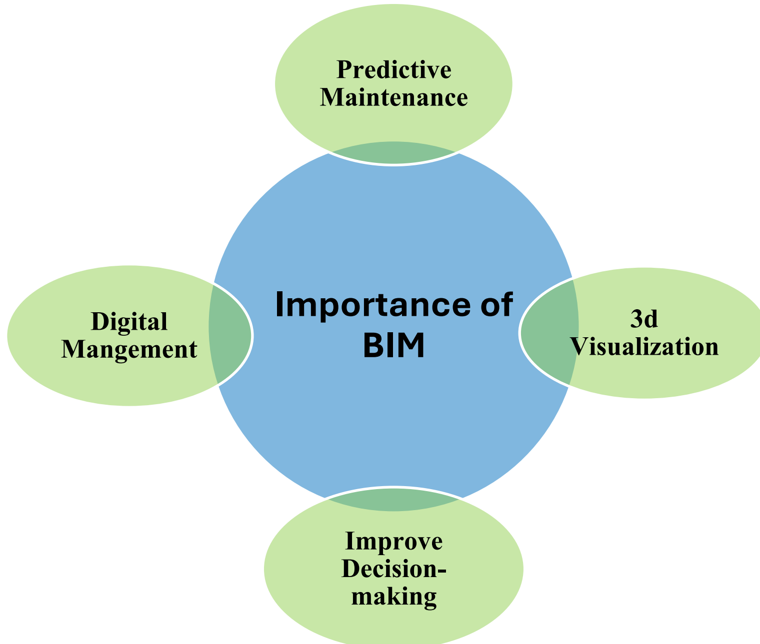


Figure 19. Importance of BIM (buildingSMART International. , n.d.)

Figure 19 represents the core contributions of BIM in infrastructure projects. It highlights four key areas where BIM adds significant value: predictive maintenance, 3D visualization, improved decision-making, and digital management. These aspects underscore how BIM goes beyond basic modeling to support operational efficiency, data integration, and long-term asset sustainability across all project phases.

1. Predictive Maintenance:

   By combining historical records with real-time data, BIM enables predictive maintenance, enabling asset managers to anticipate possible faults before they happen. Through sensor-based monitoring and data analytics, BIM supports preemptive interventions, limiting unexpected breakdowns and saving maintenance costs (Liu et al. , 2017). Large infrastructure projects like tunnels, bridges, and high-rise structures benefit greatly from this capability since it can improve safety and longevity by detecting structural problems early.

2. 3D Visualization:

   The potential of BIM to produce incredibly detailed 3D models is one of its most potent characteristics, allowing stakeholders to precisely visualize structural and architectural elements. BIM's 3D models, as opposed to conventional 2D plans, improve teamwork by offering an immersive and dynamic project view. This guarantees that design discrepancies are fixed prior to construction by assisting with clash detection, spatial planning, and virtual walkthroughs (Azhar, 2011).

3. Improve Decision-Making:

   Because BIM offers real-time access to integrated project data, it greatly improves decision-making processes. Before making changes, engineers, architects, and project managers can examine several design options, calculate costs, and analyze performance indicators. BIM lowers project risks and guarantees that all decisions are found on current and correct data by utilizing data-driven insights (Succar , 2009).

4. Digital Management:

   Throughout the project lifetime, BIM acts as a single digital platform that simplifies data administration. BIM guarantees that all project stakeholders have real-time access to the most recent information from design through construction and facility management. The accuracy of documentation, workflow efficiency, and adherence to industry standards are all enhanced by this interface. The digital management features of BIM make it easier to track assets, schedule, and estimate costs in large-scale infrastructure projects, which eventually results in more effective project execution (Eastman et al., 2008).

BIM plays a crucial role in tunnel maintenance, providing advanced 3D modeling capabilities that enhance the visualization of maintenance requirements. BIM technology helps create detailed digital models, allowing maintenance personnel to better understand the spatial arrangement and condition of tunnel components. By developing a comprehensive BIM model, maintenance teams can plan and execute maintenance tasks more efficiently. The authors propose a process that integrates BIM into maintenance workflows, improving stakeholder communication and facilitating real-time updates, ensuring a more coordinated and effective approach to tunnel management (Mitelman and Sacks , 2021).

Beyond visualization, BIM serves as a centralized digital library that aids asset management by providing up-to-date data on all infrastructure components. This centralization enables maintenance teams to access detailed asset information, including

specifications, maintenance history, and performance indicators. By streamlining maintenance operations, BIM reduces errors, enhances decision-making, and optimizes resource allocation, ultimately leading to more effective asset management and infrastructure longevity (BIM Community , 2025).
Additionally, BIM's integration with sensor technology and the Internet of Things (IoT) enables predictive maintenance, further enhancing its role in tunnel management explains that embedded sensors within tunnel components continuously monitor asset conditions, allowing BIM to collect and analyze real-time data. This predictive capability helps maintenance teams anticipate potential failures and schedule interventions in advance, minimizing downtime and extending asset lifespan. By leveraging real-time analytics, BIM-driven predictive maintenance strategies not only lead to cost savings but also enhance safety and operational efficiency in tunnel infrastructure (Novatr , 2024).

In conclusion, there are many benefits to incorporating BIM into tunnel maintenance procedures, such as better asset management, proactive predictive maintenance, detailed repair documentation, and enhanced visualization through 3D modeling. These benefits contribute to more efficient maintenance workflows, cost reductions, and extended asset lifespans.

2.8.2. GIS in Tunnel Maintenance

As shown in Figure 11, GIS offers several key benefits, including analysis of geological risks, maintenance strategies, infrastructure monitoring, and improved mapping. These functionalities make GIS an essential tool for decision-making, asset management, and environmental planning.

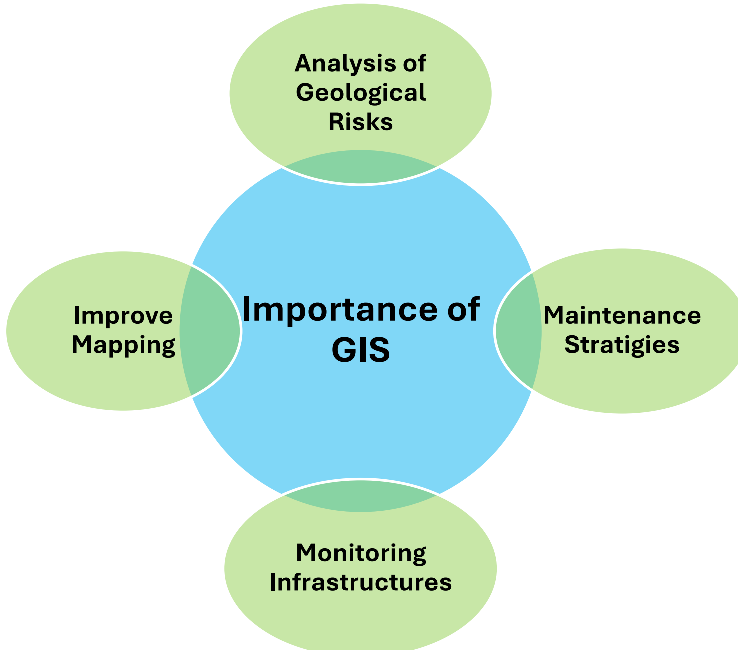


Figure 20.Importance of Geographic Information Systems

Figure 20 illustrates the key contributions of Geographic Information Systems (GIS) in infrastructure and geospatial management. The diagram highlights four main roles of GIS: improving mapping accuracy, analyzing geological risks, supporting maintenance strategies, and monitoring infrastructures. These components reflect how GIS contributes not only to spatial visualization but also to strategic planning, environmental analysis, and predictive maintenance through geodata integration.

1. Analysis of Geological Risks:

   By combining geographic data with environmental monitoring systems, GIS makes it possible to analyze geological hazards including landslides, earthquakes, and soil erosion in detail. GIS assists geologists and engineers in evaluating hazards and creating mitigation plans for infrastructure projects by charting seismic activity, subsurface conditions, and terrain stability (Smith et al., 2021). This ability is very helpful for building roads and tunnels, where geological uncertainty presents many difficulties.

2. Maintenance Strategies:

GIS-based solutions that offer predictive maintenance capabilities and real-time asset monitoring help optimize infrastructure maintenance. GIS enables maintenance teams to effectively allocate resources, schedule preventative repairs, and monitor degradation patterns (Jones & Patel, 2020). GIS aids in the detection of structural flaws in tunnel infrastructure, guaranteeing that maintenance activities are data-driven and carefully thought out.

3. Monitoring Infrastructures:

   GIS is an essential tool for tracking the performance of infrastructure throughout time. GIS offers real-time insights into the state of roads, bridges, tunnels, and utilities by combining data from satellite photography, drones, and Internet of Things sensors (Harrison et al., 2019). By detecting anomalies, structural changes, and environmental effects, this ongoing monitoring lowers the chance of catastrophic failures and allows for prompt responses.

4. Improve Mapping:

   Improving spatial visualization and mapping accuracy is one of GIS's main purposes. It makes it possible to classify land uses, do in-depth topographic study, and model urban and natural landscapes in three dimensions. Urban planning, environmental preservation, and emergency response coordination are all aided by GIS-based mapping (Garcia & Lin, 2022). This feature is crucial for planning infrastructure projects that maximize spatial efficiency while having the least possible negative impact on the environment.

GIS play a crucial role in the upkeep and maintenance of tunnel infrastructure, offering advanced capabilities for spatial analysis, risk assessment, and resource optimization. By integrating geospatial data with engineering models, GIS enhances the identification of potential hazards, monitoring structural integrity, and planning of maintenance activities.

(Kehne, 1999) highlights the importance of GIS in assessing geological risks and environmental conditions surrounding tunnels. Through the integration of spatial data, GIS allows for the proactive identification of potential risks, such as soil instability, water intrusion, and terrain deformations, that could threaten tunnel stability. By mapping subterranean infrastructure, GIS provides a comprehensive visualization of tunnel networks and their components, ensuring that maintenance teams have accurate, real-time data on structural conditions and environmental changes. This spatial awareness is essential for monitoring land movement or deformations that might compromise tunnel integrity. Moreover, by enabling targeted interventions, GIS enhances safety, optimizes resource allocation, and minimizes maintenance costs.

Beyond risk assessment, GIS significantly contributes to efficient asset management in tunnel infrastructure. GIS facilitates the organization and presentation of asset data, allowing maintenance teams to identify infrastructure components, estimate repair costs, and plan resource distribution effectively. By incorporating construction data, including hazard identification and material conditions, GIS helps establish deterioration timelines, ensuring that preventive maintenance strategies are implemented before structural issues escalate. This predictive approach minimizes unexpected failures, optimizes resource allocation, and enhances maintenance efficiency (Infotech, 2022).

GIS is also widely used in the planning, design, construction, and operation of transportation infrastructure, including roads, railways, bridges, and tunnels highlights how bridge and tunnel administrators are increasingly adopting GIS technology to enhance long-term infrastructure sustainability and safety. GIS provides deeper insights into spatial relationships and environmental factors, allowing decision-makers to develop data-driven maintenance strategies. This comprehensive approach ensures that tunnel maintenance plans are not only reactive but also sustainable and proactive, contributing to the long-term resilience of critical infrastructure (Esri, 2023).

In conclusion, there are several advantages to incorporating GIS into tunnel maintenance procedures, such as better mapping and monitoring of subterranean infrastructure, improved understanding of geological risks, and optimized maintenance plans via efficient data visualization and analysis. These benefits enhance tunnel structures' durability, effectiveness, and safety.

2.9. Importance of Geology Maps

Geological maps are specialized visualizations that show the age, distribution, and type of rock formations on the surface of the Earth. To illustrate different geological phenomena, such as rock units, faults, folds, and other structural components, they use lines, symbols, and colors. These maps are crucial resources for geologists to comprehend the structure and geological history of an area, which helps with tasks like hazard assessment, mineral exploration, and natural resource management.

The production of geologic maps, highlighting how, since the early nineteenth century, the construction of geologic maps and the gathering of field data have been essential to the interpretation of continental geology. They point out that the development of digital techniques has made geologic mapping easier and enabled more accurate and thorough depictions of geological characteristics. note that from the early nineteenth century, gathering field data and making geologic maps have been essential to understanding continental geology. They point out that the development of digital techniques has made geologic mapping easier and enabled more accurate and thorough depictions of geological characteristics (Swanger and Whitmeyer , 2021).

Geological maps are essential for predictive maintenance methods in the context of tunnel maintenance. A thorough geologic model and subsurface profile along the planned tunnel path offer crucial information regarding the ground conditions, to facilitate proactive maintenance and reduce potential dangers during tunnel construction and operation. This knowledge is essential for validating geological assumptions and constructing both temporary and permanent structures. In addition to that he explains about the significance of a thorough subsurface profile and geology model along suggested tunnel alignments. In addition to verifying geological hypotheses and supporting the construction of both temporary and permanent structures, these models offer crucial information regarding ground conditions. This method reduces possible hazards during tunnel construction and operation and enables proactive maintenance (Brierley Associates , 2019).

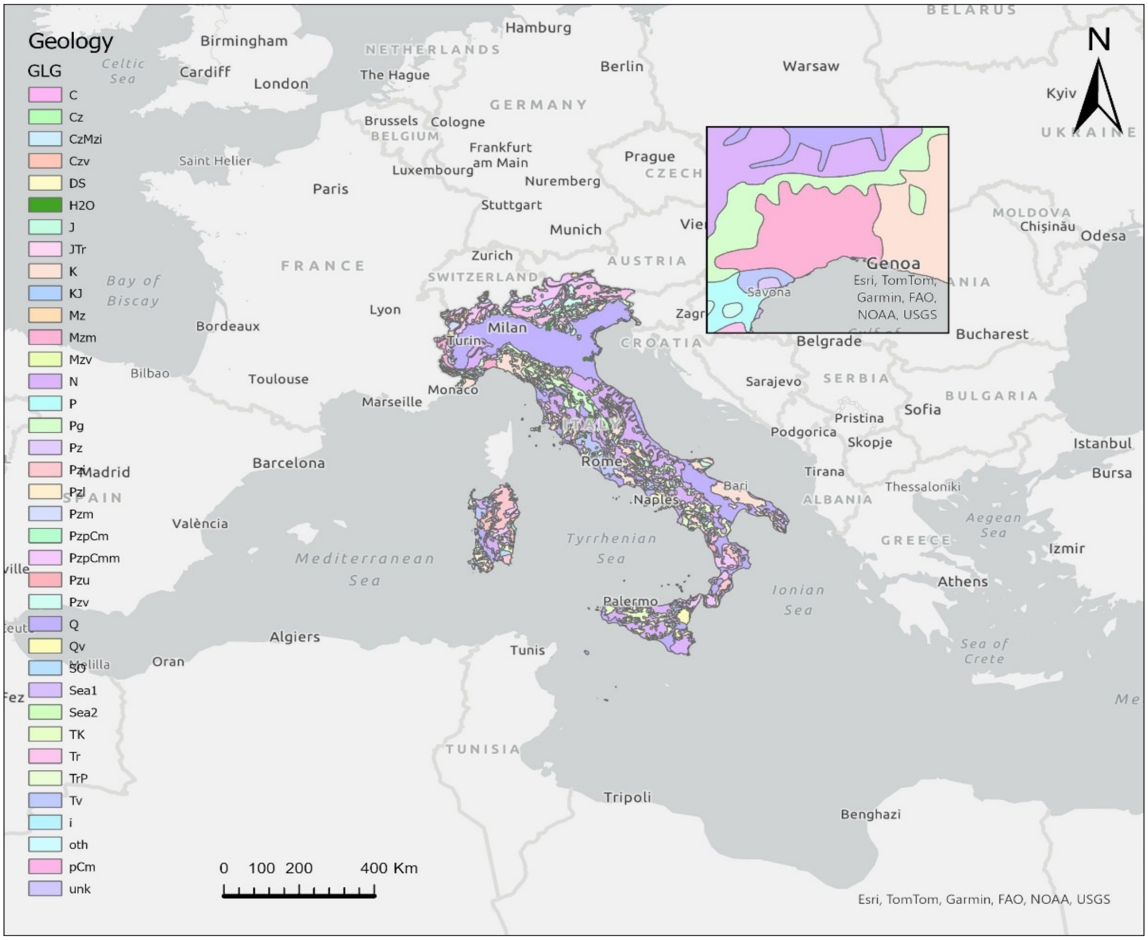


Figure 21.Geological Map of Italy

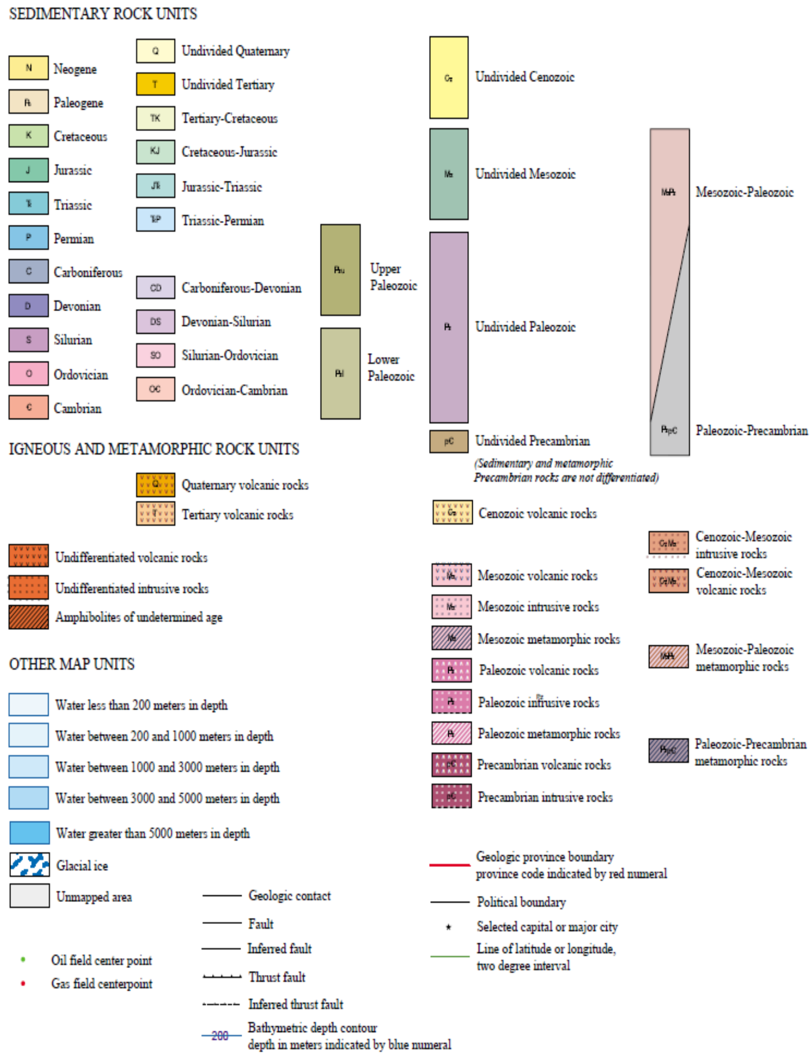


Figure 22.Explanation of Map Units and Symbols

The illustration displays a detailed legend for a geologic map that shows how different rock units, such as sedimentary, igneous, and metamorphic rocks, are categorized together with other map units and structural components. From the Cambrian to the Neogene, sedimentary rocks are arranged chronologically into undivided units like the Undivided Cenozoic, Mesozoic, and Precambrian, as well as classifications like the Upper and Lower Paleozoic. Paleozoic-Precambrian metamorphic rocks are one example of the complicated geologic histories highlighted by further subdivisions of the igneous and metamorphic groups, which are distinguished by age and composition (e.g., volcanic, intrusive, metamorphic). To provide a comprehensive geographical examination of both geological and surface features, the map also includes bathymetric layers, fault types, glacial features, and geopolitical boundaries.

3. Methodology

3.1. Case study

The figure below represents the case study of a tunnel in Italy. Completed in the 1960s, the tunnel spans approximately 957 meters and serves as a vital transportation link between northern and southern Italy. Given its strategic significance, ensuring its structural integrity, safety, and operational efficiency remains a priority.

Figure 23. Case study Tunnel

This case study investigates the use of BIM and GIS for predictive maintenance to improve tunnel longevity and management. A proactive approach to asset management, predictive maintenance uses digital modeling and data analytics to detect infrastructure issues before they happen, guaranteeing timely maintenance and reducing operating interruptions.

3.2. Software Selection

The successful integration of BIM and GIS depends heavily on the selection of the right software tools. Each software used in this workflow serves a specific function, from 3D modeling and data structuring to geospatial processing and real-world visualization. Selecting the appropriate software is essential for:

- Ensuring interoperability between BIM and GIS environments.
- Maintaining data accuracy and georeferencing consistency.
- Enhancing visualization and analysis capabilities for predictive maintenance.
- Optimizing workflow efficiency by reducing manual data conversions and errors.

This study employs a combination of **Autodesk Revit, InfraWorks, Blender, Cesium Ion, and ArcGIS**, with **IFC 4** as the key exchange format. Each software was chosen based on its capabilities to support data processing, 3D visualization, and GIS compatibility.

A. BIM Software

1. Autodesk Revit

- Used for **creating the 3D tunnel model** based on data provided by a private company.
- Features **parametric modeling**, allowing easy modification of structural elements.
- Supports **IFC 4 export**, ensuring interoperability with GIS and other BIM platforms.

2. AUTODESK InfraWorks

- Selected to test how well the Revit model integrates within a BIM environment.
- Directly reads .RVT files, making it a seamless extension of the modeling process.

- Provides contextual integration with real-world terrain and infrastructure data.

B. GIS Software

1. **Blender (Version 4.1)** with **IFC Plugin**

- Chosen as an intermediary platform to process and refine the IFC 4 model. Supports web-based geospatial applications and real-time rendering.
- A plugin was used to read and manipulate IFC data efficiently.
- The model was then exported as. DAE (Collada) for Cesium Ion visualization.
-

2. **ArcGIS pro**
   - Selected for advanced spatial analysis and GIS-based visualization.
   - The model was imported to test its compatibility with GIS tools.
   - Manual CRS (Coordinate Reference System) adjustments were necessary to ensure proper georeferencing.
3. **Cesium Ion**
   - Used to visualize the tunnel model in a real-world 3D environment.
   - Supports web-based geospatial applications and real-time rendering.
   - Required JavaScript-based georeferencing adjustments to align the model accurately.

3.3. Workflow

Figure 24. Workflow Diagram

To guarantee compatibility, georeferencing, and visualization in practical applications, figure 24 shows workflow exemplifies the process of integrating a 3D tunnel model into BIM and GIS systems. To create a smooth workflow, the procedure required several software tools, file format conversions, and geographical adjustments The tunnel's 3D BIM model was supplied by TECNE-Autostrade per l'Italia Group, a private organization in charge of infrastructure upkeep and administration. The first step was to examine and confirm the model's components, structure, and metadata after it was received as a.RVT file to make sure it would work with the next processing stage. To place the model in its immediate context, InfraWorks was then integrated with it. Cesium visualization was made possible by the successful transfer of the model into GIS applications like Blender via IFC export.

allowing for additional geographical analysis with ArcGIS Pro and visualization in Cesium Ion.

Geological maps were created using ArcGIS Pro to categorize the geological typologies along the tunnel alignment and assess the underlying conditions. Using Blender, a 3D geological model was produced based on this data, facilitating future risk assessments and improving comprehension of the soil-structure interaction.

3.3.1. Integration between BIM Software

- **Revit InfraWorks Integration**

Figure 25. Integration of Revit and InfraWorks

To facilitate seamless integration within the BIM environment, both Autodesk Revit and InfraWorks were utilized. The provided 3D tunnel model was initially received in .RVT format, which is the native file format for Autodesk Revit. Since InfraWorks is part of the Autodesk ecosystem, it was capable of directly reading the .RVT file without requiring conversion to IFC format, ensuring an efficient and lossless transition between the two software platforms.

Upon importing the model into InfraWorks, the structural elements were successfully visualized; however, the model did not align correctly with its real-world location. To address this, spatial adjustments were performed by defining precise geospatial coordinates, including longitude, altitude, and Elevation values. This process ensured that the 3D model was correctly positioned within its intended real-world location, enhancing accuracy for further GIS integration and analysis.

3.3.2. Integration between BIM and GIS software

- **Revit Blender Integration**

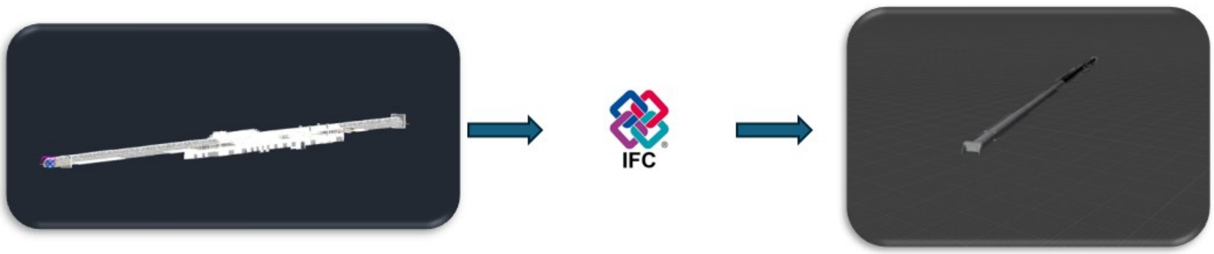


Figure 26. Integration between Revit and Blender software

To facilitate interoperability across different software environments, the model needed to be exported in IFC format. Since IFC serves as an open-standard format for BIM data exchange, selecting the appropriate IFC classification version was crucial for ensuring smooth integration with GIS platforms, we evaluated three different IFC versions IFC 2x3, IFC 4, and IFC 4.3 to determine the most suitable option for seamless integration with GIS software. The selection process aimed to ensure optimal compatibility, geospatial accuracy, and data integrity when transitioning from BIM to GIS environments.

To achieve this, the first step involved exporting the IFC file from Autodesk Revit. This required performing a series of preparatory steps within Revit to ensure that the exported model retained the necessary georeferencing, metadata, and structural elements essential for effective GIS integration.

The first step in exporting a model from Revit to IFC format is to go to the File menu, then select Export. From there, we simply choose the 'IFC' option from the list of available export formats. As shown in figure 31, Revit offers various export options like DWG, PDF, and FBX, but for interoperability and open BIM workflows, IFC is the format we go with.

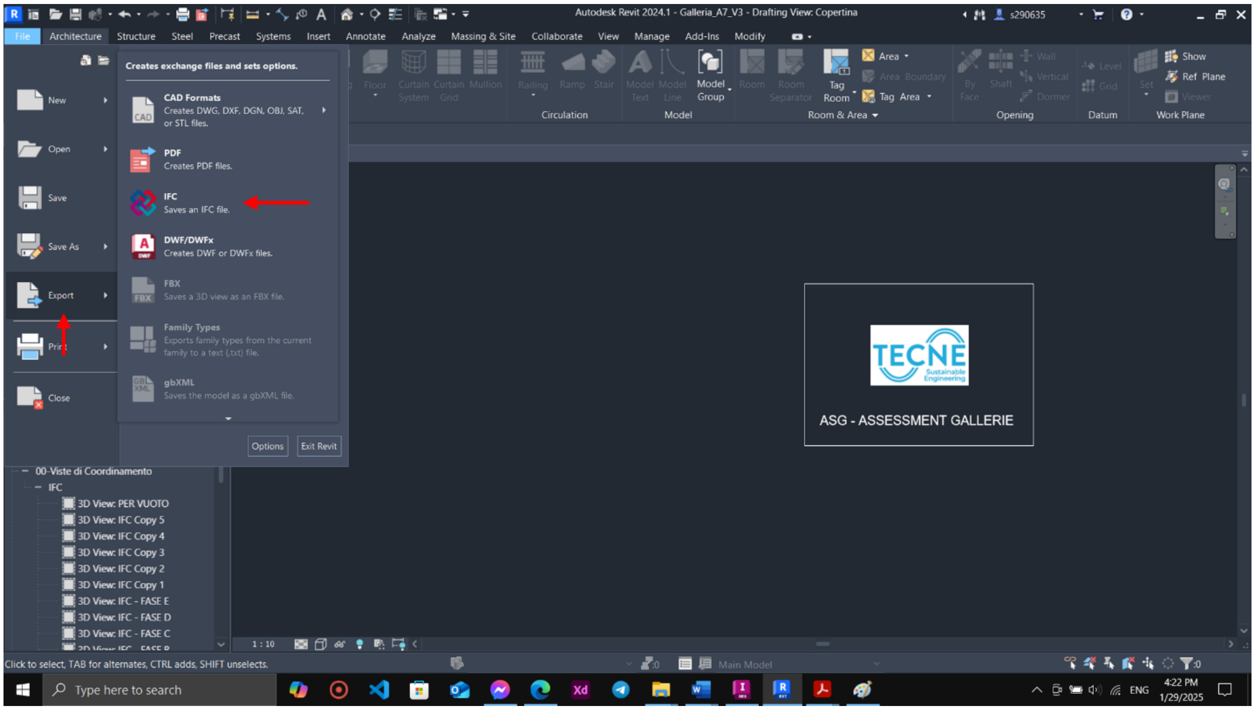


Figure 27. Exporting Revit file to .IFC

Once we reach the IFC export window, the next important step is selecting the right export setup and IFC version. As shown in figure 27 Revit provides a wide range of versions from IFC 2x3 Coordination View to IFC4 Reference Views and even experimental formats. To ensure the workflow proceeds smoothly, we tried different versions to see which one best

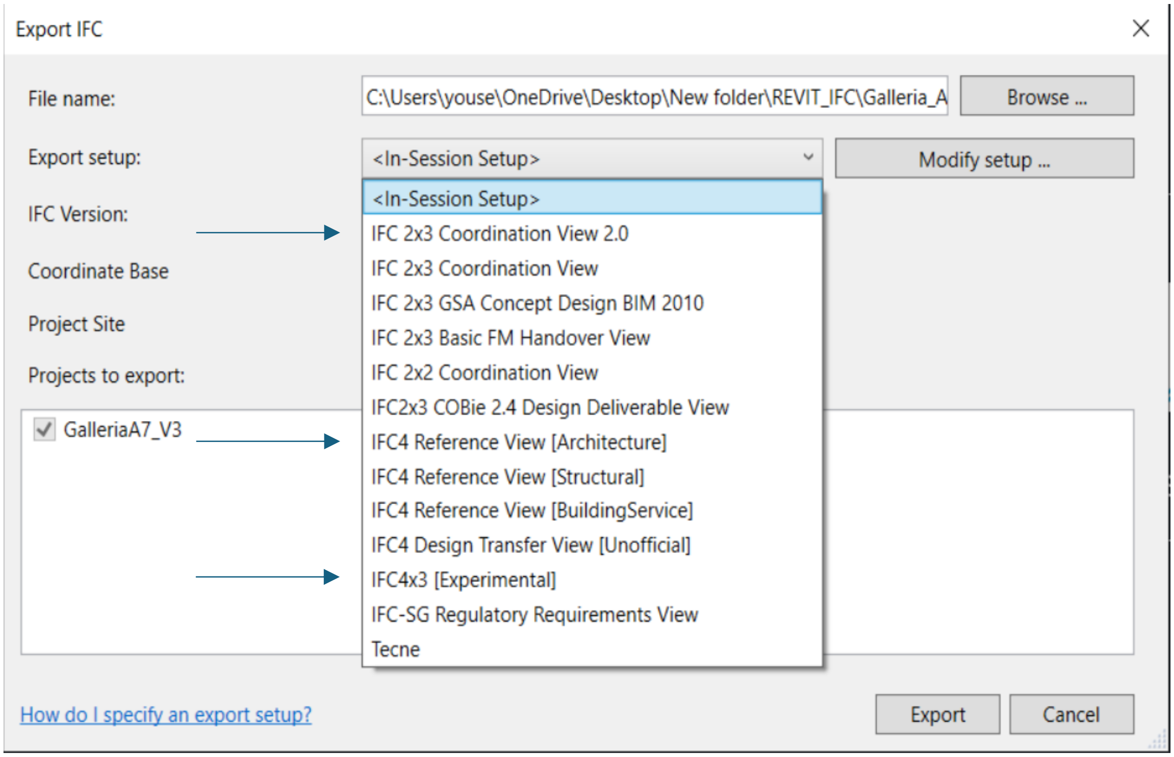


Figure 28. Different Versions of IFC

fits our needs.

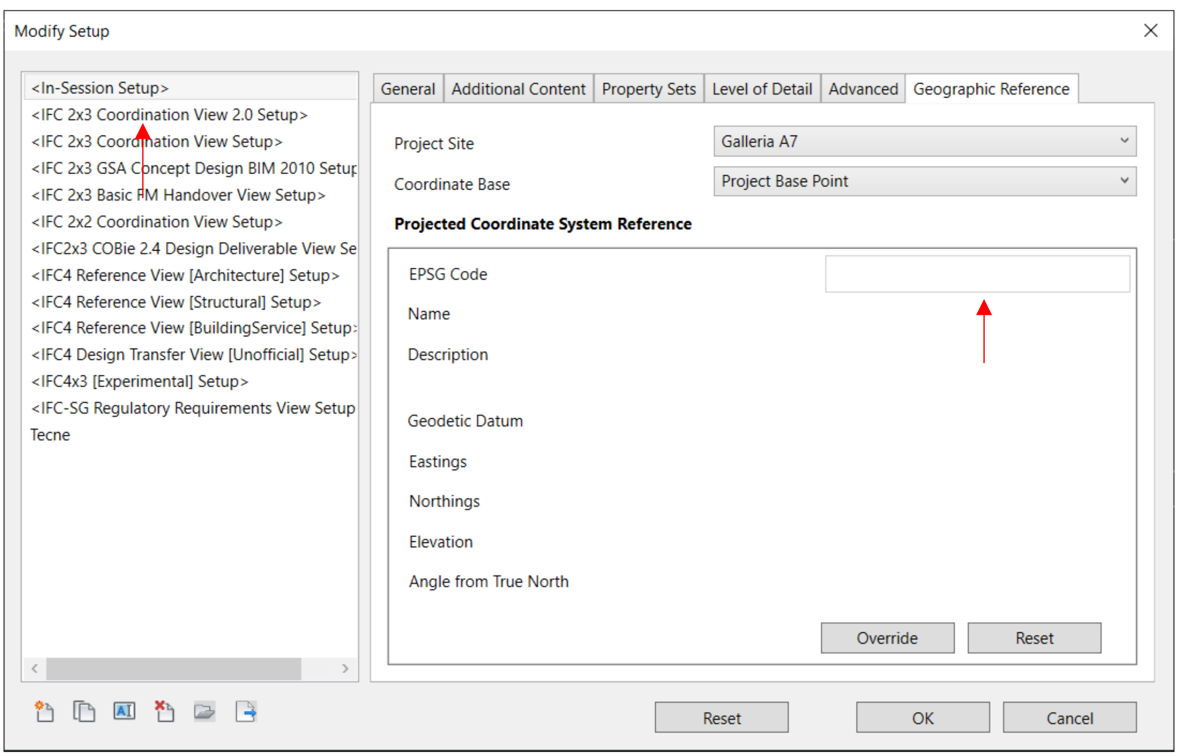


Figure 29. IFC 2x3 version

Figure 29 represents While using IFC 2x3, we noticed that the EPSG field used for georeferencing was locked, making it impossible to define the coordinate system properly, as shown in the figures below. This limitation helped us understand that choosing the right IFC version is not just a technical step, it's key to preserving geospatial accuracy and achieving interoperability with downstream software.

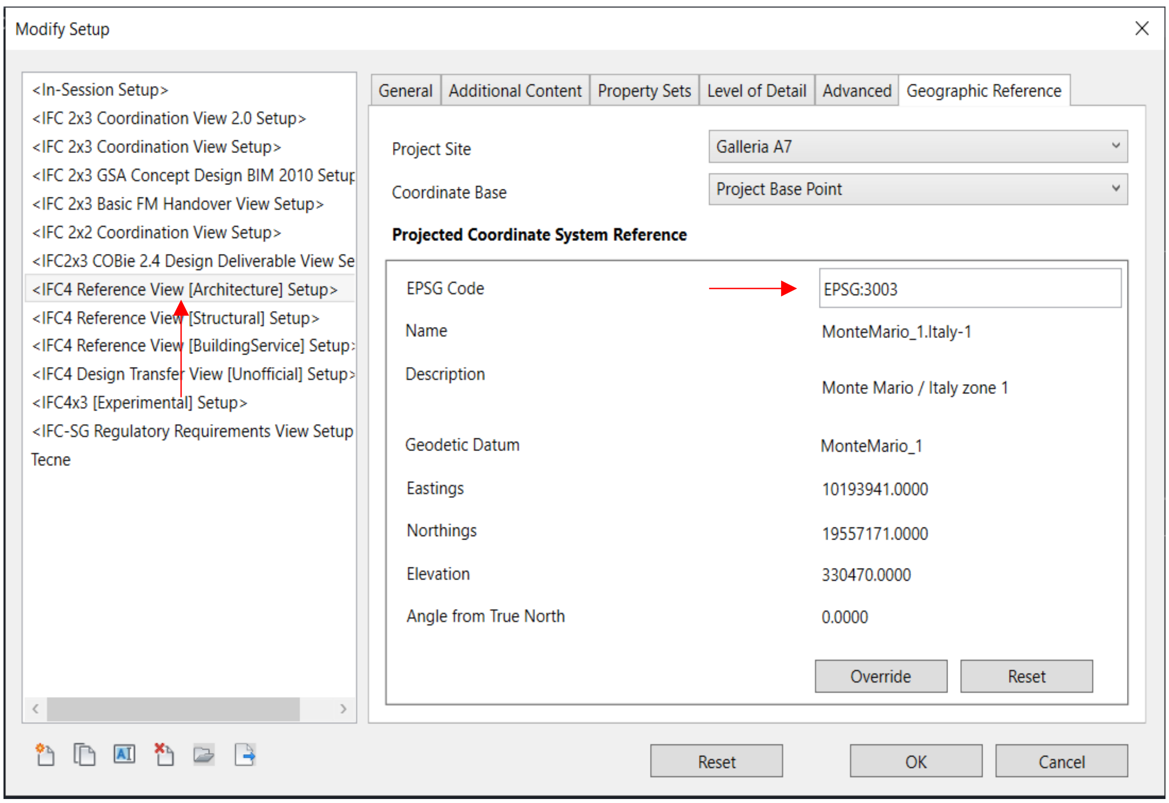


Figure 30. IFC 4 version

In Figure 30 shows that the IFC 4 format proved to be the most suitable choice for integration with GIS software, as it fully supports georeferencing parameters, including the ability to define an EPSG code. By setting the EPSG reference, we were able to establish a projected coordinate system, ensuring that the 3D model was correctly positioned within its real-world spatial context. This eliminated the georeferencing challenges encountered with IFC 2x3 and facilitated a smooth transition from BIM to GIS environments.

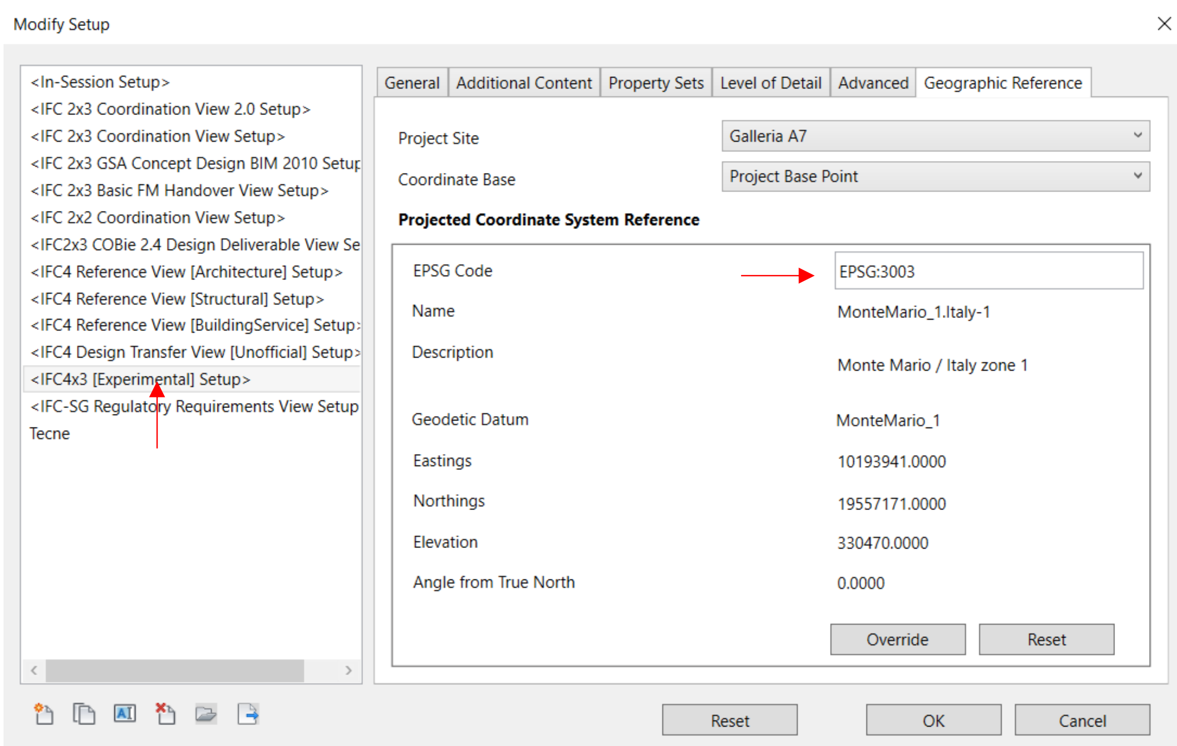


Figure 31. IFC 4x3 version

As observed in figure 31 above, there was no significant difference between IFC 4 and IFC 4.3 in terms of georeferencing capabilities. Both versions allowed us to define the EPSG code, enabling the correct projected coordinate system to be set. This ensured that the 3D model could be accurately positioned within the GIS environment.

Table 1. Comparison of IFC Versions and Their Georeferencing Capabilities

IFC Version	Georeferencing Support	EPSG Code Support	Coordinate System	GIS Integration
IFC 2x3	❌ Limited	❌ Not Supported	Basic Local Coordinates	❌ No
IFC 4	✅ Full Support	✅ Supported	Projected & Geographic	✅ Yes

IFC 4.3	✅ Full Support	✅ Supported	Projected & Geographic	✅ Yes

After successfully exporting the model in IFC 4 format, the next step was to import and validate it within a GIS-compatible environment. To achieve this, we utilized Blender 4.1, which offers a robust IFC plugin specifically designed for handling IFC models with high accuracy and detail. This plugin allowed us to thoroughly inspect and verify all model elements, ensuring that the geometric integrity, metadata, and georeferencing parameters were correctly maintained before proceeding with further GIS integration.

To ensure that Blender 4.1 can properly read and process the IFC file, it is necessary to first install the BlenderBIM add-on. This can be done by navigating to:

Edit → Preferences → Add-ons → Install and then select the BlenderBIM plugin for installation. Once the plugin is successfully installed and activated, Blender will be able to load IFC files, allowing us to visualize, inspect, and verify the model before further GIS integration. After completing these steps, we can now upload the IFC file into Blender for further processing and visualization. Additionally, an essential feature in this workflow is the ability to merge the IFC model with the real-world environment. This can be achieved by installing the **BlenderGIS** plugin, which allows us to import geospatial data and generate a real-world terrain representation within Blender. By integrating the IFC model with geospatial data, we can accurately position the 3D tunnel model within its actual environment, enhancing spatial analysis and visualization for further GIS applications. These steps are represented in the figure below.

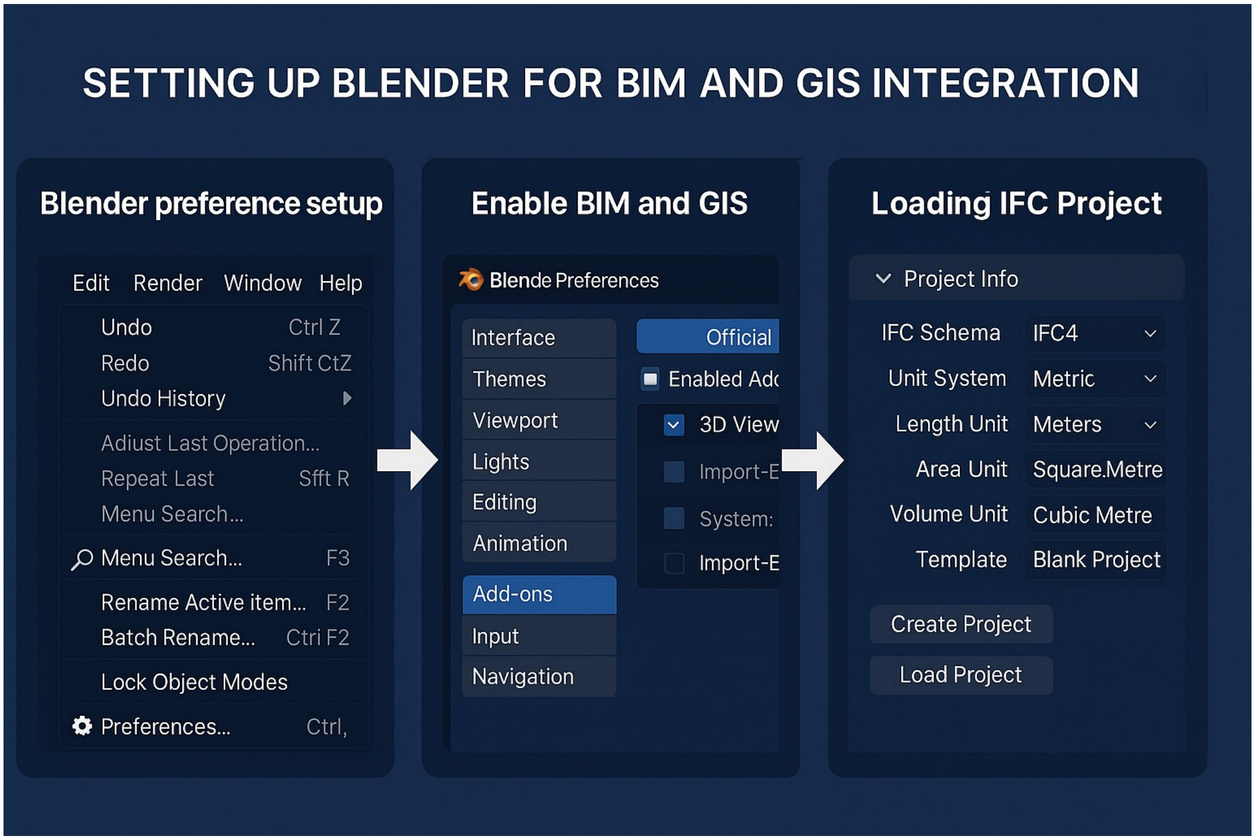


Figure 32. Blender Setup Process for IFC-Based BIM and GIS Compatibility

- **Blender Cesium ion Integration**

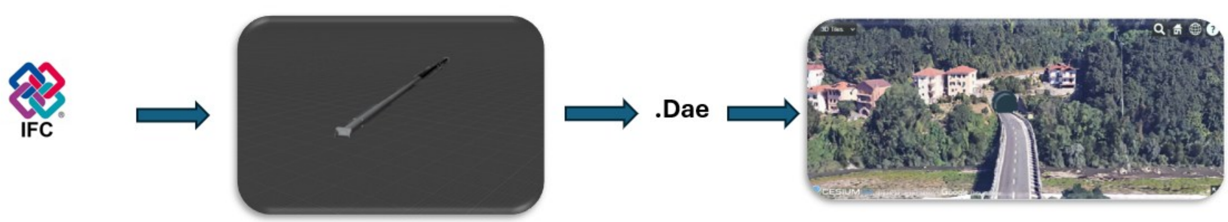


Figure 33. Integration between Blender and Cesium ion

To integrate the IFC-based tunnel model into Cesium Ion for real-world visualization, the model first needs to be exported from Blender in a compatible format. The Collada (.DAE) format was selected for this purpose, as Cesium Ion supports .DAE files for 3D geospatial rendering.

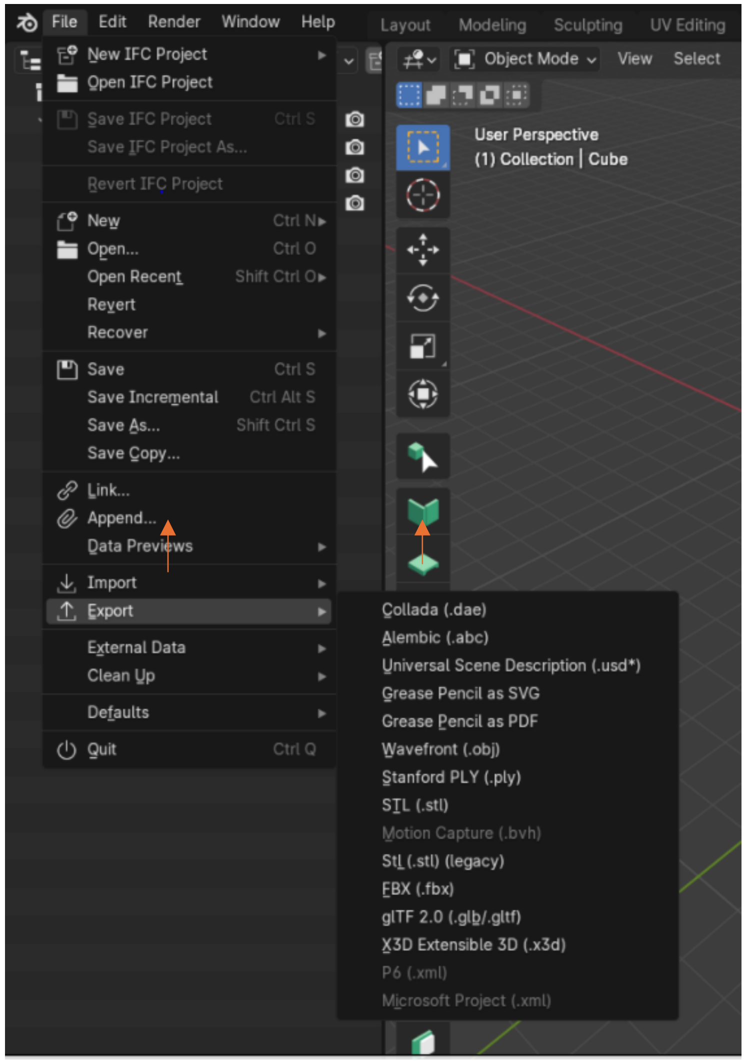


Figure 34. Exporting file as. dae format

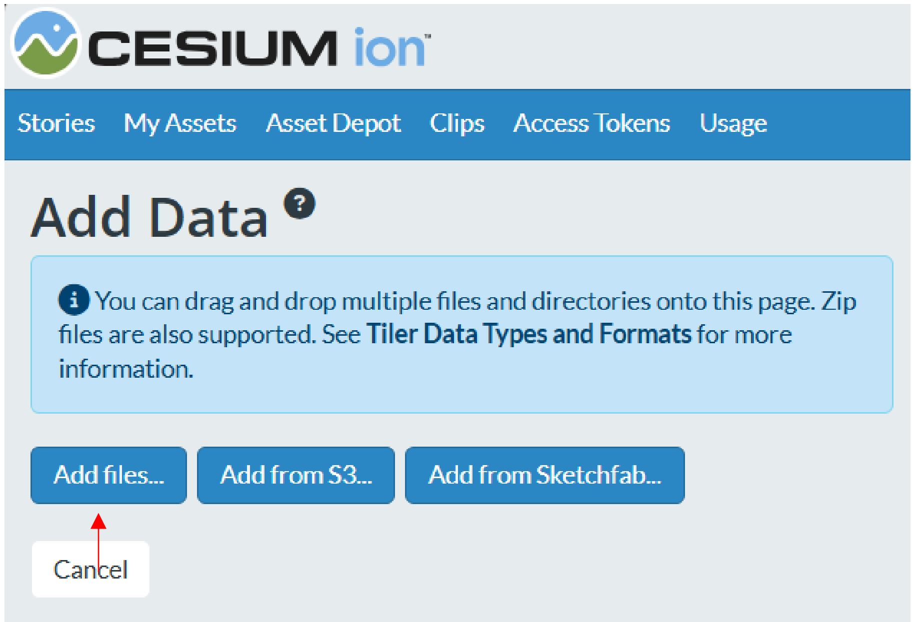


Figure 35.Uploading 3D Model Data to Cesium Ion (Cesium ion platform, n.d.)

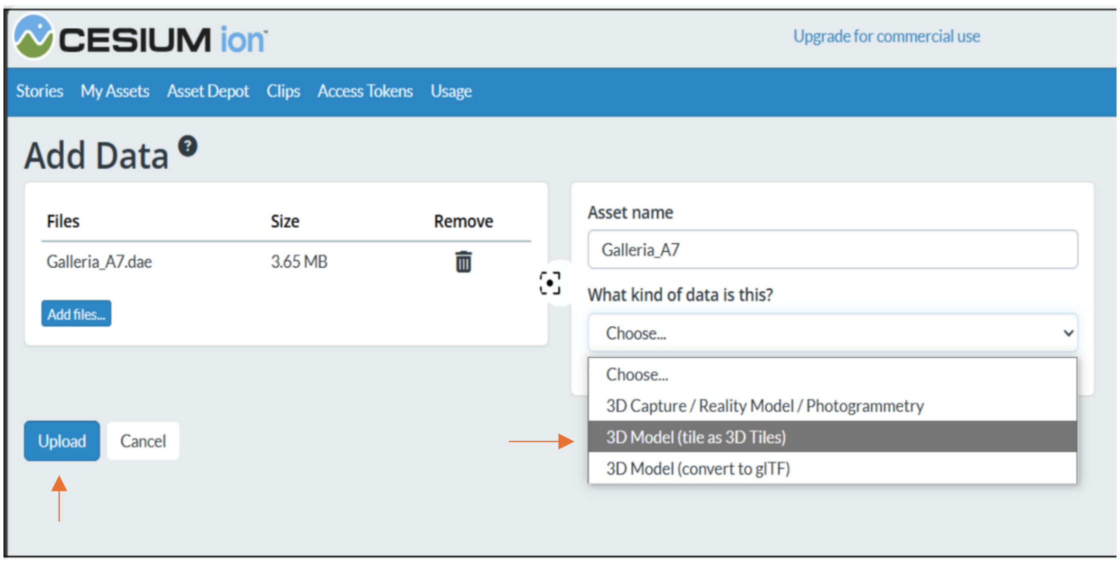


Figure 36.Uploading 3D Model Data to Cesium Ion (Cesium ion platform, n.d.)

Figure 36 shows 3D Tiles which are a smart way to handle large and detailed 3D models like entire cities, buildings, or landscapes. Trying to load something that is big all at once in a web browser can slow everything down or even make it crash.

Instead, 3D Tiles break the model into smaller, more manageable pieces like puzzle tiles. This way, your browser only loads the parts you need to see, which keeps things running smoothly and makes it much easier to explore complex 3D environments online.

After uploading the model to Cesium Ion, it was observed that the model's elevation did not perfectly match the actual terrain. The tunnel appeared elevated above its intended position, which was likely caused by inconsistencies in coordinate system transformation or differences in the terrain data used by Cesium Ion. To correct the elevation offset, we utilized Cesium Ion's JavaScript-based georeferencing tools, as Cesium Ion operates as an online 3D GIS visualization platform with customizable scripting features.

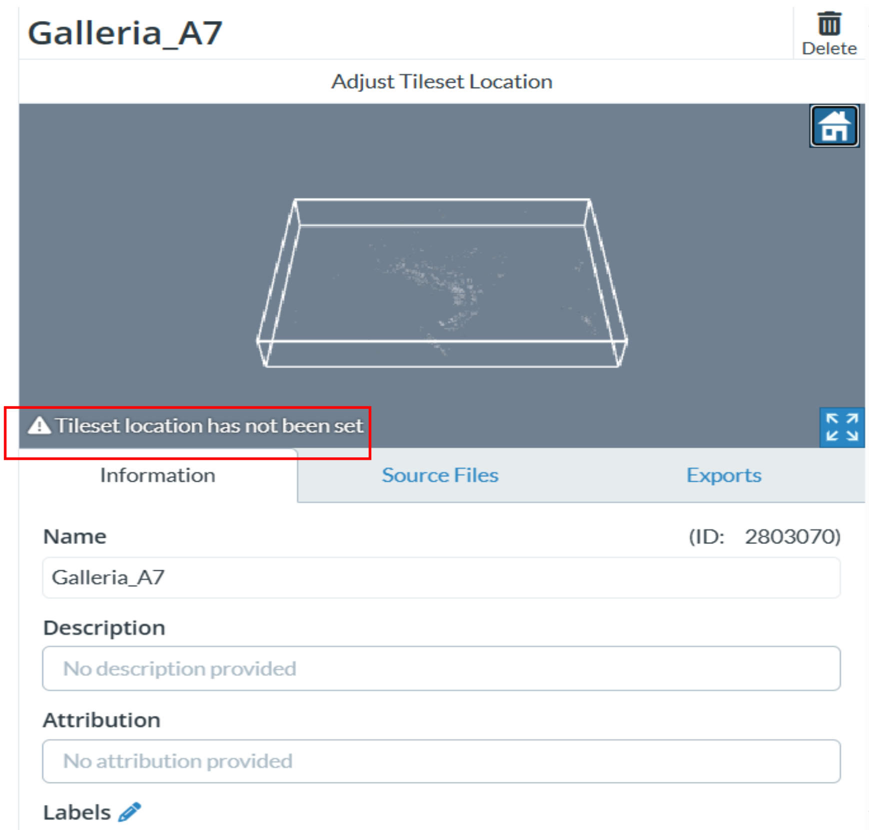


Figure 37.Adjust Tileset location for Tunnel (Cesium ion platform, n.d.)

Figure 37 shows the notice "Tileset location has not been set" and essentially indicates that although Cesium has received your 3D model, it is still unsure of where to place it on the globe. It's like having a building model but not specifying its placement on the map, so it merely floats in space without any place.

This can be fixed by manually setting the model's position, its actual location on Earth through the Cesium interface or by modifying its coordinates in code. When you do so, the model will show up on the map precisely where it should.

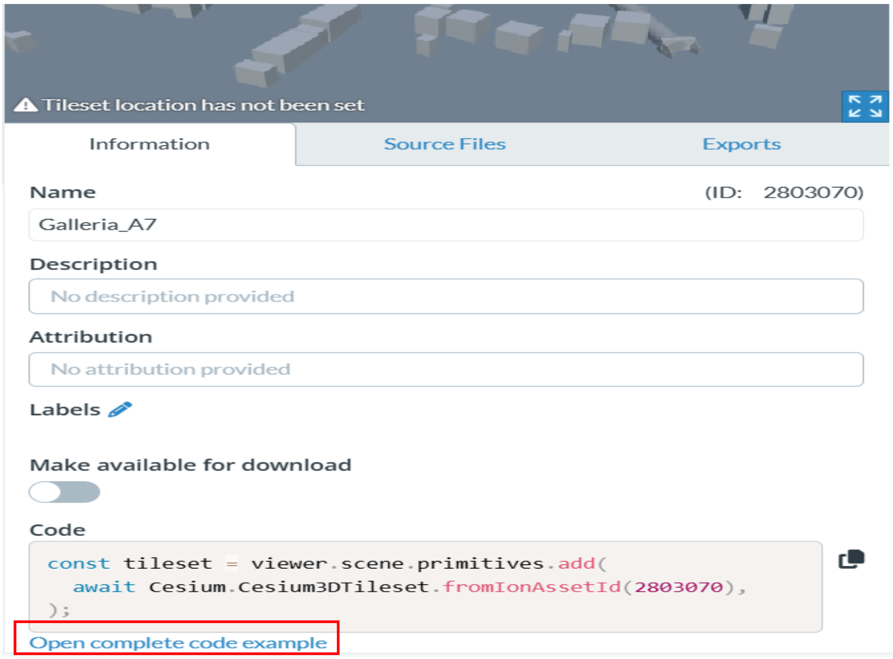


Figure 38. Editing the tileset location by JavaScript code (Cesium ion platform, n.d.)

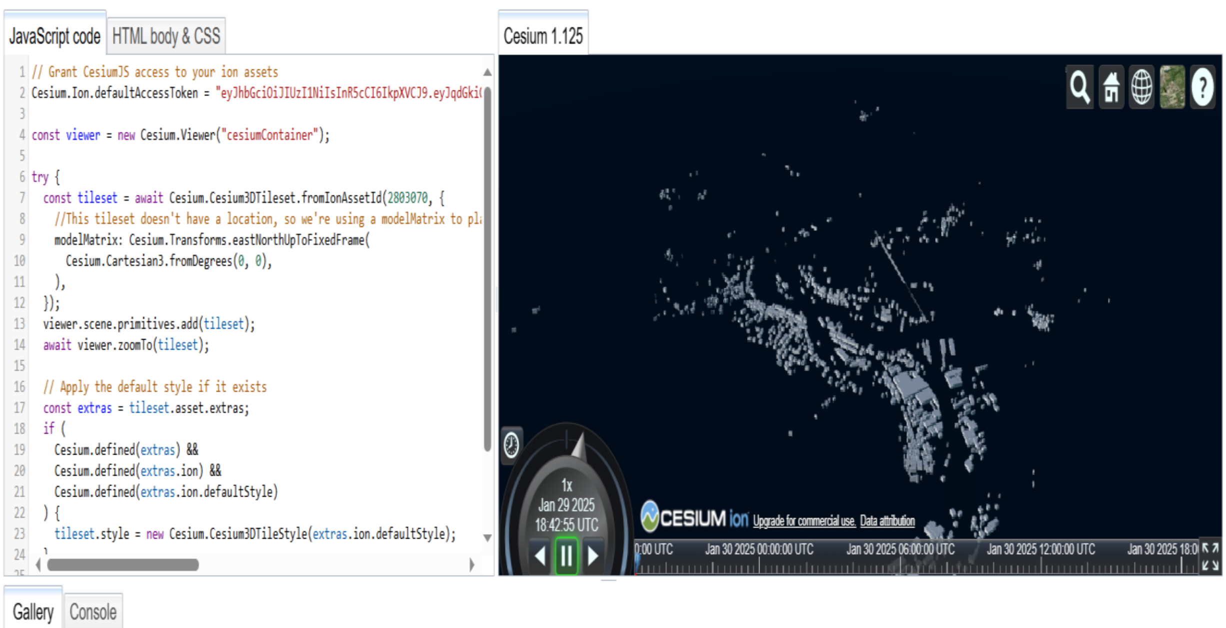


Figure 39. JavaScript code provided by Cesium ion (Cesium ion platform, n.d.)

This script shown in figure 39 is essentially performs the magic behind the scenes to enable you to view and interact with a 3D model, such as a city or building, in your web browser. After accessing the 3D data you've contributed through your Cesium ion account, it uses Cesium to load the model into a virtual globe. The model is then positioned appropriately, and the camera is zoomed in so you can begin exploring, otherwise you would be stuck with large 3D files that are difficult to utilize or share if you didn't have this script. Even with extremely intricate models, this code ensures that everything functions flawlessly in the browser. It transforms complicated 3D data into an explorable and interactive format, making it ideal for applications such as simulations, architecture, and city planning. It is, in essence, the instrument that brings 3D to life on the web.

After implementing JavaScript code in Cesium Ion, we were able to correct the georeferencing issue and properly align the 3D tunnel model with the real-world terrain. By adjusting the position, scale, and elevation parameters through Cesium's geospatial transformation functions, the model was successfully placed in its correct location. This step ensured that the BIM-GIS integration was accurate, allowing for realistic visualization and further spatial analysis.

- **Blender ArcGIS pro Integration**

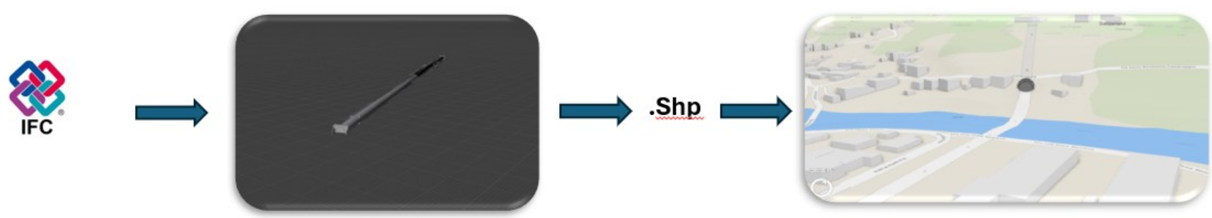


Figure 40.Integration between Blender and ArcGIS pro

To further improve the real-world visualization of the IFC model, integration between Blender and ArcGIS Pro was performed. The IFC model was exported from Blender as a Shapefile (.SHP), allowing it to be read and processed within ArcGIS Pro.

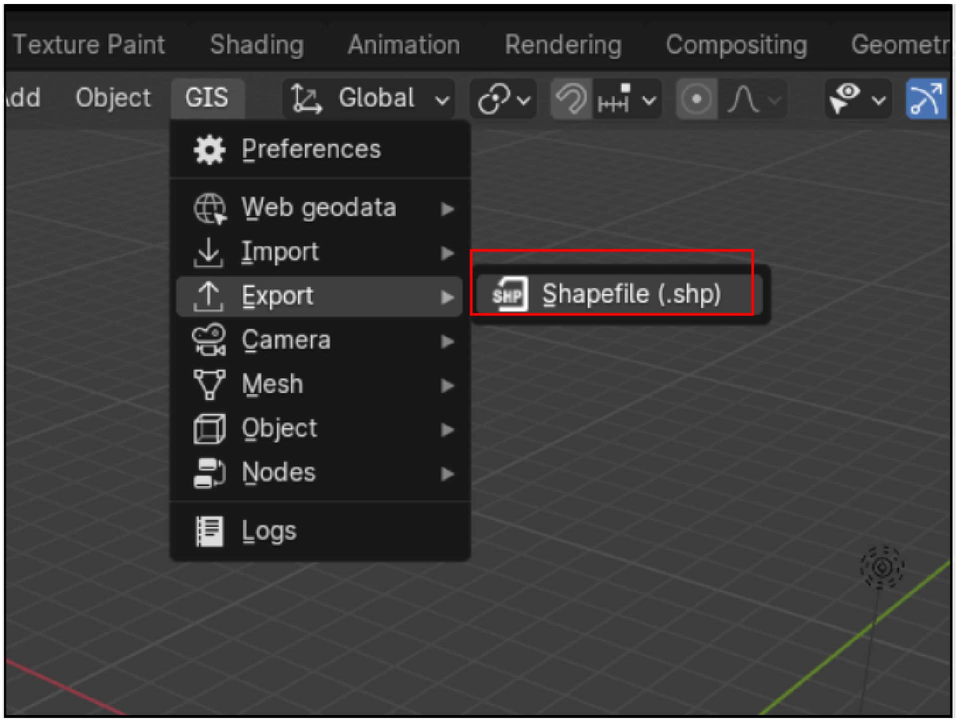


Figure 41. Exporting Model to .shp (Blender Platform, n.d.)

The figure 41 above illustrates the process of exporting a 3D model from Blender into a geospatial format using the GIS plugin. As shown in the figure, the model is exported as a Shapefile (.shp), a standard format in GIS that allows geometric features to be represented with real-world coordinates. This exported file can then be integrated into a mapping platform, as demonstrated in the second figure, where the same 3D model appears accurately positioned within a real urban environment. This workflow allows for seamless transition from 3D modeling to spatial visualization, making it easier to analyze infrastructure within its actual geographic context.

Upon importing the model into ArcGIS Pro, it became evident that the model lacked proper georeferencing, as it did not align correctly with its real-world coordinates. To address this issue, we:

1. Attempted to set the model's location using ArcGIS Pro's spatial adjustment tools, which placed it relatively close to its intended position but not perfectly aligned.
2. Performed manual georeferencing by adjusting the model's placement to ensure an accurate fit within the geospatial environment

By applying manual georeferencing corrections, the model was successfully aligned with its real-world position, ensuring better accuracy in visualization and analysis within the GIS environment.

3.4. Creating Geological model

3.4.1. Merginig GeoData with GeoBIM

To build the geological model in Blender, I first created a 3D terrain of the study area. This gave me a solid base to work on. Then, using a geological map I prepared in ArcGIS Pro, I focused on the specific area where the tunnel is located and investigated the types of rocks and soils present.

From that, I found that the subsurface mainly consists of three different geological formations: Paleozoic–Precambrian rocks (pCM), Mesozoic rocks (Mzm), and Triassic formations. I modeled each of these in Blender as separate layers and gave them different colors to make them easy to distinguish visually

Paleozoic–Precambrian rocks typically consist of crystalline basement such as granites, schists, and gneisses. These formations have extremely low matrix permeability due to their compact mineral structure and lack of connected pore space. However, in areas where faulting and fracturing occur, localized permeability may be slightly enhanced. Overall, their ability to transmit fluids is extremely limited, making them suitable as geological barriers rather than reservoirs. Permeability score: 0–10 out of 100 (Neuzil, C. E. , 1994) .

While Sandstones, limestones, and marls are among the many different types of lithologies found in Mesozoic formations, and their permeability varies greatly. Clean, well-sorted Mesozoic sandstones can be excellent reservoirs with high permeability, whereas tight limestones or marls, unless they are karstified or fractured, show low fluid conductivity. Karstified carbonates may have extremely high permeability because of dissolution-enhanced pore networks. (Nelson, P. H., 2009).

In addition to that, Triassic formations include a mix of red bed sandstones, shales, evaporites, dolomites, and carbonates. Sandstones from this period can exhibit moderate to high permeability if they are loosely cemented and well-sorted. On the other hand, shales and evaporites are extremely impermeable and are often used as caprocks in subsurface storage. Dolomites can be moderately permeable if fractured. The variability in lithology gives Triassic rocks a broad permeability spectrum (Bense, V. F., & Person, M. , 2006) .

After setting up the geology, I imported the tunnel model and aligned it with the terrain. I then checked along the tunnel's path to see which segments passed through each type of rock. This helped me assign the correct geological unit to each section of the tunnel.
Ideally, the model would have been even more accurate if we had borehole data, since that kind of information gives much better insight into what's underground at specific depths. But unfortunately, we didn't have access to borehole logs for this project, so we had to rely solely on surface geological data.
Still, this method gave a clear and useful picture of how the tunnel interacts with the surrounding geology and was a key step in supporting the spatial and risk analysis in the rest of the project.

After I finished setting up the geological layers and placing the tunnel model correctly in Blender, I moved on to connecting each part of the tunnel with the type of ground it passes through. To do this, I extracted the names of the tunnel segments and matched them to the geological volumes they intersect.
I used something called the GUID from the IFC file which stands for Globally Unique Identifier. Basically, it's a special code that every object in the model has, kind of like a fingerprint. It helps keep track of each tunnel segment no matter where the data is used, which makes everything more organized and easier to reference later.
By linking each tunnel segment to the type of soil or rock it passes through, I created a dataset that's useful for predictive maintenance. For example, if a segment crosses through soil that's more permeable, we can flag it as more vulnerable to water infiltration or even leaks during heavy rainfall. That way, instead of just reacting to problems when they happen, we can anticipate them.
This kind of insight helps us make smarter decisions, like predicting if a certain tunnel segment is likely to move into a higher risk category in the future. So, even though we didn't have borehole data, this process still gives us a strong foundation for proactive tunnel monitoring and maintenance.

Table 2. BIM–GIS–GeoBIM Integration Summary

	Software	File Format	Integration Output	IFC Version Used	BIM-GIS Integration Level
Data Collection	–	PDF	Initial data source	–	–
BIM Modeling	Autodesk Revit	RVT, IFC	3D tunnel model with metadata	IFC 2x3 / IFC4	High (with IFC4), Limited (IFC2x3)
Infrastructure Contextual.	InfraWorks	RVT	Integrated terrain + infrastructure	IFC4	–
GIS Preparation	Blender	IFC	3D visualization and spatial referencing	IFC 2x3 / IFC4	Medium–High geolocation required (IFC4), georeferencing not possible (IFC 2x3)
GIS Visualization	Cesium ion, ArcGIS Pro	3D Tiles, SHP, IFC	Real-world visualization + terrain integration	IFC4	High (with correct EPSG in IFC4)
Geological Mapping	ArcGIS Pro	SHP	Geological layers and subsurface interpretation	–	Full GIS integration
Geological Modeling	Blender	OBJ, custom mesh	Geological volume and soil classification	–	Linked through GIS/BIM coordinates

This table summarizes the complete workflow used for integrating BIM and GIS tools to create a GeoBIM environment. Each step is linked to a specific software and file format, showing how the data was transferred and processed.

3.5. Analysis of Relevant Risks and Classification Tunnel

Focusing on the evaluation of existing road tunnels defined as underground structures where one dimension greatly exceeds the other two. This includes not only traditional tunnels but also artificial tunnels, underpasses, and rockfall shelters, as long as at least one structure in the system exceeds 200 meters *(Ministry of Sustainable Infrastructure and Mobility, 2022)*.

The proposed framework for tunnel safety assessment at the territorial level is built on a series of coordinated steps. It begins with cataloging all relevant infrastructure and collecting design, operational, and maintenance history. This includes both structural data and insights from previous interventions. Initial on-site inspections are then performed to identify visible defects and assign each tunnel section a preliminary "attention class" based on various risk categories: structural (local and global), geotechnical, seismic, hydraulic, geological, road safety, and non-structural risks.

Each of these risks is evaluated independently through three main parameters: **hazard**, **vulnerability**, and **exposure**. Together, they form the basis for assigning a risk level, which is then consolidated into an overall attention class. Special attention is given to hydraulic and geological risks, which often require dedicated data and analysis. A "diffusion index" is used to map the severity of risks along the tunnel, helping to prioritize areas that may require urgent intervention.

To make this framework compatible with predictive maintenance strategies, all parameters were carefully modeled and structured within the BIM environment. Using Autodesk Revit, custom property sets (Psets) were created for each risk category. These include attributes such as material degradation indicators, inspection dates, geotechnical layers, groundwater levels, and structural conditions. These properties were configured to ensure compatibility with the IFC schema, allowing full export of risk-related data into open formats like IFC 4. This not only enables interoperability with GIS and asset management systems but also allows data to be used for predictive analysis, monitoring, and scheduling of future interventions.

By embedding these risk parameters into the BIM model, the tunnel becomes a dynamic asset that supports not just visualization but also long-term performance tracking. The exported IFC model can be integrated into GIS tools, where the data is used to generate heatmaps, risk profiles, and maintenance forecasts.

This standardized approach is aligned with, ensuring consistency across Italy's extensive tunnel network. While past efforts largely focused on new tunnel design and construction, the shift today is toward managing aging infrastructure ensuring safety, service continuity, and cost-effective maintenance. Predictive maintenance plays a important role in reducing emergency repairs and extending the useful life of assets, ultimately supporting better financial planning for both public authorities and concession operators.

Table 3. Level of Assessment

Assessment Level	Description
Level 0	Cataloging all tunnels, collecting geometric and structural data, and compiling a national database for systematic monitoring.
Level 1	Conducting initial inspections to validate tunnel conditions, identify defects, and determine potential risks.
Level 2	Classifying tunnels based on risk factors such as structural, geological, and hydraulic conditions to assign an attention class.
Level 3	Preliminary safety evaluations to assess potential failures in the tunnel lining and interaction with surrounding geological formations.
Level 4	Detailed safety assessments following technical standards to ensure regulatory compliance and safety measures.
Level 5	Reserved for critical tunnels requiring advanced resilience studies, analyzing socio-economic impacts of tunnel failures.

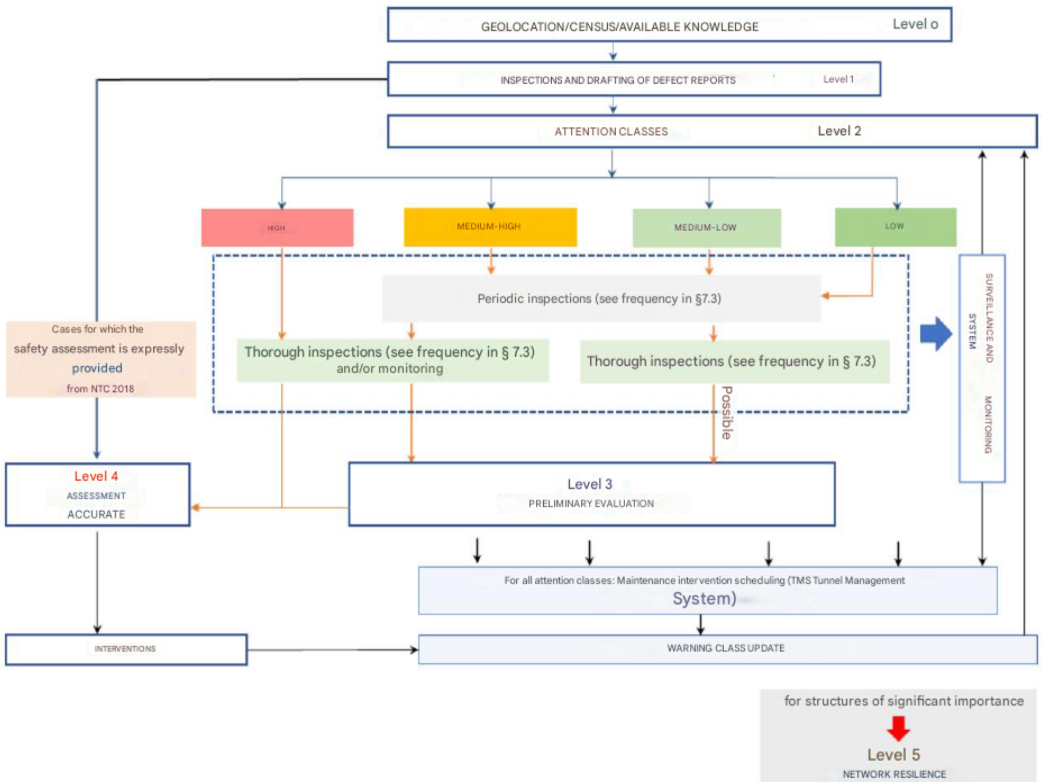


Figure 42. Multilevel approach and relationships between levels of analysis (Ministry of Sustainable Infrastructure and Mobility, 2022)

We will be focusing on Level 2 tunnel classification which provides an approximate risk assessment based on expert judgment rather than a precise calculation. This classification assigns each tunnel an "Attention Class" (CdA) to help prioritize inspections, maintenance, and interventions. While it does not replace detailed risk analysis, it helps in decision-making regarding tunnel safety.

Table 4. Attention Classes

Attention class	Risk Level
High Class	Severe
Middle-Upper Class	Significant
Lower-Middle Class	Moderate

Low Class	Minimal

Each tunnel is classified based on three key parameters:

Table 5. Key Parameters

Danger	Structural integrity, external risk factors.
Exposure	traffic volume, tunnel length, infrastructure interactions.
Vulnerability	Susceptibility to defects, degradation rate.

To assess and manage tunnel safety, the classification system evaluates six major risk categories:

Table 6. Risk Categories

Global Structural and Geotechnical Risks	Tunnel interaction with natural formations.
Local Structural Risks	Non-structural elements like signs or ventilation.
Seismic Risks	Effects of earthquakes and fault activity.
Road Risks	Traffic-related hazards and road safety conditions
Geological Risks	Landslide susceptibility and rock stability.
Hydraulic Risks	Water ingress, flooding risks.

Each risk type is assigned a separate Attention Class, which is then combined to determine the tunnel's overall Degree of Danger (BoD). This BoD rating influences decision-making on further inspections and necessary structural reinforcements.

3.5.1 General Structure of the Attention Classification Method

The Attention Classification Method is based on a systematic set of procedures intended to evaluate tunnel safety conditions impartially and rank maintenance tasks. The essential elements of the classification process are described in this sub-chapter. The first step is to identify the primary and secondary factors that provide a framework for risk assessment.

Each of the three primary risk factors exposure, vulnerability, and danger is categorized into four risk classes using these parameters. To determine the overall Attention Class for each tunnel segment, the technique then uses a logical classification framework that integrates these judgments. A transparent, data-driven strategy for evaluating tunnel conditions and organizing interventions is ensured by this methodical approach.

Key Steps in the Classification Process:

1. Primary and Secondary Parameters:
   - Primary parameters are the most important factors influencing the classification and are identified based on expert judgment, drawing from data collected in the Level 0 census and Level 1 inspections.
   - Secondary parameters are additional factors that can adjust or refine the classification, further specifying risk levels.
2. Risk Factor Classes:
   - For each of the three risk factors (danger, vulnerability, and exposure), four possible classes are identified: low, medium-low, medium-high, and high. These are determined by specific criteria and ranges for each primary parameter.
   - Once the primary parameters are classified, they are further refined based on secondary parameters, which can adjust the initial classification.
3. Logical Classification Scheme:

Figure 43.Logical flow for determining the attention class (Ministry of Sustainable Infrastructure and Mobility, 2022)

- The determination of the Attention Class for each tunnel is carried out using a logical flow approach, where each primary and secondary parameter is grouped into relevant classes. These classes are then combined logically to determine the overall danger, vulnerability, and exposure levels, leading to the final Attention Class.

The attention class, also divided into 4 classes, is finally obtained from the combination of the hazard, vulnerability and exposure classes according to the general scheme, valid for all aspects that contribute to the definition of the risk as reported in the following tables:

Table 7.HIGH hazard/ susceptibility class

		Exposure class			
		High	**Medium-High**	**Medium-low**	**low**
Vulnerability class	**High**	**HIGH**			
	Medium-High	**High**		**Medium-High**	
	Medium-low	**Medium-High**		**Medium-low**	
	Low	**Medium-low**		**Low**	

Table 8.. MEDIUM-HIGH hazard/ susceptibility class

		Exposure class			
		High	**Medium-High**	**Medium-low**	**low**
Vulnerability class	**High**	**HIGH**			
	Medium-High	**High**		**Medium-High**	
	Medium-low	**Medium-High**		**Medium-low**	
	Low	**Medium-low**		**Low**	

Table 9.MEDIUM-LOW hazard/ susceptibility class

		Exposure class			
		High	**Medium-High**	**Medium-low**	**low**
Vulnerability class	**High**	**HIGH**			
	Medium-High	**High**		**Medium-High**	
	Medium-low	**Medium-High**		**Medium-low**	
	Low	**LOW**			

Table 10.Low hazard/ susceptibility class

	Exposure class			
	High	**Medium-High**	**Medium-low**	**low**

<table>
<tr><td rowspan="4">Vulnerability class</td><td>High</td><td colspan="2">HIGH</td></tr>
<tr><td>Medium-High</td><td>High</td><td>Medium-High</td></tr>
<tr><td>Medium-low</td><td>Medium-High</td><td>Medium-low</td></tr>
<tr><td>Low</td><td colspan="2">LOW</td></tr>
</table>

3.5.1.1 Estimate of The Global Structural and Geotechnical Hazard Level

The Global Structural and Geotechnical Attention Class evaluates the overall structural behavior of the tunnel, particularly the final lining, and its interaction with the surrounding rock or soil. This involves considering factors such as the magnitude and variation of loads acting on the structure, compared to the design expectations, as well as the inherent structural characteristics of the tunnel lining and the extent of any defects present.

The parameters for determining the CdA are divided into "primary parameters" and "secondary parameters", as indicated in the following table.

Table 11.. Primary and secondary parameters for determining the hazard, vulnerability and exposure factors associated with global structural

	Primary parameters	Secondary Parameters
Dangerousness	Level of knowledge of the characteristics geotechnical, hydrogeological and hydraulic aspects of the rock mass and reliability of the geomechanically model	Geomechanically characteristics of the rock mass and/or soil External factors interacting with the tunnel structure
Vulnerability	Defect level Type of tunnel, constituent materials and construction problems	Rapidity of evolution of degradation Presence of circulating or infiltrating water and presence of the waterproofing layer
Exposure	TGM level Length of the tunnel	Heavy vehicles (mass 3.5 tons) Vehicles transporting dangerous goods Maximum design speed. Interference with buildings and infrastructure

The danger is related to the likelihood that the tunnel's final lining will experience stresses that differ from the design specifications, potentially approaching its structural limits. The potential for stress variations from the designed state depends on:

the geomechanically properties of the surrounding rock or soil, the reliability of the geomechanically model (i.e., the geological and geotechnical models), and external factors that interact with the tunnel structure.

Starting from an expert evaluation concerning the level of knowledge of the tunnel and the reliability of the overall geomechanical model, it is possible to define 3 different classes shown in *Table below.*

1. Geomechanical characteristics of rock and/or soil

   Assessing the level of knowledge about the tunnel and the surrounding geology is the first parameter. This is predicated on professional judgment regarding the degree of research and the geomechanical model's dependability. Three knowledge levels can be identified, as seen in Table 12:

Table 12. Classification of the level of knowledge of the geological model

High	Level of knowledge and reliability of the null geomechanical model
Average	Average level of knowledge and reliability of the geomechanical model
Low	Level of knowledge and reliability of the in-depth geomechanical model

2. External factors interacting with the tunnel structure

   This component considers the effects of the surrounding geology on tunnel stability. Strong geomechanical rock masses and soils typically serve as stabilizing factors, lowering possible risks. Table13 classification illustrates how the type of support utilized during excavation is influenced by ground quality:

Table 13. Classification of rock mass and/or soil characteristics

Class A	Medium to poor rock or soil requiring preliminary support (e.g., lining or consolidation)
Class B	Good-quality self-supporting ground with limited reinforcement (e.g., occasional bolting)

3. External Factors Interacting with the Tunnel Structure

   External factors such as adjacent infrastructure, unstable slopes, or continuing surface activity might cause additional stress on tunnel linings after construction. Table 14 classifies these outside factors according to how likely they are to cause variations in stress:

Table 14. Classification of external factors

Class A	Major load variation due to nearby works or slopes for tunnels with **low cover**
Class B	Moderate load variation for **medium cover** tunnels or minimal variation for low cover

The danger associated with the tunnel can therefore be assessed by combining the factors analyzed as shown in the following figure 44.

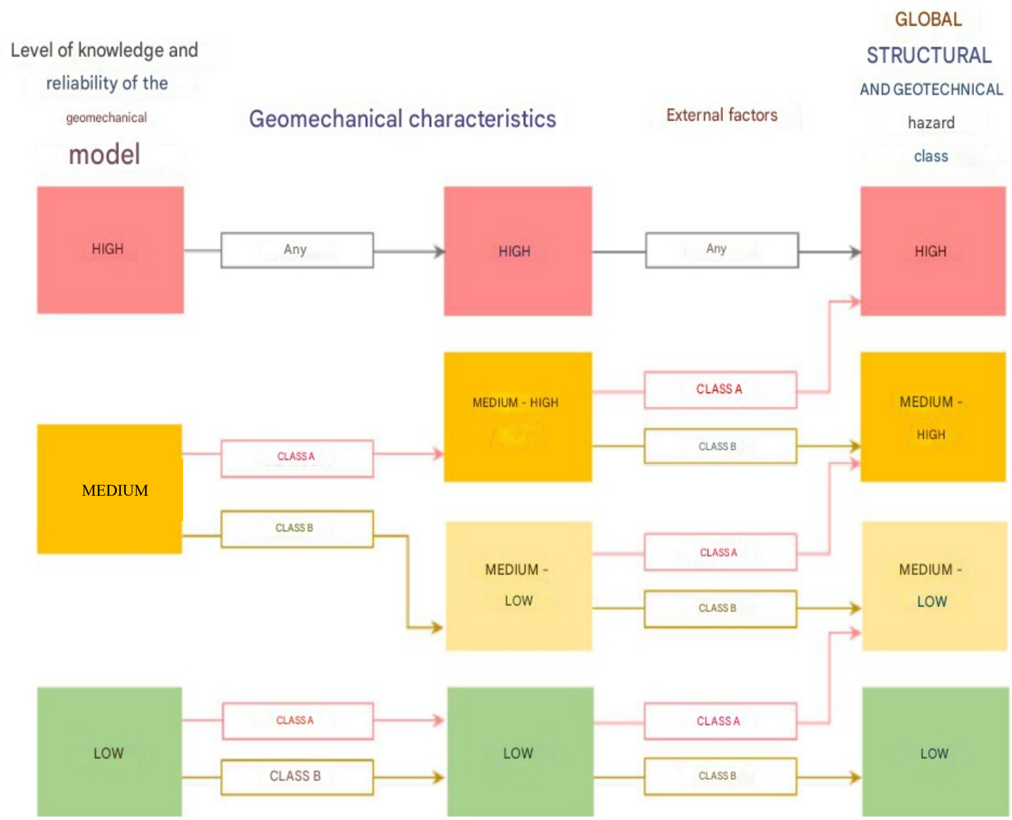


Figure 44.Logical flow for determining the global structural and geotechnical hazard class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.1.2. Estimation of the Level of Global Structure and Geotechnical Vulnerability

Defect severity, tunnel type, building method, and structural complexity are the primary indicators of vulnerability. Together, these are evaluated to give a comprehensive risk assessment.

The level of vulnerability depends on several parameters in particular:
When classifying vulnerabilities, the degree and scope of current flaws are quite important. Defects are classified by location (critical vs. non-critical zones) and intensity, as indicated in Table 13:

Table 13. Level of Vulnerability Parameters

Main parameters	level of defects, type of tunnel, construction techniques and complexity
Secondary parameters	speed of evolution of degradation, presence of the waterproofing layer

4. **Level of defects**

Table 14.Brief description of the level of defects for global structural and geotechnical vulnerability

HIGH	Defects of high or medium-high severity (G=4, G=3) and of any intensity on critical elements (cap and/or kidneys) or presence of critical conditions (very extensive and intense crackpatterns, construction defects, lowering of key of the ashlar)
MEDIUM-HIGH	Defects of high or medium-high severity (G=4, G=3) and of high intensity on non-critical elements such that they could trigger a crisis in the future which could compromise the statics of the work or its functionality
MEDIUM-LOW	Defects of medium-high severity (G=3) with medium-low intensity or defects of medium low and low severity (G=2, G=1) and of any intensity, in large numbers
LOW	Defects of medium-low or low severity (G=2, G=1) and of any intensity, in small numbers

5. Rapidity of degradation over time

The vulnerability of a tunnel is not determined solely by its level of defectiveness but also by how quickly defects have developed. A long-standing tunnel with defects may indicate normal aging, while similar defects in a newer tunnel suggest rapid deterioration, posing a greater risk. The year of construction or the last major maintenance intervention is a key reference. If maintenance has significantly restored the structure, the focus shifts to the most recent intervention. Tunnels with recent maintenance but persistent defects are considered more vulnerable.
To assess degradation progression, documentation from Level 0 surveys and detailed

inspections are analyzed. Based on construction or maintenance last year, tunnels were classified into three vulnerability categories:

1. Before 1950
2. Between 1950 and 1990
3. After 1990

After determining the year of construction and identifying or hypothesizing the maintenance interventions performed (when sufficient information is available), the appropriate category is assigned. Subsequently, the classification of the current defect level is adjusted following the logical framework illustrated in Figure 49**.**

6. Influence of water circulation and presence of the waterproofing layer

Water ingress is a major accelerator of structural degradation. Depending on its severity and the presence of waterproofing systems, the tunnel's vulnerability is adjusted. As shown in Table 16, water-related risks are assessed and can either increase, maintain, or reduce the tunnel's vulnerability class:

Table 15..Evaluation of the influence of water circulation and the presence of the waterproofing layer

HIGH	Presence or evidence of percolating water
MEDIUM-HIGH	Presence of widespread dripping at the casting joints and cracks or traces of water passage
MEDIUM-LOW	Presence of occasional drips in tunnels with a waterproofing layer or absence of drips in nonwaterproofed tunnels
LOW	Absence of percolating water or dripping in the tunnel with a waterproofing layer or traces of water passage

7. Type of tunnel, constituent materials and construction techniques and complexities

The type of tunnel, defined by its structural and dimensional characteristics, is also a key factor in evaluating vulnerability. This involves considering several related aspects:

1. The geometry and static design of the structure (e.g., shape, presence or absence of an inverted arch).
2. The material used for the lining.

3. The tunnel's diameter.

By consolidating these factors, the vulnerability class specific to the tunnel type can be determined, as outlined in the table below.

Table 16.Determination of the vulnerability class in relation to the type of Tunnel

Geometry and pattern static	Material	D < 7 m	7m < D < 11m	11m D < 15m	D > 15m
Uncoated gallery	/	For tunnels of this type refer to instability phenomena local			
Gallery of coating with shotcrete	Concrete	MEDIUM-HIGH	HIGH	HIGH	HIGH
Iron gallery of horse (without back bow)	masonry	MEDIUM-HIGH	HIGH	HIGH	HIGH
	concrete	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH	HIGH
	Approx.	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH	MEDIUM-HIGH
	mixed*	MEDIUM-LOW	MEDIUM-HIGH	MEDIUM-HIGH	HIGH
Horseshoe tunnel (with sub-horizontal contrast plate)	masonry	MEDIUM-HIGH	HIGH	HIGH	HIGH
	concrete	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH	HIGH
	Approx.	LOW	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH
	mixed*	MEDIUM-LOW	MEDIUM-HIGH	MEDIUM-HIGH	MHIGH
Gallery (with inverted arch)	concrete	LOW	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH
	Approx.	LOW	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH
Circular tunnel (precast segments)	Approx.	LOW	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH
Box gallery	Approx.	MEDIUM-LOW	MEDIUM-LOW	MEDIUM-HIGH	HIGH

*The term “mixed” refers to a composite structure (cast concrete-masonry).

Special attention should be given when a slab is present, typically used for ventilation compartmentalization, as well as in cases involving niches or extensions (such as parking areas) with sub-horizontal slabs. These scenarios require a detailed analysis, including an assessment of the quality of the supports. Based on this analysis, the tunnel type's vulnerability class in Table 16 can be increased by one level.

The quality of the final tunnel linings, especially in very old tunnels, is influenced by operational challenges encountered during construction (e.g., cold joints, water circulation near the lining during casting). This macro-factor includes an index to account for the construction techniques and complexity of the work. For instance:

- Excavation using explosives creates greater disturbance compared to full-section machine excavation.
- The use of consolidation, reinforcements, or improvements reduces the overall disturbance to the rock masses.
- Collapses observed at the excavation face during construction signal a potentially challenging condition that must be considered in assessing the vulnerability of the final lining.

Three categories of construction techniques and complexities are defined, as outlined in the following table.

Table 17.Classification of construction complexities

Class A	High degree of disturbance during the excavation phase - High construction problems - high complexity of the rock mass/soil -formation of chimneys and collapses during construction - parietal tunnels in landslides
Class B	Medium degree of disturbance during the excavation phase - medium construction problems - medium complexity of the rock mass/soil and/or sporadic collapses and absence of stoves during construction
Class C	Low degree of disturbance during the excavation phase - Absent construction problems - Low complexity of the rock mass/soil and/or absence of stoves during construction

As construction complexity increases, with reference to *Table 18,* the vulnerability class must be increased as shown in the following table.

Table 18. Determination of the vulnerability class according to the construction complexities and the type of tunnel

		Type of gallery			
		High	***Medium-High***	***Medium- Low***	***Low***
Construction	***Class A***	*High*	*High*	*Medium-High*	*Medium-*

complexity					*Low*
	Class B	*High*	*Medium-High*	*Medium-Low*	*Low*
	Class C	*Medium-High*	*Medium-Low*	*Low*	*Low*

In summary, vulnerability is the result of the combination of the various parameters, according to the logical scheme reported in Figure 49. From the diagram it is easy to see how, if the current defect level is high, the tunnel is still characterized by a high vulnerability class, regardless of the other factors considered.

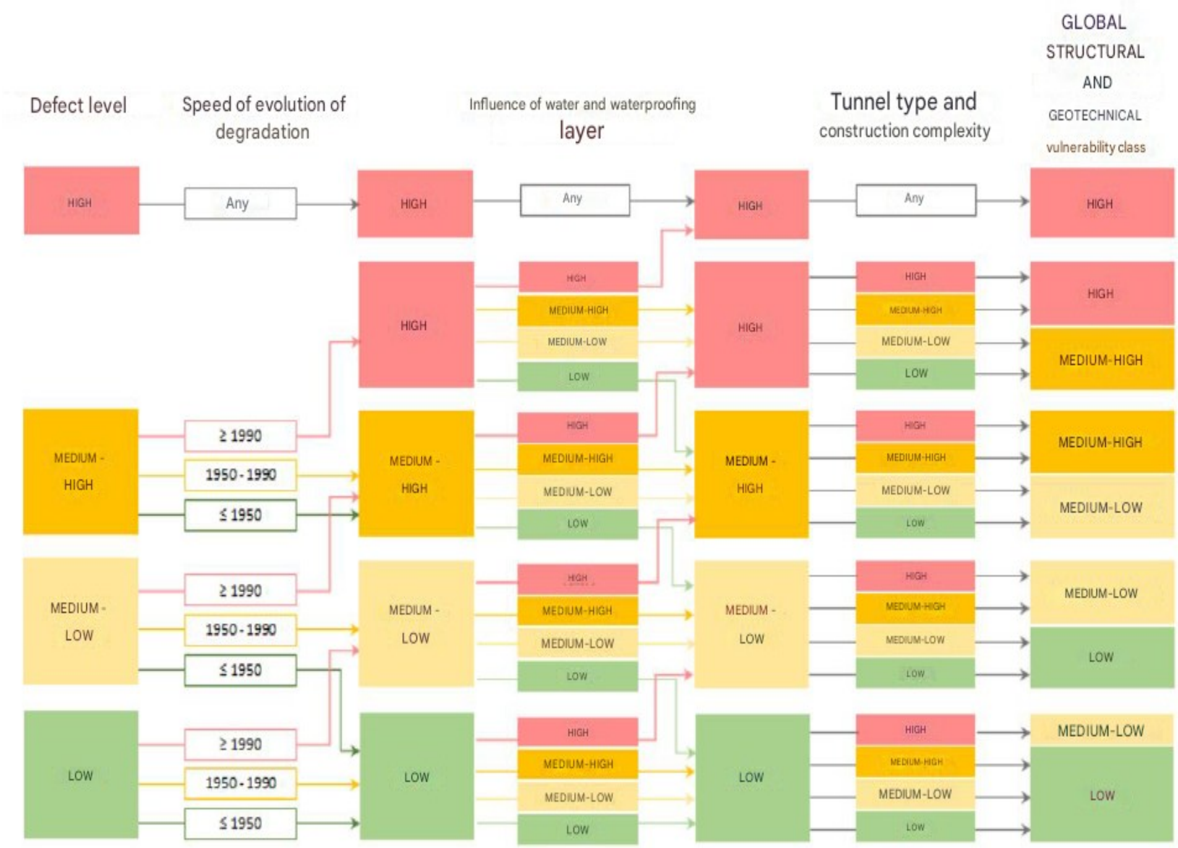


Figure 45. Logical flow for determining the global structural and geotechnical vulnerability class (Ministry of Sustainable Infrastructure and Mobility, 2022).

3.5.1.3. Estimation of the Level of Global and Structural Exposure

The evaluation of exposure level relies on traffic data related to the road network in question, considering the frequency of vehicle passage and factors associated with the network's resilience to unexpected events. This includes traffic characteristics and the potential risk to surface structures and infrastructures that could be affected by a tunnel failure.

8. ***The primary parameters: Average Daily Traffic (TGM) level and tunnel length***

Table 19. Average daily traffic level (vehicles/day on the entire roadway)

HIGH	*40000 vehicles/day*
MEDIUM-HIGH	*25000 vehicles/day < 40000*
MEDIUM-LOW	*10000 vehicles/day < 25000*
LOW	*< 10000 vehicles/day*

Table 20.Tunnel length

Class A	*L > 3000 m*
Class B	*1000m < L < 3000m*
Class C	*500m< L < 1000m*
Class D	*L < 500 m*

The classes thus determined relating to the TGM and the length of the tunnel are then combined according to the scheme indicated in the following table:

Table 21.Combination of primary parameters for evaluating the attention class

	L > 3000 m	*1000m < L < 3000m*	*500m< L < 1000m*	*L < 500 m*
40000 vehicles/day	*MEDIUM-LOW*	*MEDIUM-HIGH*	*HIGH*	*HIGH*
25000 vehicles/day < 40000	*MEDIUM-LOW*	*MEDIUM-HIGH*	*HIGH*	*HIGH*
10000 vehicles/day < 25000	*LOW*	*MEDIUM-LOW*	*MEDIUM-HIGH*	*HIGH*
< 10000 vehicles/day	*LOW*	*MEDIUM-LOW*	*MEDIUM-HIGH*	*HIGH*

9. ***Secondary parameters***

relating to heavy vehicles (mass >3.5 t) and the maximum design speed is reported in the following tables, respectively.

Table 22.: percentage of heavy vehicles

High	***Average***	***Low***
heavy vehicles > 15%	*5% < heavy vehicles <15%*	*heavy vehicles <5%*

High	***Average***	***Low***
120 <Vmax < 140 km/ h	*80 < Vmax < 120 km/ h*	*Vmax < 80 km/ h*

Table 23.maximum design speed (Vmax)

Similarly to the other factors, the value of the primary parameters determines a distinction into 4 classes or levels of exposure which is then modified by the secondary parameters, according to the scheme shown below:

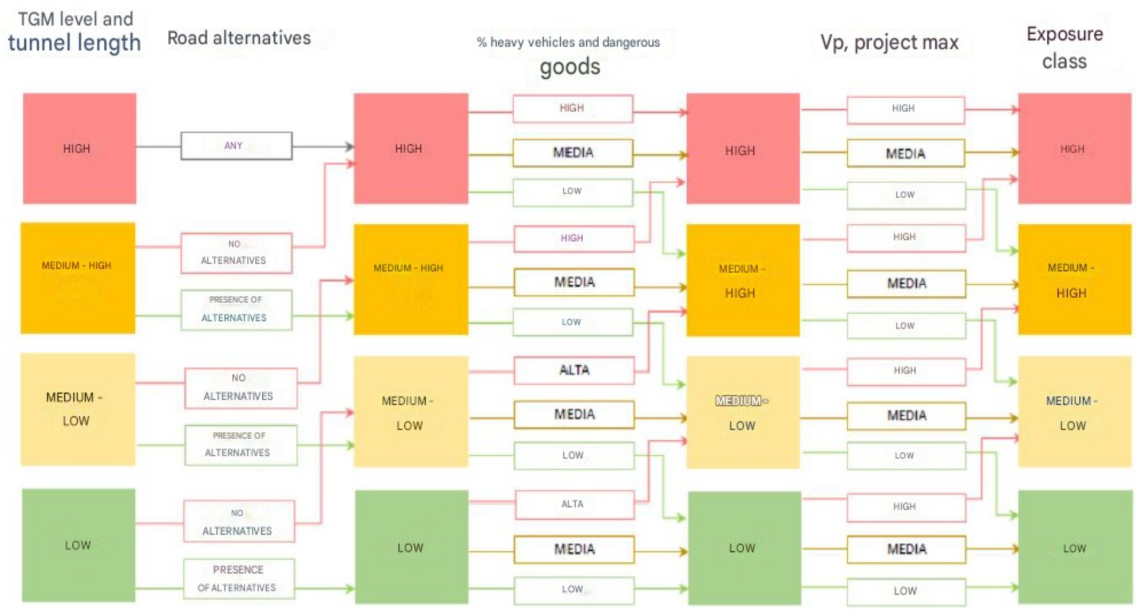


Figure 46.Logical flow for determining the Exposure Class (Ministry of Sustainable Infrastructure and Mobility, 2022)

The existence of buildings or surface-level infrastructures that interfere with the tunnel alters the exposure class defined in Figure 46 as outlined in Table 24. This table specifies the class of potential interference with buildings and infrastructures. Additionally, Table 25 adjusts the attention class based on the classification established in the previous table

Table 24.Potential interference with buildings and infrastructures

Class A	*In the presence of buildings/superficial infrastructures interfering with the tunnel with low coverage (for example entrances)*
Class B	*In the presence of deep tunnels or tunnels with low coverage without evident interference with superficial works*

Table 25..Correction of the Exposure Class defined in Figure 47

	Type of gallery			
	High	***Medium-High***	***Medium-Low***	***Low***

Interference with buildings and infrastructure	***Class A***	*High*	*High*	*Medium-High*	*Medium-Low*
	Class B	*High*	*Medium-High*	*Medium-Low*	*Low*

3.5.1.4. Estimation of the Global Structural and Geotechnical Danger

Once the relevant parameters are identified, the next step is to determine the overall structural and geotechnical attention class (CdA) by combining the tunnel's danger, vulnerability, and exposure classes, as outlined in Table 7. In these combinations, the vulnerability class of the tunnel is given greater weight. If the vulnerability is high, the final CdA remains high regardless of the danger and exposure classes. This approach ensures that, since the vulnerability class is directly linked to the level of deterioration, a tunnel with a concerning state of preservation one that reveals issues affecting its structural integrity at either a global or local levelwill always receive high priority attention, typically from the Board of Directors.

3.5.2. Local Structural Attention Class

The local attention class refers to situations where, for example, there are conditions possibly widespread, such as the detachment of sections of cladding that may interact with the road network, but do not cause overall instability of the structure. The key primary and secondary parameters to be considered in the calculation are outlined in the table below:

Table 26..Primary and secondary parameters for determining the hazard, vulnerability and exposure factors associated with local structural risk

	Primary parameters	***Secondary parameters***
Dangerousness	*Presence of water*	*Fck resistance of the coating*
Vulnerability	*State of fracturing Slab thickness (residual from construction defects) or presence of internal discontinuities in the cladding (for example cold joints, casting inhomogeneities). For unlined tunnels, reference is*	*Presence of armor History of the cladding and existing damage*

	made to the possibility of unstable slabs or dihedrals	
Exposure	*TGM level* *Length of the tunnel*	*Heavy vehicles (mass < 3.5 ton)* *Maximum design speed.* *Alternative itineraries*

3.5.2.1. Estimate of the Local Structural Hazard Level

To evaluate the presence of water for the tunnel lining, reference is made to the defect sheets. The following table shows the classification with reference to the characteristic resistance level of the coating considered

Table 27.Classification with reference to the resistance level of the final coating

Class A	*fck < 20 Mpa or masonry cladding*
Class B	*fck > 20 Mpa*

The local structural hazard associated with the tunnel can be assessed by combining the factors analyzed as shown in the following figure

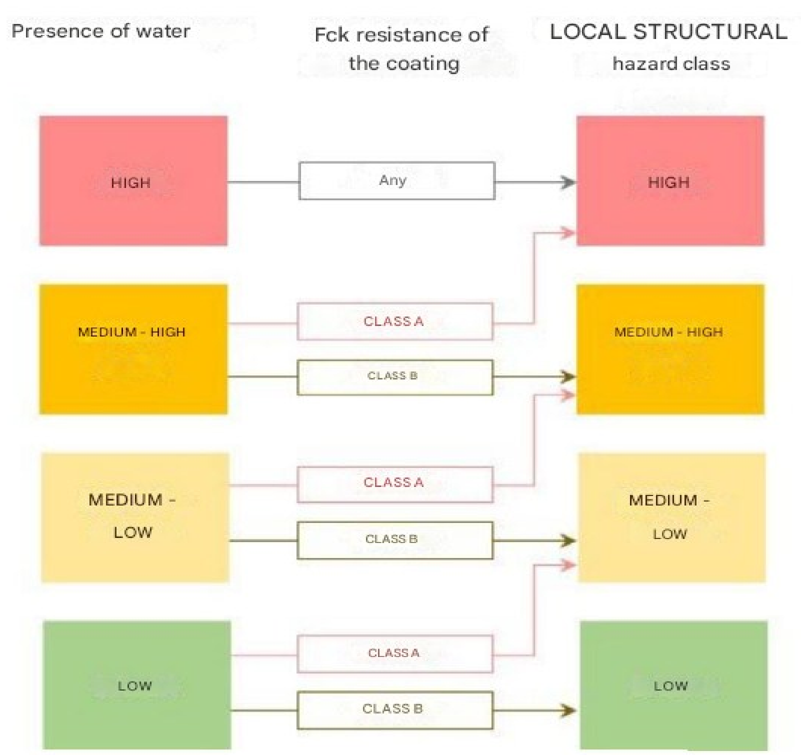


Figure 47.Logical flow for determining the local structural hazard class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.2.2. Estimation of Local Structural Vulnerability Level

The presence of insufficient thickness in the final lining during casting or cold joints caused by construction inconsistencies can lead to localized detachments in the tunnel cap or sidewalls, resulting in blocks or slabs detaching, even from the weight of the lining concrete itself. Conversely, the presence of reinforcement in the cladding helps mitigate the risk of this phenomenon. Table 28 outlines the classes based on the residual thickness of the coating due to construction defects. Special attention should be given when there are niches or widenings with any sub-horizontal slabs. In such cases, a specific evaluation must be conducted, also considering the quality of the support. The effect of reinforcement presence (or absence) in the cladding is accounted for by the classes defined in Table 29. Consequently, the Attention Class of the tunnel's local structural vulnerability can be assessed by combining the factors analyzed, as illustrated in Figure 48.

Table 28. Thickness of the sheet remaining from construction defects

CLASS A	*< 10cm*
CLASS B	*10-20 cm*
CLASS C	*>20 cm*

Table 29. Definition of the class depending on the presence of reinforcement

CLASS A	*Final covering without reinforcement or with corroded reinforcement*
CLASS B	*Reinforced permanent cladding*

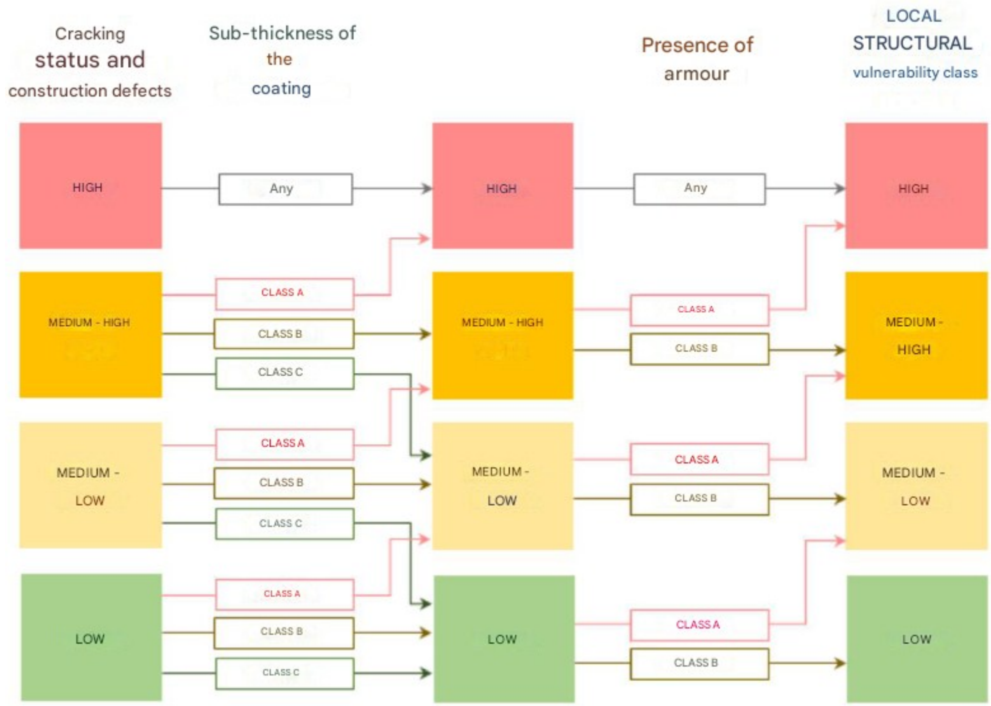


Figure 48.Logical flow for determining the local structural vulnerability class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.2.3. Estimation of the Local Structural Exposure Level

The definition of the Exposure Class is determined using the guidelines provided with reference to Figure 48.

3.5.2.4. Estimation of the Local Structural Attention Class

Once the parameters in play are known, we proceed with the determination of the attention class by combining danger, vulnerability and exposure of the tunnel using the logical relationships already presented in Figure 39.

3.5.3. Road Attention Class

The road attention class is determined by considering the key parameters that impact the safety and functionality of the tunnel under normal operating conditions. These parameters include the tunnel's geometric features, the condition and wear of the road surface over time, and the volume and composition of vehicular traffic. Additionally, factors related to the operation and management of the associated road network are considered. These parameters are categorized into primary and secondary groups, as detailed in the following table.

Table 30.Primary and secondary parameters for determining the danger, vulnerability and exposure factors associated with road risk.

	Primary parameters	Secondary parameters
Dangerousness	Road accidents	Fires
Vulnerability	Level of defectiveness of the road surface. Materials.	Rapidity of evolution of degradation. Design standards.
Exposure	TGM level Length of the tunnel	Heavy vehicles (mass < 3.5 t) Vehicles transporting dangerous goods at maximum design speed. Alternative itineraries

The danger on the road, arising from disruptions to the road surface, is associated with the likelihood of traffic accidents and/or potential fires, particularly in cases of severe collisions between vehicles or with fixed obstacles within the tunnel. The road danger indicator is represented by the accident rate, measured in accidents/108 vehicle-kilometers. All else being equal, longer tunnels may present a higher level of risk, making it beneficial to classify tunnels by their length, as shown in Table 23. Furthermore, for tunnels of the same length, those with more complex routes may pose greater risks. Danger classes can thus be defined based on the combination of tunnel length and route tortuosity, as illustrated in Table 34. The planimetric tortuosity of the route is quantified using a parameter known as CCR, which is defined as the ratio of the total angular deviation to the length of the curvilinear section (including colthoods and circular arcs).

Table 31.Road hazard classes

	TOTUOSITY OF THE TUNNEL ROUTE		
	High	Average	Low
CLASS A	High	High	High
CLASS B	High	High	Medium-High
CLASS C	High	Medium-High	Medium-Low
CLASS D	Medium-High	Medium-Low	Low

3.5.3.1. Estimation of The Level of Road Vulnerability

Vulnerability is influenced by various factors, particularly:

Table 32.Main and Secondary parameters of Road Vulnerability

Main parameters	Type of road surface defects. Extent and intensity of the defects
Secondary parameters	Rate of deterioration progression.

	Maintenance and/or renovation interventions.

The primary indicator of road surface defectiveness is the **IRI,** expressed in mm/m. The defect level reflects the condition of the road surface and can be evaluated by identifying defects through rapid assessments or, if necessary, using high performance measurement techniques. Data collected is analyzed to determine the severity of the defects. Defects are classified into four classes based on their severity, extent, intensity, and impact on vehicular traffic safety (or pedestrian safety, where pavements or platforms serve as escape routes). This classification considers significant accidents with notable consequences in tunnels, as detailed in the following table.

Table 33.Level of defects

HIGH	High severity defects of the road surface and of any extent and intensity whose presence can be caused in compromising the safety of users with high levels of severity of accidents.
MEDIUM-HIGH	Defects of medium-high severity and high extension and intensity on the road surface, the presence of which can contribute to compromising traffic safety with an attributable medium-high level of accident severity.
MEDIUM-LOW	Defects of medium-low severity with medium-low intensity and extension, the presence of which can compromise traffic safety with medium-low severity levels of accidents
LOW	Low severity defects of any extent and intensity that do not significantly contribute as a co-cause to compromising user safety.

The vulnerability of the road surface also depends on the structural strength of the road superstructure, including the layer thickness, material properties, and the subgrade's load-bearing capacity. Road surfaces will exhibit higher vulnerability when the superstructure has lower structural resistance or when the materials are more prone to degradation. For materials with identical physical and mechanical properties, Table 33 outlines the proposed vulnerability class based on the type of superstructure (flexible, semi-rigid, rigid with plates, rigid with continuous reinforcement), the materials' sensitivity to degradation, and their thickness (S), referring to the thickness of the individual layers forming the road superstructure

Table 34.Vulnerability classes depending on the type of road superstructure, sensitivity to degradation of materials and thicknesses (S)

Type of superstructure	Material	S < 15cm	15 < S <25cm	25 < S < 35cm	35 < S < 45cm
Flexible	Bituminous conglomerate	HIGH	MEDIUM-HIGH	MEDIUM-LOW	LOW
	Granular mix	HIGH	MEDIUM-HIGH	MEDIUM-LOW	LOW
Semi-rigid	Bituminous conglom	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Cemented mix	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Granular mi	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
Rigid in concrete jointed slabs	Cement conglomerate	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Cemented mix	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Granular mix	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
Rigid reinforced concrete continues	Cement conglomerate armed	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Cemented mix	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW
	Granular mix	MEDIUM-HIGH	MEDIUM-LOW	LOW	LOW

3.5.3.2. Estimation of the Level of Road Exposure

The assessment of the exposure level relies on traffic data from the relevant road network, considering the frequency of vehicles passing through, as well as factors related to the network's capacity to handle unforeseen events, such as its resilience and traffic characteristics. The parameters used to evaluate the exposure factor are categorized into:

- **Primary parameters:** Average Daily Traffic (TGM), tunnel length.
- **Secondary parameters:** Heavy vehicles (weighing ≥ 3.5 t), maximum design speed, alternative routes.

The determination of the Exposure Attention Class is made by following the guidelines, with reference to Figure 44.

3.5.3.3. Estimation of the Level of Road Attention Class

The determination of road attention classes is achieved by combining the danger, vulnerability, and exposure classes, as specified in Table 15. Notably, greater weight is given to the vulnerability class of the road surface. When vulnerability is high, the attention class is typically elevated, indicating a high priority for intervention.

3.5.4. Geological Warning Class Associated with Landslide Risk

The geological attention class for landslide risk considers parameters that assess the structure's spatial and temporal involvement in potential landslides. While artificial tunnels and underpasses in flat areas are generally excluded, particular focus is given to low-coverage tunnels and entrance zones. Like other attention classes, this classification combines hazard (termed "susceptibility" here), vulnerability, and exposure factors, using primary and secondary parameters. Unlike other classifications, "susceptibility" emphasizes spatial prediction based on Lith structural and hydrogeological factors, rather than temporal prediction due to challenges in estimating event occurrence probabilities.

Table 35..Parameters necessary for the definition of the geological attention class

	Primary parameters	Secondary parameters
Susceptibility	Slope instability (Magnitude, Speed, activity status)	Mitigation or monitoring measures
Vulnerability	Relationships between tunnel and morphological conditions: deep instabilities along the development or at the entrances Model uncertainty/assessment reliability	-
Exposure	TGM level Length of the tunnel	Heavy vehicles (mass < 3.5 t) Vehicles transporting dangerous goods Alternative itineraries Interference with buildings and infrastructure

Comparing Table 35 with those for global structural and geotechnical attention, class Table 10 reveals overlapping parameters. Specifically, exposure parameters like Average Daily Traffic (TGM), road alternatives, type of structure under passed, and strategic importance are defined similarly to the global structural and seismic CdA. However, the vulnerability parameter focuses on potential instability and the system's or structure's ability to withstand natural events.

The geological attention class varies based on the relationship between the structure and its surroundings. This includes artificial underpass tunnels, parietal tunnels, and tunnels with medium to high coverage, with particular focus on entrance areas prone to local instabilities, such as debris flows or collapses. These risks also depend on design decisions made during construction.

3.5.4.1. Estimate of the Level of Geological Susceptibility Associated with Landslide risk

The susceptibility of tunnels to landslide risks depends on the geomorphological context (e.g., plains or slopes) where they are located. This can be assessed using Level 0 data and confirmed through Level 1 inspections. If no instability or landslide risk is identified near the tunnel entrances, further assessment of landslide risks can be skipped, as it would not significantly impact the overall risk classification.

However, tunnels in areas with past or ongoing instability events require detailed Level 4 assessments, extending beyond basic attention class evaluations. Hazard maps and risk assessments from relevant authorities serve as initial references but are not fully comprehensive. Landslide susceptibility is evaluated using parameters like slope instability characteristics (e.g., activity status, magnitude, speed), focusing on factors that might affect the tunnel. These parameters are combined into a slope instability index. When paired with the presence or absence of mitigation or monitoring measures, this index determines the degree of landslide susceptibility.

3.5.4.2. Slope instability

Acknowledging the complexity of predicting occurrences, which also depends on the inherent variability in explanatory methods for landslide events, three key parameters have been identified as particularly significant for underground works. These parameters can be observed or inferred from documentation and field observations and are as follows:

1. **Activity Status** – Whether the landslide is active, inactive, or suspended.
2. **Magnitude** – Defined as the mobilizable volume of the landslide.

3. **Expected Speed** – The anticipated rate of movement and its potential impacts on the tunnel and entrance areas.

Logical operators are assigned to each of these parameters, which are then combined as outlined in Table 36.

The task, based on existing documents and available data, and to be cross-referenced with findings from the initial Level 1 inspection, is to identify any active or potential landslides and instabilities near the entrances, classifying them according to scientific literature and the materials involved. Emphasis is placed on the activity status and the presence (or absence) of mitigation or stabilization measures.

Specifically, identifying tunnel sections that interact with active or suspended landslides, as part of defining the BoD and its subsequent developments, necessitates further in-depth evaluations. Conversely, the identification of inactive or stabilized landslides generally corresponds to a lower instability index.

Table 36.State of landslide activity along the tunnel development or instability at the entrances

Active now of the exam or with signs of ongoing movement	Suspended Active in the last seasonal cycle)	Quiescent (Not active for more than one seasonal cycle but can be reactivated)	Inactive (Not active for several cycles seasonal) or stabilized
HIGH	MEDIUM-HIGH	MEDIUM LOW	LOW

Table 37.Volumetric magnitude in cubic meters

$> 1 \times 10^{6}$	$1 \times 10^{6} \div 3 \times 10^{4}$	3×10^{4}-$\div 1 \times 10^{3}$	$< 1 \times 10^{3}$
Extremely/very large	Great	Average	Small - Very small
HIGH	MEDIUM-HIGH	MEDIUM LOW	LOW

Table 38..Expected speed in relation to possible effects on the tunnel

> 50mm/year	50mm/year ÷ 10mm/year	< 10 mm /year
HIGH	AVERAGE	LOW

Table 39..Determination of the instability index

<table>
<tr><td colspan="2" rowspan="2"></td><th colspan="4">Magnitude class</th></tr>
<tr><th>High</th><th>Medium-High</th><th>Medium-Low</th><th>Low</th></tr>
<tr><th rowspan="2">Class Speed</th><th>High</th><td colspan="4">High</td></tr>
<tr><th>Average</th><td colspan="2">High</td><td colspan="2">Medium-High</td></tr>
</table>

	Low	Medium-High	Low

Activity class LANDSLIDE ACTIVE OR SUSPENDED

		Magnitude class			
		High	**Medium-High**	**Medium-Low**	**Low**
Class Speed	**High**	High		Medium-High	
	Average	High		Medium-Low	
	Low	Low			

QUIESCENT activity class

3.5.4.3. Mitigation measures

An additional factor influencing the determination of the tunnel's susceptibility class is whether stabilization systems are in place for the unstable slope or entrance areas, as well as the presence of monitoring systems and their current condition. A clear distinction is made between stabilized slopes, where risk mitigation measures are properly implemented and recognized as effective, and monitored slopes, where monitoring systems are in place to track the potential onset of landslide events. The lack of systems designed to reduce landslide risk results in an increased susceptibility class, thereby elevating the attention class. On the other hand, the presence of stabilization measures leads to a lower susceptibility index, following the logical progression depicted in the figure below.

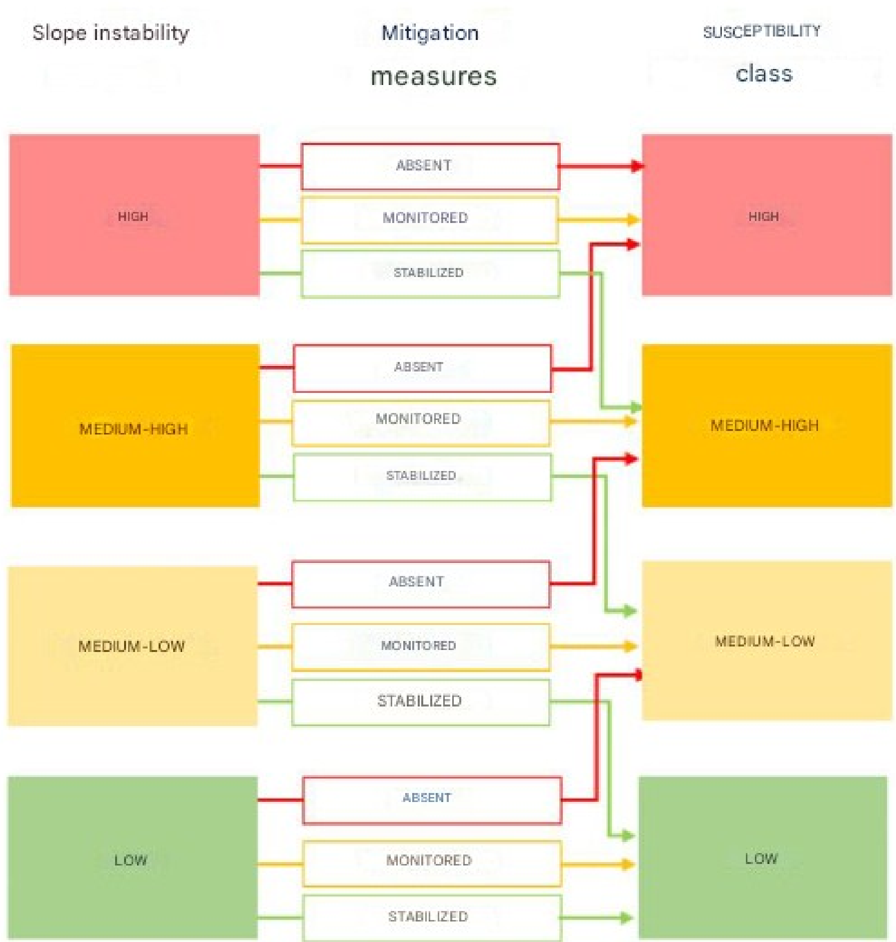


Table 40..Logical flow for determining the susceptibility class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.4.4 Estimate of the Level of Geological Vulnerability Associated with Landslide Risk

The primary factor in evaluating geological vulnerability related to landslides is the relative position of the tunnel in relation to the surrounding morphological conditions, with further consideration given to the extent of available knowledge. This is then supplemented by secondary parameters, such as the type of tunnel and the condition of the final lining, particularly its level of defectiveness.

10. **Relationships between tunnel and morphological conditions**

Various scenarios can arise regarding the geomorphological conditions and the development of the tunnel section, along with the interactions and relationships between them. The extent of available knowledge influence’s reliability and uncertainty in predicting potential impacts on the tunnel, further refining the assessment of vulnerability, as detailed in the table below.

Table 41. Determination of the geological vulnerability class

	Knowledge level	
	Limited	*Good*
large coverage (>50) m	MEDIUM-LOW	HIGH
Medium coverage (20-50m) and parietal galleries	MEDIUM-HIGH	MEDIUM-LOW
Low coverage (<20m) and entrance areas	HIGH	MEDIUM-HIGH

3.5.4.5 ESTIMATION OF THE LEVEL OF GEOLOGICAL EXPOSURE ASSOCIATED WITH LANDSLIDE RISK

The assessment of the exposure level relies on traffic data from the relevant road network, considering the frequency of vehicles passing through, as well as factors related to the network's capacity to handle unforeseen events, such as its resilience and traffic characteristics. The parameters used to evaluate the exposure factor are categorized into:

- **Primary parameters:** Average Daily Traffic (TGM), tunnel length.
- **Secondary parameters:** Heavy vehicles (weighing ≥ 3.5 t), maximum design speed, alternative routes.

The determination of the Exposure Attention Class is made by following the guidelines, with reference to Figure 47.

3.5.4.6 Estimation of the Geological Attention Class

After identifying the relevant parameters, the geological attention class (CdA) is determined by combining the tunnel's susceptibility, vulnerability, and exposure classes, following the general framework previously outlined for all types of Attention Class, as shown in Table 6.

3.5.5 SEISMIC WARNING CLASS

In defining the seismic attention class, it was considered that an underground structure, except for the entrance areas and where it intersects with active faults, is generally not very sensitive to seismic activity. Nevertheless, the general approach was followed, making the class seismic dependent on hazard, vulnerability, and exposure factors, which are determined by combining the primary and secondary parameters listed in Table 42.

As shown by comparing Table 35 with Table 11, which relates to the global and geotechnical structural attention class, some of the parameters are the same. However, unlike the exposure parameters such as Average Daily Traffic (TGM), tunnel length, alternative roads, heavy vehicle traffic, and the strategic importance of the structure, all of which retain the same definitions, the vulnerability parameters are considered using criteria that are partially

Table 42.Primary and secondary parameters for determining hazard, vulnerability and seismic exposure factors

	Primary parameters	Secondary parameters
Dangerousness	Presence of capable faults, landslides, unfavorable geological conditions, Seismic acceleration	Potential local amplification phenomena
Vulnerability	Morphological position coverage	-
Exposure	TGM level and tunnel length	Road alternatives Heavy traffic Strategic nature of the work

3.5.5.1. Assessment of the Seismic Hazard Level

To assess the seismic hazard, the evaluation considers factors such as the crossing of capable faults or the proximity of such faults to the tunnel, as well as the tunnel's interaction with landslides that could be reactivated due to seismic activity. Additionally, the geological-structural complexity of the lithotypes intersected by the tunnel is considered. In areas of high fracturing or where there is a transition between more rigid and more deformable masses, the tunnel could potentially be damaged due to seismic impedance contrasts resulting from differences in lithological, structural, and geomechanical characteristics.

To rank the level of seismic hazard, a point system is proposed. Numerical values are assigned to both the primary parameter (Pg) and the secondary parameter (Pa). The hazard level is then determined based on the sum (P) of the scores for these two parameters, as outlined in Table 43.

In particular, the verifier’s task is to identify, using the most up-to-date geological documentation and cartography, whether the tunnel crosses or is near a capable fault. This includes assessing the possibility of encountering masses with poor geomechanical quality or those exhibiting significant stiffness contrasts. Once this is done, the verifier will assign the first score (Pg), selecting the appropriate value from the corresponding row in Table 40 Considering the impact of seismicity, the seismic hazard class depends on the damage that could be induced by a seismic event. This is determined by the intensity of the maximum expected surface acceleration, which is represented by the second score (Pa), with values provided in Table 41.

Table 43.Parameters for determining seismic hazard

Geological structure				
	Crossing or proximity to active faults and capable	Geological structures extremely complex: Intense degree of fracturing and significant contrasts of stiffness of the lithotypes crossed	Complex geological structures: fractured lithotypes and contrasts of stiffness of the lithotypes crossed	Geological structures simple (training crossed homogeneous a behavior ductile)
Pg	8	6	4	2
	Acceleration at the surface with a probability of exceeding 10% in 50 years (ag)			
	>0.25	0.15 <ag< 0.25	0.05 <ag<0.15	ag < 0.05
Pa	4	3	2	1
Ps = Pg + Pa			**Seismic Hazard**	
10 – 12			HIGH	
8 - 9			MEDIUM – HIGH	
5 - 7			MEDIUM-LOW	
3 - 4			LOW	

As a secondary parameter affecting the hazard class, the potential for local amplification phenomena is considered when a section of the tunnel passes through particularly weak or unstable terrain. To address this, the classification into different hazard classes is outlined in the following table.

Table 44.Seismic amplification effects

Subsoil category in class C or D	Class A

Absence of potential amplification phenomena	Class B

Finally, the seismic hazard classification is determined as depicted in the logical diagram in the following figure

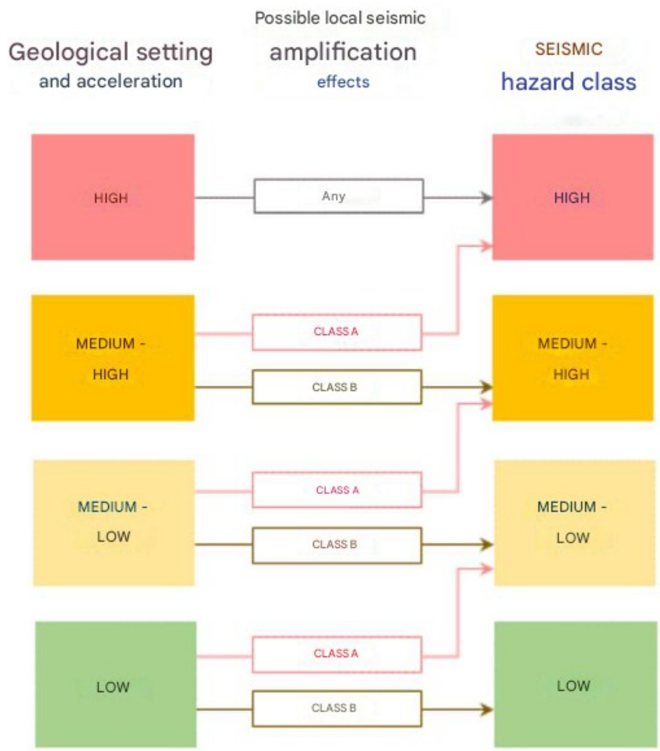


Figure 49.Logical flow for determining the seismic hazard class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.5.2 Estimate of the Level of Vulnerability Related to Seismic Risk

Given the significant complexity and multiple factors that influence the definition of vulnerability in seismic risk, the classification of the tunnel's position was considered essential in relation to two parameters: "surface morphology" (including tunnel walls and entrance slopes) and "coverage." These parameters are evaluated for segments with a length equal to the distance between casting joints or for sections of 20 meters, as outlined in Table 39.

Table 45. Determination of the seismic vulnerability class

Morphological position					
	Tunnel sections parietal with take it	**Tunnel sections parietal with take it up slopes with**	**Tunnel sections with covering less than 50 m galleries**	**Tunnel sections deep (> 50m)**	**Tunnel sections artificial of plain and**

	up slopes with slope >= 25°	slope < 25°	superficial		underpasses
CdV	HIGH	MEDIUM HIGH	MEDIUM HIGH	MEDIUM-LOW	LOW

3.5.5.3 ESTIMATION OF THE SEISMIC EXPOSURE LEVEL

The determination of the seismic exposure level follows the same criteria and uses the same parameters as those applied to assess the structural and geotechnical exposure class. These parameters include the TGM level, tunnel length, availability of road alternatives, heavy vehicle traffic, and the strategic importance of the structure, particularly in emergency situations. Therefore, the seismic exposure class is derived from the structural and geotechnical exposure class, which is evaluated using the framework in Figure 43, adjusted based on the strategic nature of the work as shown in Figure 50.

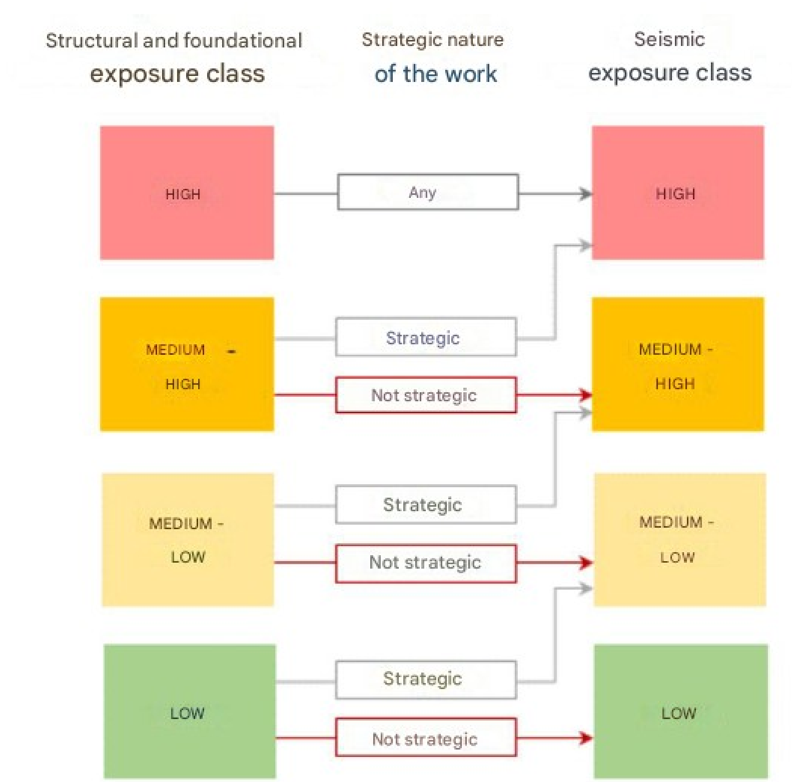


Figure 50. Logical flow for determining the seismic exposure class (Ministry of Sustainable Infrastructure and Mobility, 2022)

3.5.5.4 Estimate of the Seismic Warning Class

Once the parameters in play are known, we proceed with the determination of the seismic attention class (CdA) by combining the class of danger, vulnerability and exposure of the tunnel as indicated in general for all possible aspects in Table 5.

3.5.6 Hydraulic Warning class

The hydraulic attention class evaluates factors that could lead to flooding within tunnels, considering any event that might impact on the tunnel's functionality or user safety. This assessment is required for all tunnel sections, even those shorter than 200 meters. While percolation and dripping, which affect the tunnel lining, are covered in the structural and geotechnical attention class, flooding risks related to water on the tunnel roadway are the focus here, particularly water that could cause aquaplaning. The average speed of vehicles and road conditions influence the water depth threshold, which is commonly set between 2.5 and 10 mm for vehicle speeds ranging from 70 to 90 km/h.

Water usually originates from external sources at tunnels or underpass entrances and may be influenced by additional escape tunnels. Underpasses are at greater risk of flooding than tunnels due to their design and the size of approach galleries, which can collect rainwater if not equipped with proper drainage systems. Even minor water inflows, such as from filtration, can lead to flooding if the drainage system fails.

The hydraulic attention class is determined on a global scale, although flooding tends to affect the lowest parts of the tunnel. The evaluation of this class is based on both primary and secondary parameters listed in Table 46, with the classification being determined by assessing the danger, exposure, and vulnerability of the tunnel based on visual inspection results.

Table 46.Hydraulic Attention Class: primary and secondary parameters

	Primary parameters	Secondary parameters
Dangerousness	Precipitation intensity Groundwater / piezometric quota	Contributing surface at the accesses Soil hydraulic conductivity/ lack of waterproofing
Vulnerability	Capture system Conveyor system	Clogging of the capture system Flammable / dangerous liquid collection system Automatic

	Gravity return / with lifting	traffic light system
Exposure	TGM level	Transport of flammable/hazardous liquids Maximum design speed Exposure reduction systems

ESTIMATE OF THE LEVEL OF HYDRAULIC HAZARD

Hydraulic risk examines the likelihood of water-related issues in tunnels, ranging from minor seepage to full-scale flooding, both of which can endanger tunnel functionality and safety, albeit to varying degrees based on context and response times. The key parameters are:

1. Rainfall intensity

2. Groundwater level (water table or piezometric level)

For rainfall intensity, the analysis emphasizes short-duration events, particularly over one-hour periods, as they reflect intense rainfall patterns. Certain regions, such as Piedmont, provide rainfall intensity data through resources like the *Atlas of Intense Rainfall* by ARPA Piedmont, though this data is not consistently available across all areas.

The hazard is assessed using rainfall events with a 20-year return period, a metric chosen for its reliability in characterizing short, intense storms, even with limited historical data. This parameter is commonly available via regional VAPI reports or ARPAs, ensuring broad applicability.

The rainfall intensity thresholds and their corresponding attention classifications are presented in the table below.

Table 47.Attention classes in relation to precipitation intensity (reference event: duration=1 hour, return time Tr=20 years)

HIGH	>60 mm/h
MEDIUM – HIGH	50-60 mm/h
MEDIUM – LOW	40-50 mm/h
LOW	<40 mm/h

The water table or piezometric level with reference to the minimum level of the road surface of the entire underpass or tunnel section in question, and the fund attention classes is shown in the following table

Table 48.Attention classes relating to the groundwater / piezometric level

HIGH	Equal to or higher than the tunnel ceiling
MEDIUM – HIGH	Between the sky and half the height of the tunnel
MEDIUM – LOW	Between half the height of the tunnel and the bottom
LOW	Equal to or lower than the tunnel floor

The **secondary parameters** influencing hydraulic risk are:

1. **Contributing surface**:

- This refers to the area that channels water into the tunnel or underpass, including escape or access tunnels constructed for safety or service purposes.
- Determining the contributing surface involves **topographic observations** to identify watershed boundaries or structures like **guard ditches** that limit the contributing basin.
- **Attention class levels**:
    - **Low**: If the contributing surface is limited to uncovered sections near tunnel entrances (pre-tunnels) due to their elevation.
    - **High**: If a larger contributing surface exists, but this can be reduced to **Medium** if guard ditches are present to control water flow.

2. **Hydraulic conductivity of the soil**:

- **High conductivity**: Associated with coarse-grained soils or fractured rocks, leading to faster water infiltration.
- **Low conductivity**: Associated with fine-grained soil or compact rocks.
- The presence of a **waterproofing system** and absence of dripping results in a **Low attention class**, regardless of soil characteristics.

The primary and secondary hazard parameters are combined to evaluate the overall hydraulic risk, as shown in the relevant tables for surface and underground inflows.

Table 49.Total hazard classes for combinations of surface and underground inflows

Superficial inflows	***Underground inflows***	***Hazard class***
HIGH	*HIGH*	*HIGH*
	MEDIUM-HIGH	
	MEDIUM-LOW	
	LOW	
MEDIUM – HIGH	*HIGH*	
	MEDIUM-HIGH	***MEDIUM-HIGH***
	MEDIUM-LOW	
	LOW	
	HIGH	***HIGH***

MEDIUM – LOW	*MEDIUM-HIGH*	***MEDIUM-HIGH***
	MEDIUM-LOW	***MEDIUM-LOW***
	LOW	
LOW	*HIGH*	***HIGH***
	MEDIUM-HIGH	***MEDIUM-HIGH***
	MEDIUM-LOW	***MEDIUM-LOW***
	LOW	***LOW***

3.5.6.1 Estimation of the Level of Hydraulic Vulnerability

Hydraulic vulnerability is primarily influenced by the features of the water return system (either by gravity or lifting), the inspect ability of the pipeline that transports the water, and the type and efficiency of the surface water collection system. In these guidelines, the presence of a traffic light system that can automatically signal abnormal water levels in the tunnel is a mitigating factor, but only if it's controlled by backup safety systems for activation and signaling. The system's capacity to collect and store hazardous liquids from accidental spills is considered a secondary factor but does not directly impact hydraulic vulnerability levels. However, the transportation of dangerous goods may be restricted based on sections 2.6.1 and 2.6.2 of Legislative Decree no. 264 of 5.10.2006. The vulnerability attention levels are outlined below:

Return System:

- **Lifting**: Required when a mechanical evacuation system is necessary to ensure the water return level is higher than the minimum drainage surface level.
- **Gravity**: When the water return level is consistently lower than the minimum drainage surface level.

Conveyor System:

- **Inspectable**: Composed of ducts that can be uncovered along their length, or closed ducts with inspection wells at each change in direction or at intervals no greater than 50 meters in straight sections.
- **Non-inspectable**: Made with different construction characteristics than the inspectable system.

Capture System (by type):

1. Point capture systems, with one every 200 m² or less.

2. Linear and point capture systems, with more than one every 200 m^2.

Degree of Clogging:

1. Capture systems with significant clogging (capture area >30% occupied).
2. Capture systems with minimal clogging (capture area <30% occupied).

The combination of clogging type and degree results in the following three attention classes for the capture system:

- **A**: Combination of 1 and 3.
- **B**: Combination of 1 and 4, or 2 and 3.
- **C**: Combination of 2 and 4.

The overall vulnerability of the flow evacuation system is summarized in the table below

Return	***Conveyor system***	***Capture system***	***Vulnerability***
WITH LIFTING	*NOT INSPECTABLE*	*A,B*	***HIGH***
		*C**	***MEDIUM – HIGH***
	INSPECTABLE	*TO*	
		*B, C**	***MEDIUM – LOW***
GRAVITY	*NOT INSPECTABLE*	*A, B**	***MEDIUM – HIGH***
		*C**	***MEDIUM – LOW***
	INSPECTABLE	*TO*	
		B, C	***LOW***

* Only if in combination with the presence of an automatic traffic light system controlled by redundant safety systems for its activation and signaling does the vulnerability move to the lower level.

3.5.6.2 ESTIMATION OF THE LEVEL OF HYDRAULIC EXPOSURE

By using data from transport studies or information provided by managing bodies, the expected traffic volume, measured as Average Daily Traffic (TGM), can be determined. This refers to the average number of vehicles passing through the entire width of the roadway served by the tunnel. The TGM is considered alongside secondary factors such as "maximum speed" and "exposure reduction systems," which could include alternative routes clearly marked based on local conditions. The maximum speed of 80 km/h is significant, as speeds above this threshold can lead to aquaplaning if water tensions on the road surface are between 2.5 and 10 mm.

Exposure reduction systems are considered a mitigating factor for low TGM levels

(<10,000 vehicles/day). However, for higher traffic volumes, these systems are only effective if paired with appropriate signage. For very high TGM values (≥40,000 vehicles/day) and speeds over 80 km/h, exposure reduction systems do not influence the exposure classification. The overall results are summarized in the table below.

Table 50. Overall exposure to hydraulic vulnerability

TGM	***SPEED MAXIMUM***	***REDUCTION SYSTEMS OF THE EXHIBITION***	***EXPOSURE***
vehicles/day > 40000	*> 80 km/h*	*NO*	***HIGH***
		YES	
	< 80 km/h	*NO*	
		YES YES**	***MEDIUM-HIGH***
25000 < vehicles/day < 40000	*> 80 km/h*	*NO*	***HIGH***
		*YES**	***MEDIUM-HIGH***
	< 80 km/h	*NO*	
		*YES**	***MEDIUM-LOW***
10000 < vehicles/day < 25000	*> 80 km/h*	*NO*	***MEDIUM-HIGH***
		*YES**	***MEDIUM-LOW***
	< 80 km/h	*NO*	
		*YES**	***LOW***
vehicles/day < 10000	*> 80 km/h*	*NO*	***MEDIUM-LOW***
		YES	***LOW***
	< 80 km/h	*NO*	***MEDIUM-LOW***
		YES	***LOW***

** Only if combined with the presence of appropriate signaling systems, otherwise it is NO and the exposure moves to a higher level*

3.6.4 Estimate of the Overall Hydraulic Warning Class

The hydraulic attention class (CdA) is determined by combining the tunnel's danger, vulnerability, and exposure classifications, as shown in the following tables. To simplify the process of defining the attention class, the table below assesses the specific danger as a combination of danger and vulnerability.

Table 51. Specific hazard obtained from the combination of hydraulic hazards and vulnerabilities

Dangerousness	***Vulnerability***			
	HIGH	***MEDIUM-HIGH***	***MEDIUM-LOW***	***LOW***
HIGH	***HIGH***	***HIGH***	***MEDIUM-HIGH***	***MEDIUM-LOW***
MEDIUM-	***HIGH***	***MEDIUM-***	***MEDIUM-***	***MEDIUM-***

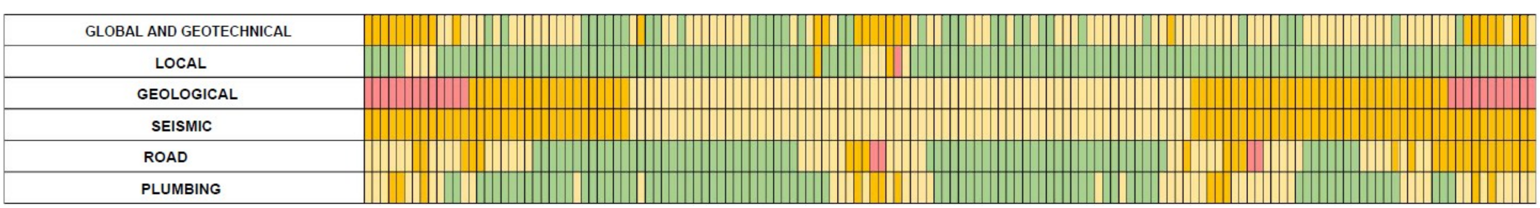
HIGH		***HIGH***	***HIGH***	***LOW***
MEDIUM-LOW	***MEDIUM-HIGH***	***MEDIUM-HIGH***	***MEDIUM-LOW***	***LOW***
LOW	***MEDIUM-HIGH***	***MEDIUM-LOW***	***MEDIUM-LOW***	***LOW***

Table 52. . Hydraulic attention class obtained from the combination of specific hazard and exposure

Dangerousness	***Vulnerability***			
	HIGH	***MEDIUM-HIGH***	***MEDIUM-LOW***	***LOW***
HIGH	***HIGH***	***HIGH***	***MEDIUM-HIGH***	***MEDIUM-LOW***
MEDIUM-HIGH	***HIGH***	***MEDIUM-HIGH***	***MEDIUM-HIGH***	***MEDIUM-LOW***
MEDIUM-LOW	***MEDIUM-HIGH***	***MEDIUM-LOW***	***MEDIUM-LOW***	***LOW***
LOW	***MEDIUM-LOW***	***MEDIUM-LOW***	***LOW***	***LOW***

MULTI-RISK ANALYSIS AND DEFINITION OF THE OVERALL ATTENTION CLASS

Calculate the Attention Classes for all the previously listed areas (Global Structural and Geotechnical, Local Structural, Geological, Seismic, Road, Hydraulic). These should be reported for each homogeneous survey section of the tunnel. Each area is also categorized by its diffusion index along the tunnel. Below is a graphical example showing the synthetic representation of the results and the corresponding diffusion index.



To implement the Attention Classification Method, we required specific parameters as outlined in its general structure. However, due to the lack of complete parameter availability from the company, the classification of attention classes for our tunnel was carried out using a random approach, solely for demonstration purposes.

Despite the randomized classification, the results were not only visualized in Blender but

Figure 51. Overall Attention Class (Ministry of Sustainable Infrastructure and Mobility, 2022)

also integrated directly into the BIM model using Autodesk Revit. For each tunnel ring segment, the assigned attention class was embedded as a custom parameter within the model's properties, ensuring the classification data could be retained during IFC exports. This allowed the BIM model to serve as a structured information base, aligning with the guidelines for digital asset management and predictive maintenance.

For visualization, we utilized Blender 4.1, leveraging its GIS capabilities and advanced scripting tools. Through Blender's scripting functionality, we developed a customized approach to classify the tunnel segments into four distinct attention classes, represented by the following colors:

- Red
- Yellow
- Orange
- Green

Additionally, to enhance the clarity and spatial context of the visualization we used a custom Python script in Blender shown below, we applied a blue color scheme to the surrounding buildings, ensuring a more comprehensive and visually intuitive representation of the tunnel within its urban environment.

```
import bpy

# Define risk levels and their corresponding colors
risk_levels = {
    "Low Risk": (0.0, 1.0, 0.0, 1.0),        # Green
    "High Risk": (1.0, 0.0, 0.0, 1.0),       # Red
    "Medium-Low": (1.0, 1.0, 0.0, 1.0),      # Yellow
    "Medium-High": (1.0, 0.5, 0.0, 1.0)      # Orange
}

def create_material(name, color):
    """Creates a material with a given name and color."""
    material = bpy.data.materials.get(name)

    # Create new material if it does not exist
    if material is None:
        material = bpy.data.materials.new(name=name)

    material.use_nodes = True
    bsdf = material.node_tree.nodes.get("Principled BSDF")

    if bsdf:
        bsdf.inputs["Base Color"].default_value = color  # Apply color
```

```
    return material

# Loop through the dictionary and create materials
for name, color in risk_levels.items():
    create_material(name, color)

print("Materials created successfully!")
```

A unique parameter called "Attention Class" was added to the Autodesk Revit BIM model to facilitate data integration and classification transfer between BIM and GIS environments. To match the tunnel segments, the parameter was made as a Project Parameter with a Text data type and assigned to the Generic Models category, the table below shows the parameters added to BIM model. To enable the assignment of distinct attention class values (such as High, Medium-High, Medium-Low, and Low) to every tunnel ring, it was set as an instance parameter. For the sake of organization, these parameters were placed under Text in the Revit properties palette.

Table 53. Parameters enriched by BIM model

Parameter Name	Purpose
Attention Class	Supports visualization and maintenance prioritization
Risk Classification	Enables condition-based analysis and decision-making
Number of Sensors	Supports monitoring coverage and reliability assessment
Permeability (%)	Used in hydrogeological risk evaluation and infiltration modeling
Type of Soil	Supports interpretation of ground conditions and risk classification

Type of Ring	Enables structural performance analysis and lifecycle planning

The classification data was incorporated and exportable in IFC format thanks to the BIM model's definition of this parameter. This made it possible for the output IFC file to include attribute data in addition to geometric information that was needed for visualization and additional analysis in third-party platforms like Blender, where a programmed color scheme was used to represent the attention classes. This method facilitates the smooth transfer of structured data between software environments and is in line with the objectives of data interoperability and predictive maintenance.

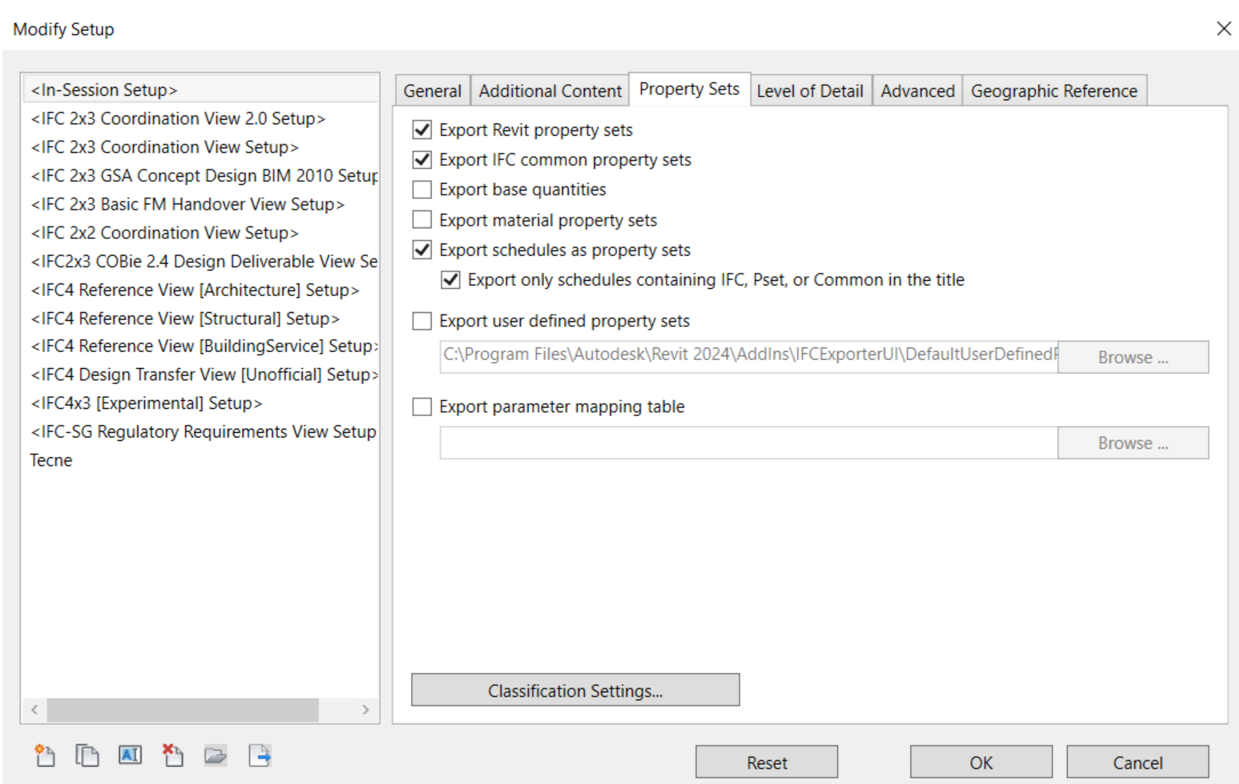


Figure 52. IFC Export Setup in Revit for Including Custom Parameters in Property Sets

3.6. Creating hillshade , Aspect and Slope Maps

To begin the analysis, we first need to acquire a suitable Digital Elevation Model **(DEM)** that can be imported into **ArcGIS Pro** for further processing. Our initial approach is to source the DEM from the **Istituto Nazionale di Geofisica e Vulcanologia (INGV)**, as it provides high-resolution elevation data covering Italy.
Once the DEM is obtained, we will refine the selection by defining smaller sub-regions (bounding boxes) within the study area. This step ensures improved visualization, enhanced computational efficiency, and better precision in subsequent terrain analyses, such as slope, aspect, and hillshade mapping.

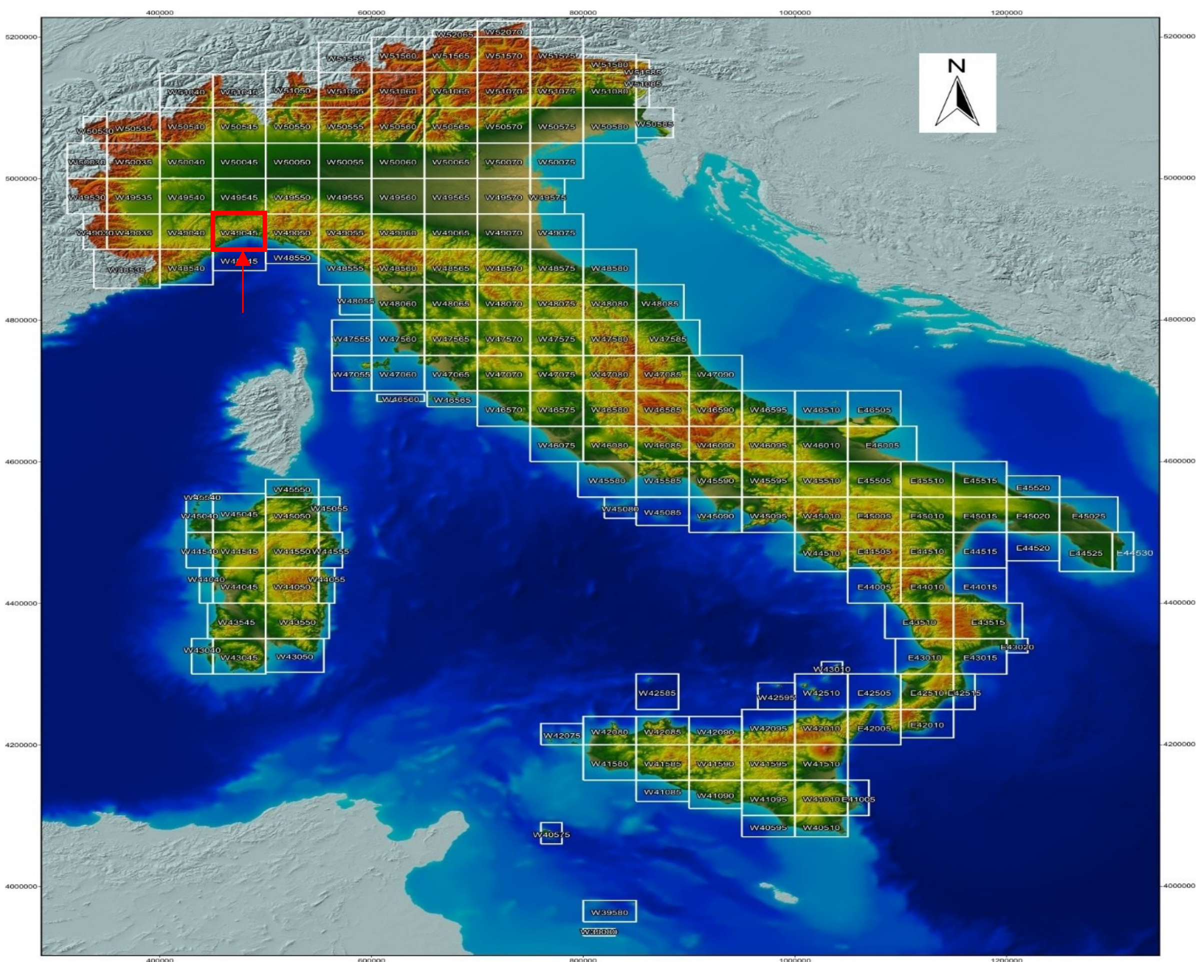


Figure 53.DEM Tile Index Map of Italy(https://tinitaly.pi.ingv.it/Download_Area1_1.html)

Figure 53 represents a **DEM tile index map** for Italy, showing the division of the country into smaller grid tiles, each corresponding to a specific elevation dataset. These tiles allow users to select and download the most relevant DEM data for their area of interest.

For my study area, I identified that it falls within **tile W49045**, which encompasses the relevant terrain. I downloaded the DEM dataset shown in figure 54 corresponding to this tile and imported it into **ArcGIS Pro** for further analysis, including slope, aspect, and hillshade calculations. This approach ensures that the elevation data is appropriately focused on the study region, optimizing both accuracy and computational efficiency.

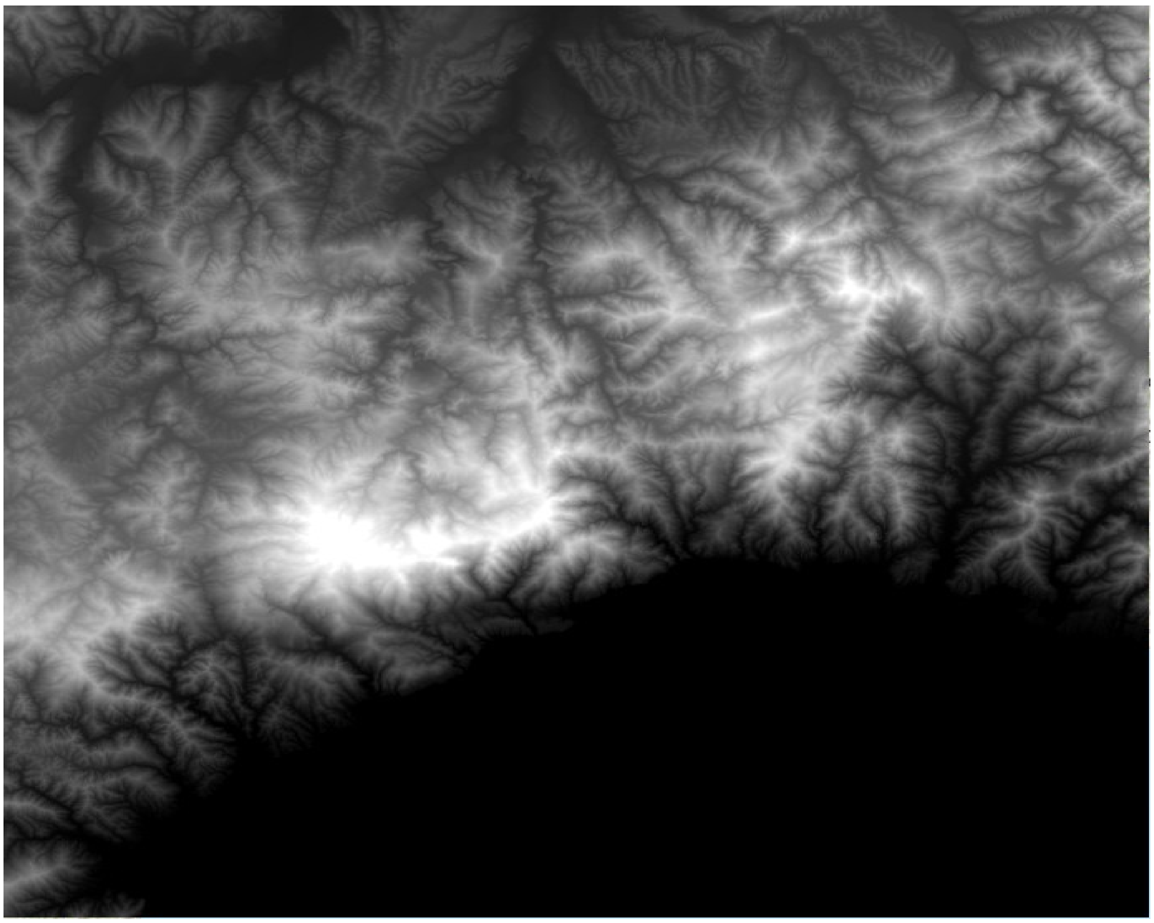


Figure 54. DEM (https://tinitaly.pi.ingv.it/Download_Area1_1.html)

After importing the Digital Elevation Model into ArcGIS Pro, we can leverage its advanced spatial analysis tools to generate key terrain maps, including Aspect, Hillshade, and Slope. These specialized features allow for detailed analysis of the topographic characteristics of the study area:

- Aspect: Identifies the compass direction of terrain slopes, crucial for understanding sunlight exposure, water drainage patterns, and environmental modeling.
- Hillshade: Creates a shaded relief map, simulating sunlight interaction with the

terrain to enhance the visualization of elevation changes and landforms.

- Slope: Calculates the steepness or incline of the terrain, essential for assessing geological stability, erosion risks, and construction feasibility.

These outputs provide critical insights for terrain analysis and decision-making within the study area.

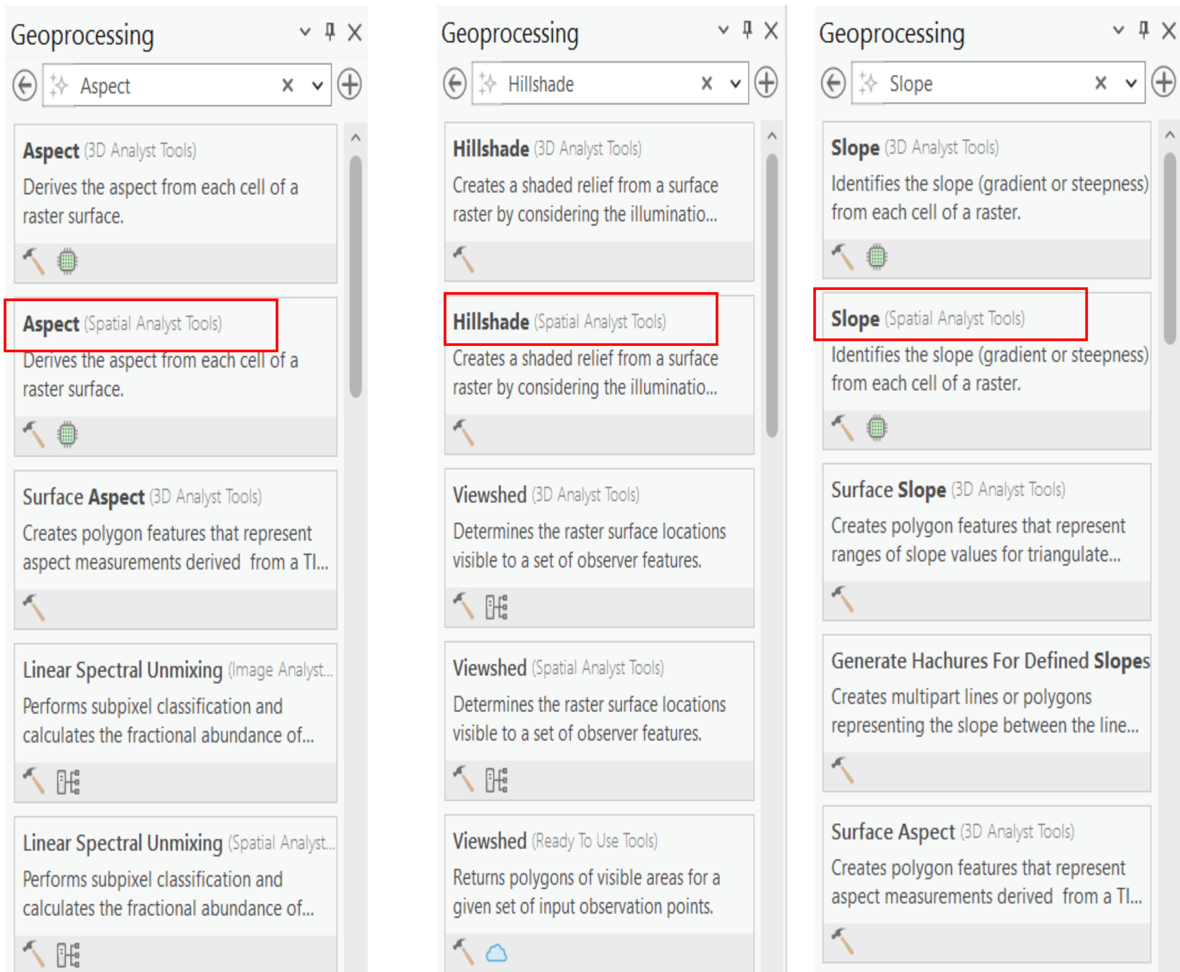


Figure 55. Creating Hillshade, Aspect and Slope Maps by using ArcGis pro

After selecting the appropriate geoprocessing tools in **ArcGIS Pro**, we can generate key terrain analysis maps.

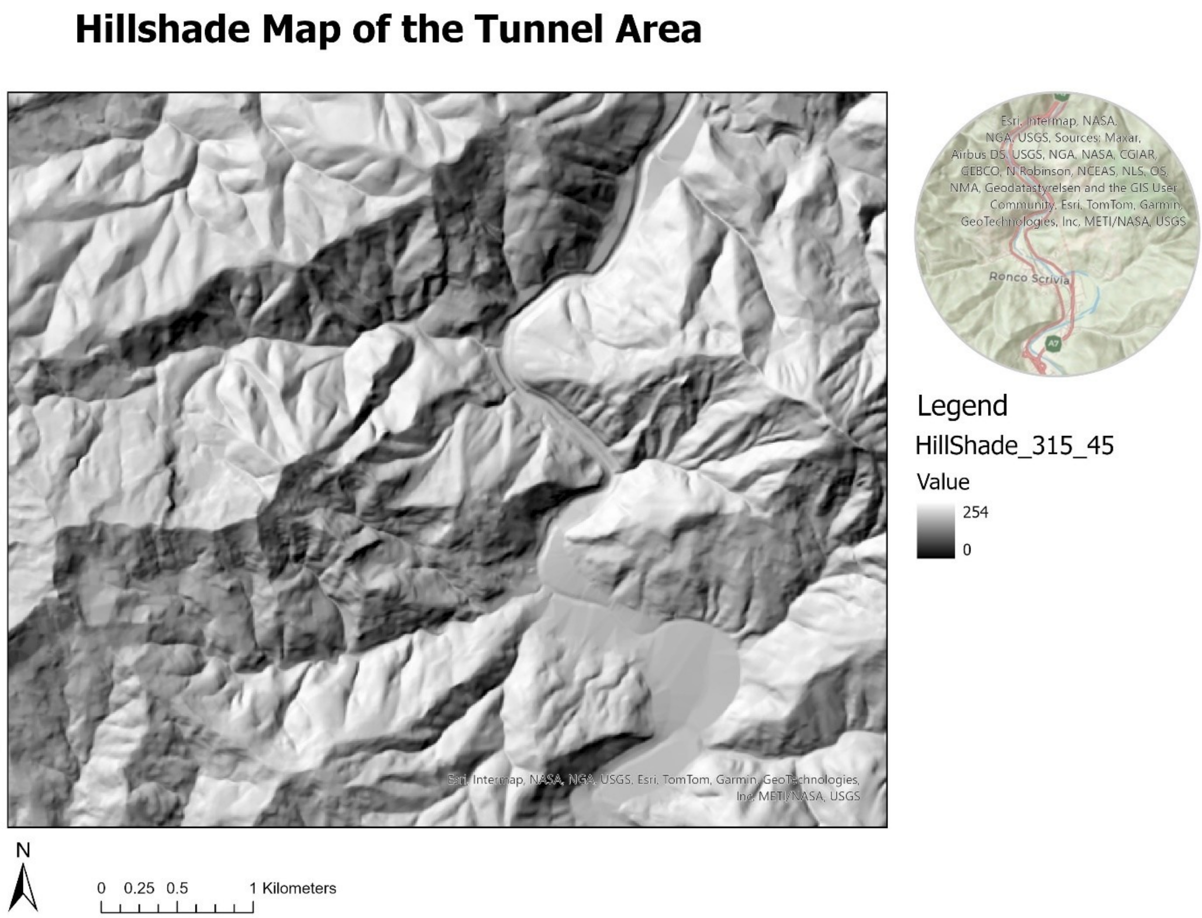


Figure 56. Hillshade Map Created by ArcGIS pro

The landscape surrounding the case study is depicted in detail on the hillshade map. DEMs are used to create this kind of map, in which an artificial light source generates highlights and shadows according to the slope and elevation of the ground. The grayscale shading enhances the feeling of relief, helping people appreciate the changes in topography. Lighter areas show more exposed, higher places, whereas darker portions show steeper slopes or darkened areas.

Although Hillshade improves terrain visualization, geographical analysis, and infrastructure design, it is essential for both GIS and BIM. It helps engineers determine the optimal tunnel routes, evaluate drainage patterns, and identify geological dangers by supporting route optimization, hydrological analysis, and geological evaluations in GIS. Hillshade is a crucial component of BIM's site analysis, 3D terrain modeling, and risk assessment processes, which guarantee that building projects complement the surrounding landscape while reducing stability hazards. Professionals are able to make well-informed decisions that enhance project sustainability, safety, and efficiency by incorporating hillshade data into GIS and BIM workflows.

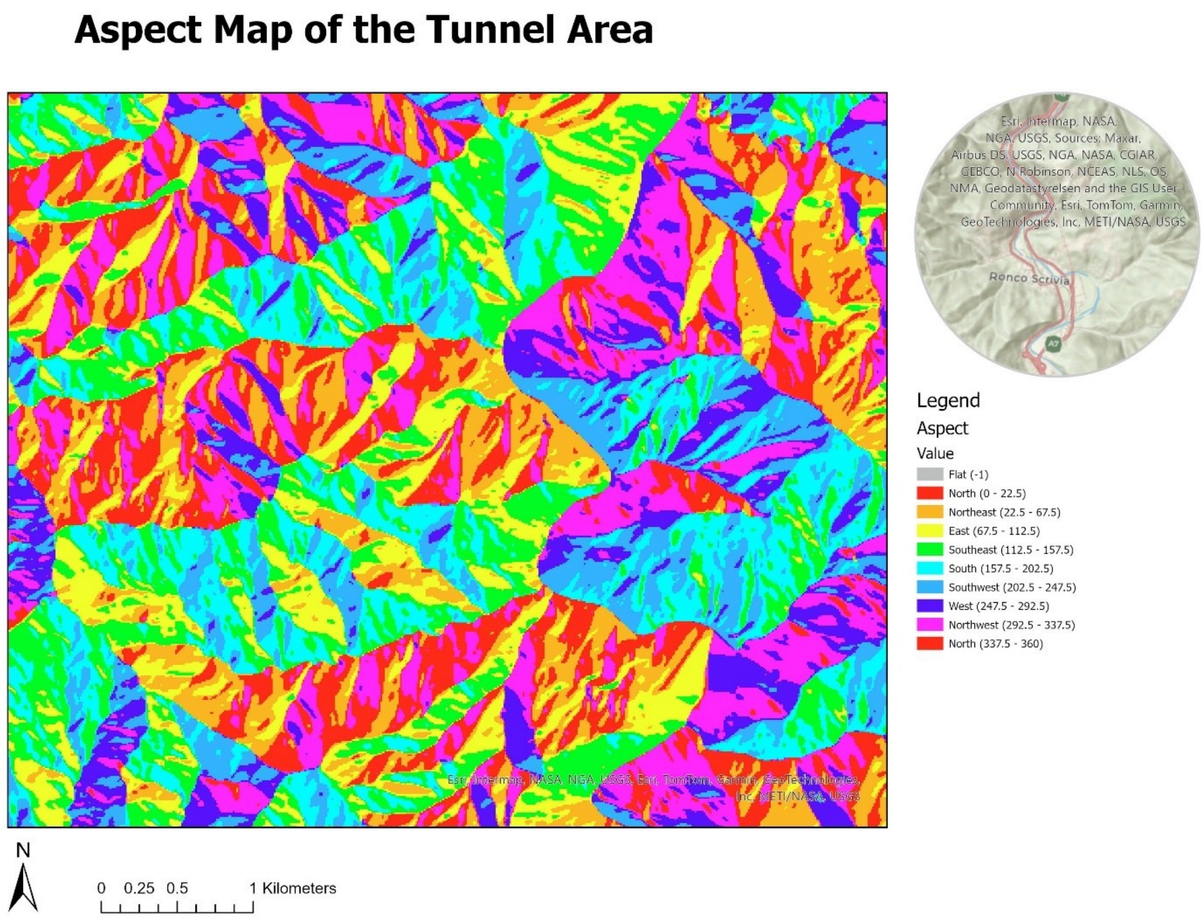


Figure 57. Aspect Map Created by ArcGIS pro

Including degrees ranging from 0° to 360°, an aspect map shows which way a slope faces (0° for north, 90° for east, 180° for south, and 270° for west). It is an essential tool for terrain study, particularly for applications in engineering, infrastructure development, geomorphology, and environmental studies. Understanding how the landscape interacts with sunshine, wind, and water drainage is made easier by the map's hues, which correlate to various slope orientations.

The legend categorizes aspect values into cardinal (N, E, S, W) and intermediate (NE, SE, SW, NW) directions, with flat terrain (-1) as a separate category. While the legend is well-structured, improvements could include:

- A circular compass rose to visually show the aspect distribution, making it easier to interpret.
- A clearer distinction of colors for similar hues (e.g., red and orange for north and northeast).
- A note about the aspect value range (0–360°) to explain how directions are classified

As they facilitate terrain analysis, infrastructure design, and environmental impact assessments, aspect maps are crucial to BIM and GIS. Aspect maps in GIS aid planners and engineers in managing water flow, optimizing routes, and determining if a piece of land is suitable for a project like a roadway or tunnel. Aspect data in BIM improves site analysis and 3D modeling, enabling engineers and architects to create infrastructure and structures that are in harmony with the environment and the terrain. In engineering projects, integrating aspect analysis with GIS and BIM guarantees efficiency, safety, and sustainability.

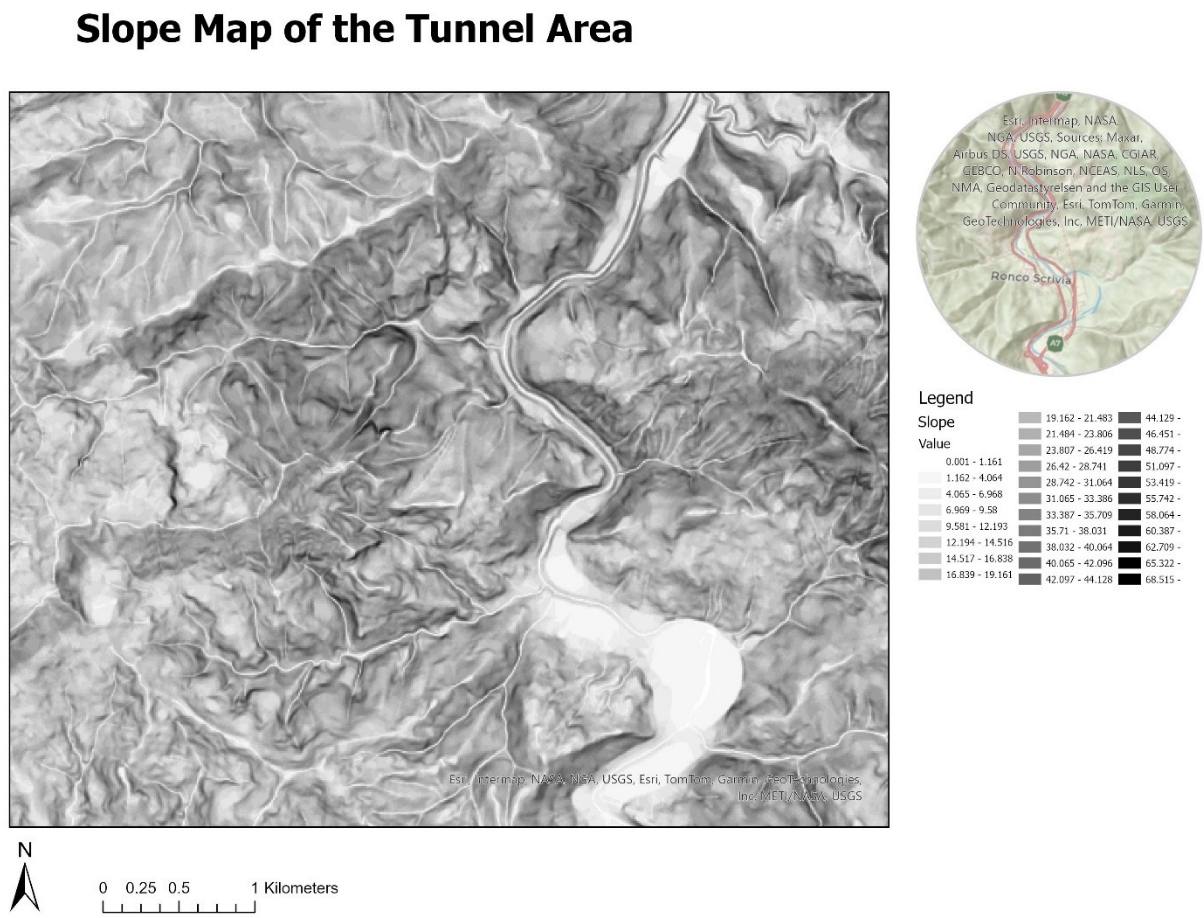


Figure 58. Slope Map Created by ArcGIS pro

Slope map shows the terrain's inclination or steepness, expressed in percentages or degrees. It comes from DEMs and is essential for environmental management, transportation planning, and geotechnical engineering. The map displays changes in height and hardness, with lighter parts denoting gentler terrain and darker ones denoting steeper slopes.

Given that they facilitate risk management, structural design, and terrain analysis, slope maps are crucial for both BIM and GIS. Slope data is utilized in GIS for hydrological research, hazard mapping, and road and tunnel alignment, guaranteeing that infrastructure is constructed in stable areas. Slope maps assist engineers optimize the grading, excavation, and earthworks processes in BIM by integrating with 3D modeling and construction planning. In large-scale projects, the integration of slope analysis with GIS and BIM processes improves sustainability, efficiency, and safety.

The hillshade, aspect, and slope maps collectively provide a comprehensive geospatial analysis of the Galleria A7 tunnel area, each offering unique insights into the terrain's characteristics and their implications for engineering, environmental management, and infrastructure development. These maps are essential tools in geotechnical assessments, hydrological planning, and risk mitigation, ensuring that infrastructure is designed with safety, efficiency, and sustainability in mind.

1. Hillshade Map – Enhances visual interpretation of terrain relief, helping engineers and planners understand topographical variations. It is crucial for route selection, tunnel alignment, and geological hazard assessment, improving infrastructure planning in rugged landscapes.
2. Aspect Map – Determines slope orientation, influencing solar exposure, water runoff, and wind exposure. This data is vital for climate-sensitive engineering, including solar energy projects, erosion control, and ecological preservation.
3. Slope Map – Identifies terrain steepness, critical for landslide risk assessment, tunnel stability analysis, and hydrological management. This information is fundamental in geotechnical engineering, ensuring infrastructure is built in safe and stable locations.

These maps, when integrated into GIS and BIM workflows, provide data-driven decision-making for engineers, architects, and planners. GIS enables spatial analysis and hazard mapping, while BIM incorporates terrain data into 3D models for accurate design and construction planning. The synergy between GIS and BIM ensures that projects are optimized for terrain conditions, reducing costs, minimizing environmental impact, and enhancing safety.

4. Results

As a result of the integration between two **BIM software solutions** from the same family, **Revit** and **InfraWorks**, the following outcomes have been generated. The **.IFC file extension** is not a critical factor in this process, as **.RVT files** can be directly read and imported into **InfraWorks**, ensuring seamless interoperability between the two platforms.

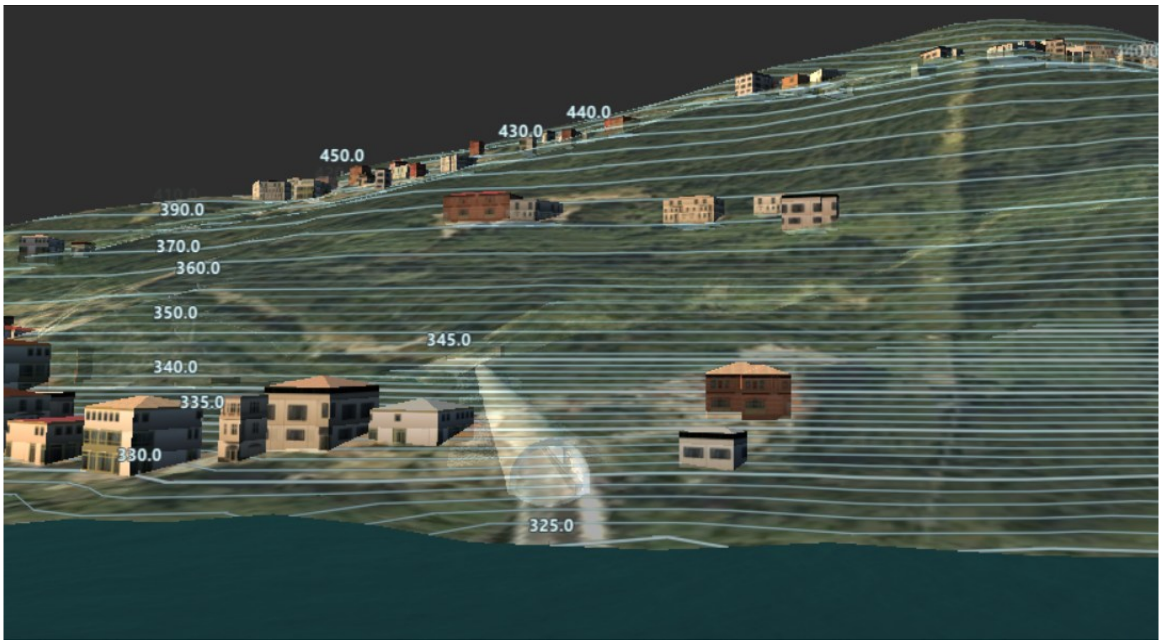


Figure 59. Tunnel Integration from Revit to InfraWorks within a 3D Terrain Model

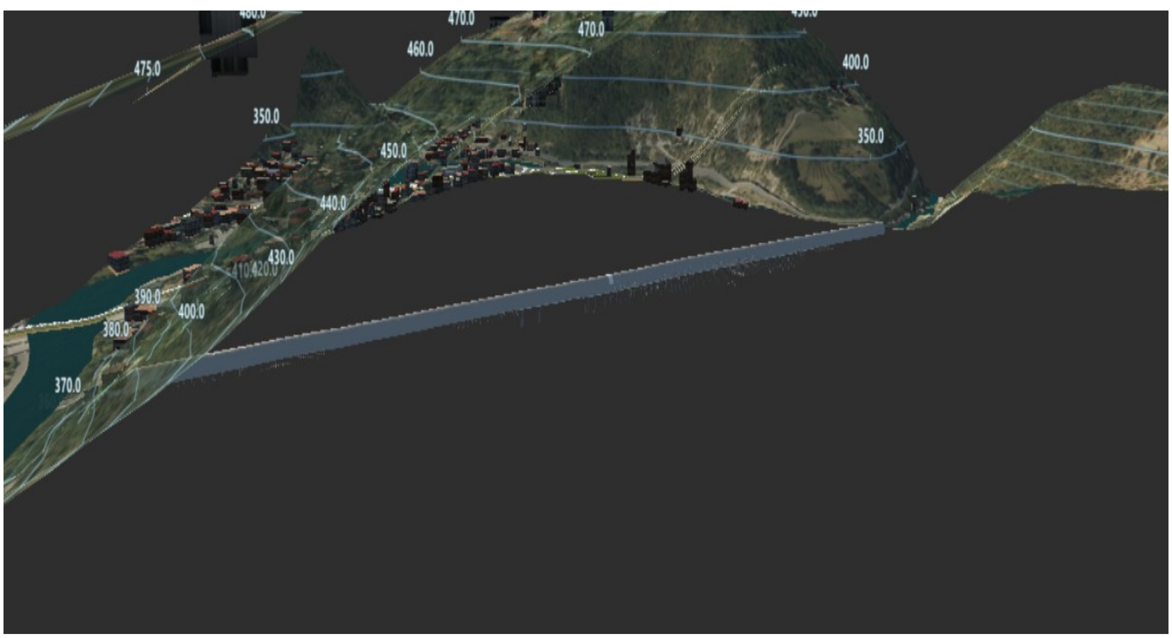


Figure 60. Tunnel Integration from Revit to InfraWorks within a 3D Terrain Model

The figure below illustrates the outcome of the **integration between Revit and Blender**. In **Blender**, there is a dedicated feature that allows visualization of the model within its surrounding environment directly. This is achieved through the **Blender GIS integration**, which enables the incorporation of geospatial data, enhancing the realism and contextual accuracy of the model.

Figure 61. Importing 3D BIM Model to Blender

Applying attention classes to our tunnel segments while integrating them within the surrounding environment for enhanced visualization and analysis shown in the figure below.

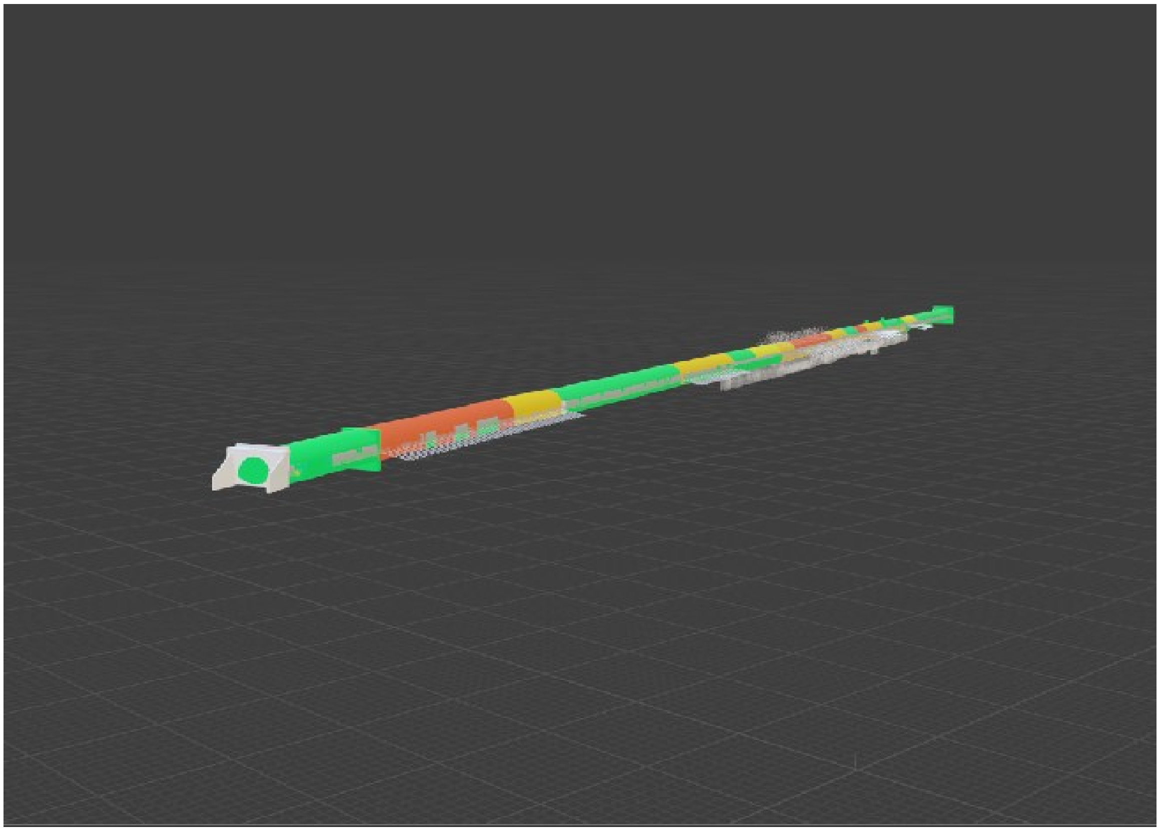


Figure 62. Attention Class Applied to Tunnel

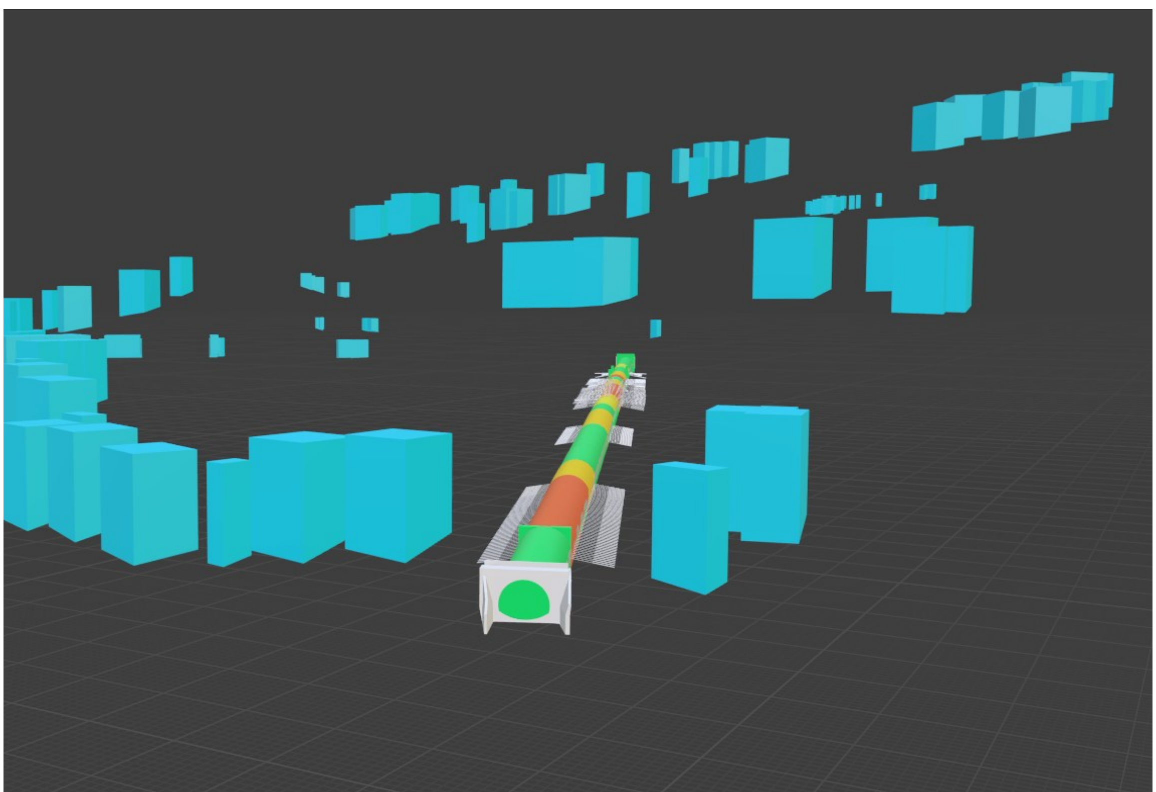


Figure 63. Attention Class with Surrounded Environment

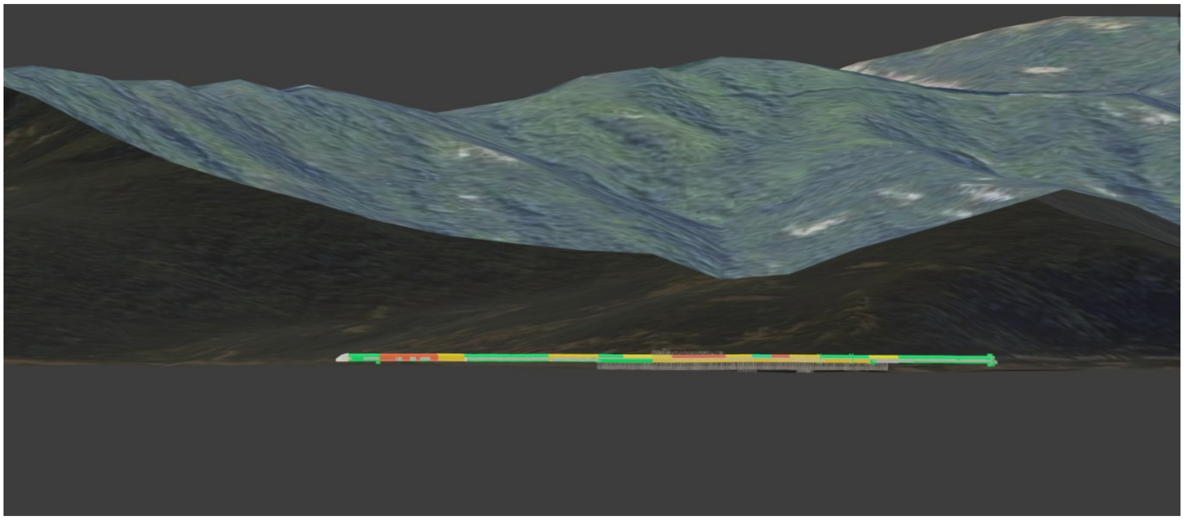


Figure 64. GIS-Integrated Tunnel Visualization in Blender

The **integration between Blender and Cesium** was achieved by exporting the model in **.DAE (Collada) format**. The alignment with the real-world coordinates was successfully resolved through **JavaScript coding** in **CesiumJS**, ensuring precise georeferencing and accurate positioning within the virtual environment, the result as shown in the figure below.

Figure 65. Integration Result of Blender and Cesium ion

The integration of Blender with ArcGIS Pro successfully addressed the georeferencing challenge by utilizing the manual georeferencing option within ArcGIS Pro. This approach ensured precise alignment of spatial data, resulting in accurate and visually refined outcomes, as demonstrated in the figure below.

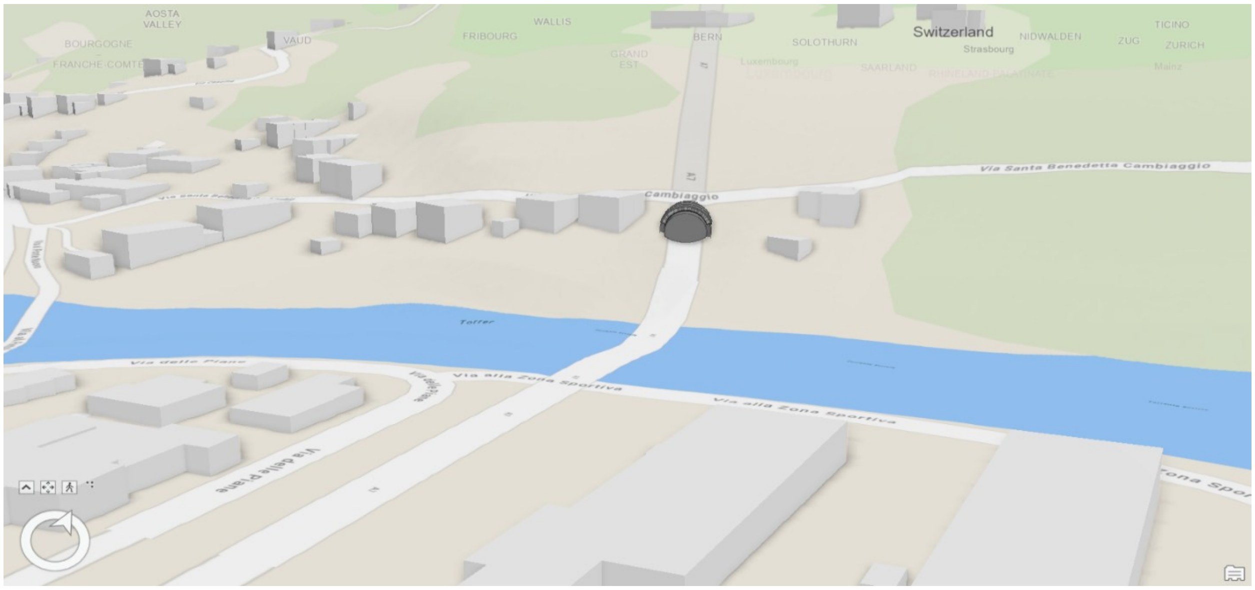


Figure 66. Integration Result of Blender In ARCGIS pro

Figure 67. Integration Result of Blender In ARCGIS pro

After we have successfully generated the aspect, slope, and hillshade maps as shown in figure 12, 13 and 14 the next step is to integrate our BIM model with these layers.

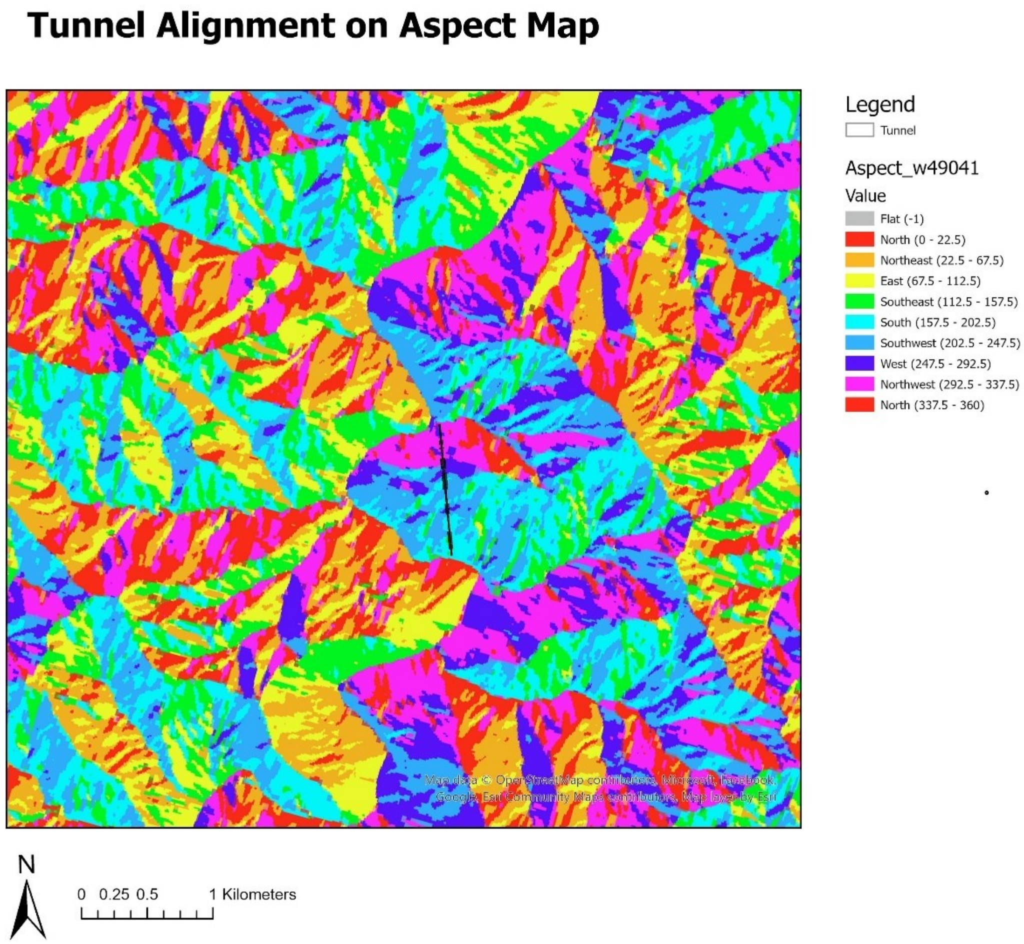


Figure 68. Tunnel Alignment on Aspect Map

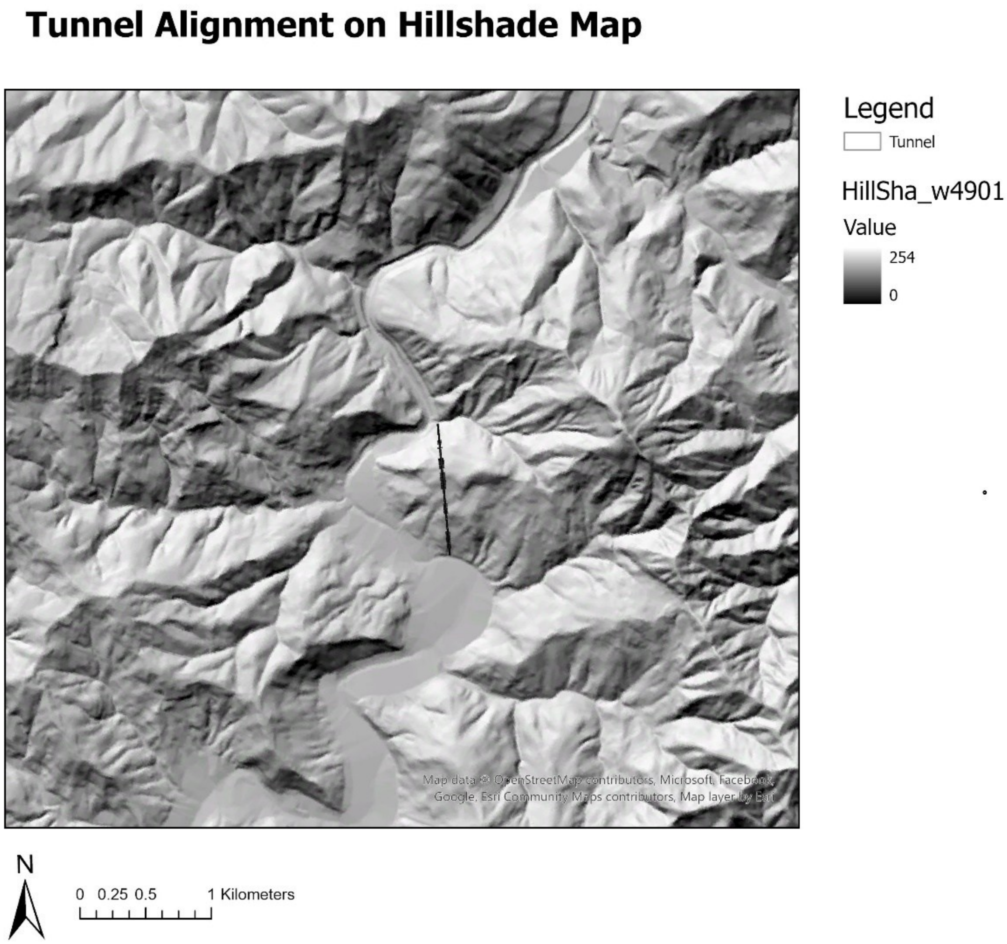


Figure 69. Tunnel Alignment on Hillshade Map

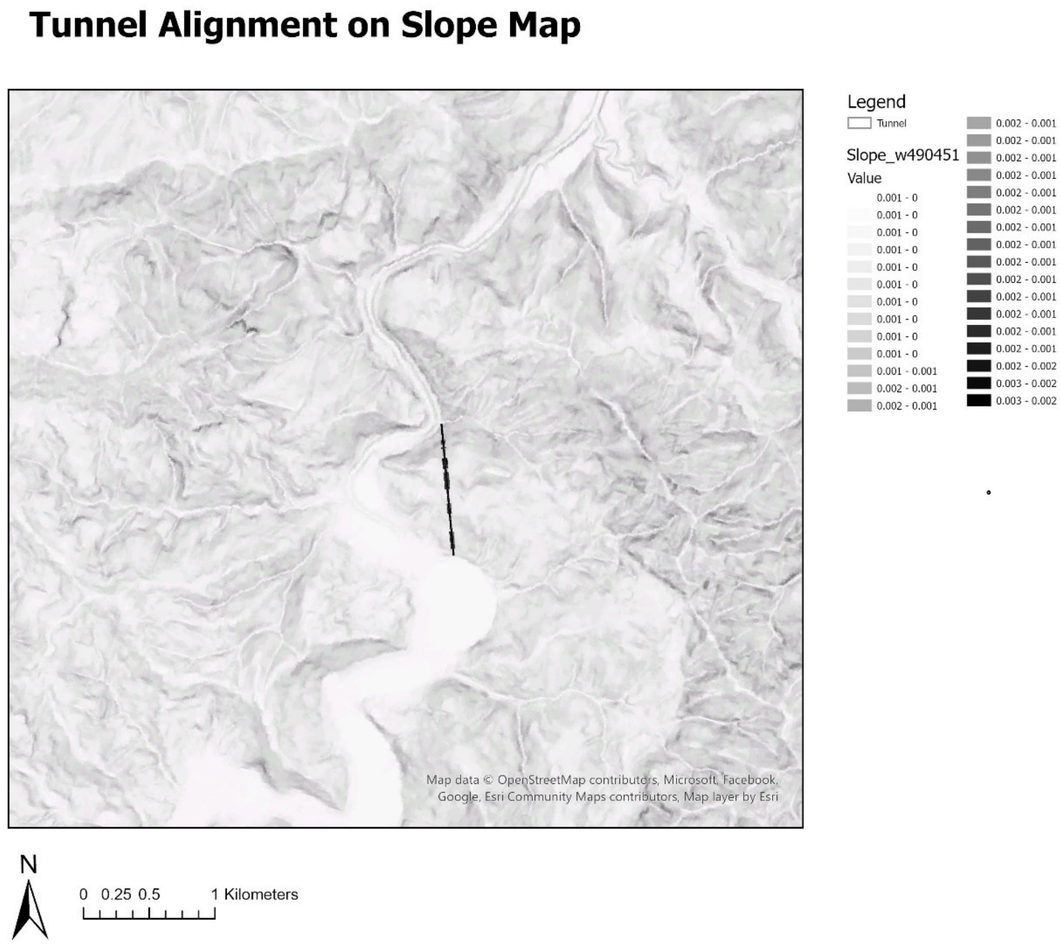


Figure 70.Tunnel Alignment on Aspect Map

As shown in figures 71, 72 and 73 results of Alignment of our BIM model with These maps this integration is crucial for maintaining ongoing control and awareness of the tunnel environment. As conditions in the terrain may change over time or as new data becomes available, we must remain attentive to any updates in these maps that could impact the model. This proactive approach ensures the reliability and adaptability of our design, helping us to mitigate risks and preserve the structural integrity of the tunnel in the long term.

Software Comparison Conclusion

Table 54. Software Interoperability Verifications

Source Software	Target Software	Format Used	Geometry Transferred	Attribute Data Transferred	Comments
Revit	Infraworks	IFC, RVT	✅	✅	Full model loaded with data,
Revit	Blender	IFC	✅	✅	Geometry was visible but metadata was lost during conversion unless we set the parameters properly to do the right conversion of data.
Blender	ArcGIS Pro	.SHP	❌	✅	Attribute table loaded but geometry did not render properly.
Blender	Cesium Ion	.DAE	✅	❌	Geometry was visible but needed to be set in the proper place and materials were preserved.
Revit	ArcGIS Pro	RVT	✅	✅	The geometry displayed correctly but required manual positioning; material properties remained intact.

To better appreciate the topographic environment of the research area, a 3D model of the terrain was created as part of the workflow. The figures below display the outcomes of this procedure.

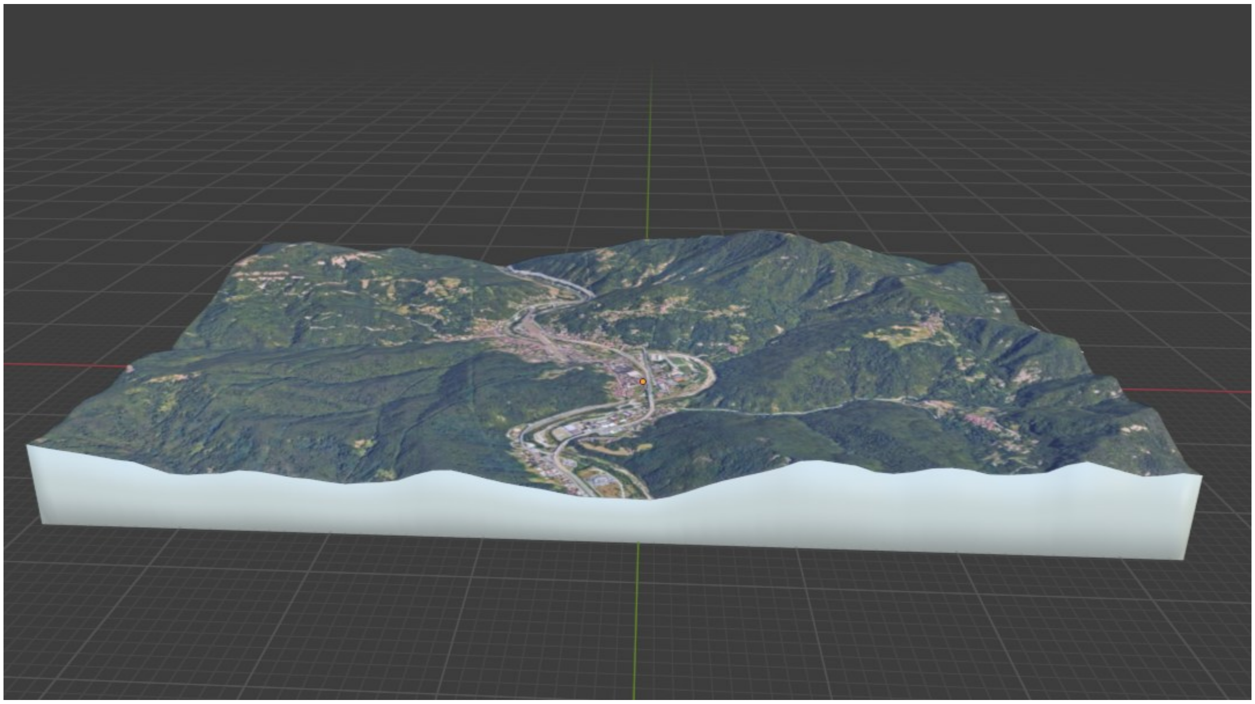


Figure 71. Creation of the 3D Terrain Model with Satellite Texture in Blender

In Blender, several soil and rock types were defined using different materials to facilitate the visualization of the tunnel alignment in respect to underlying geology. This made it possible for us to differentiate between areas like Mesozoic rocks, Triassic formations, and Paleozoic–Precambrian soil as shown in figure 75.

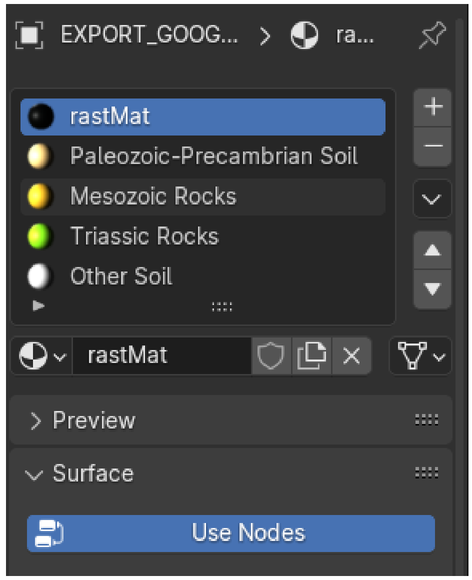


Figure 72. Definition of Geological Units in Blender Using Material Slots for Visualization

Figure 76 shows the visualization of the tunnel's interaction with the geological context, soil categorization zones were applied to the subsurface once the 3D topography was generated.

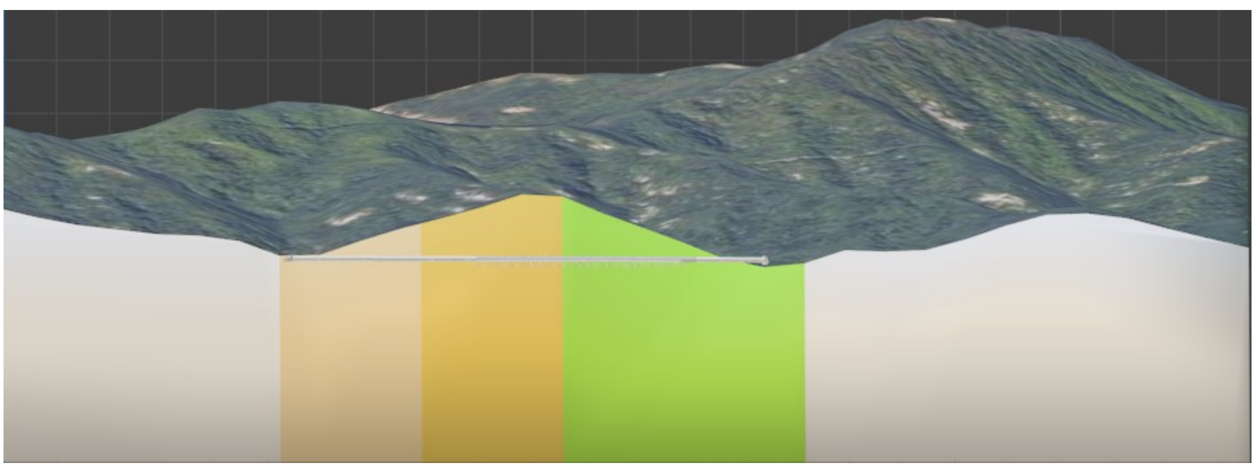


Figure 73. 3D Terrain Model with Applied Soil Classes and Tunnel Alignment

Understanding and categorizing the geological data came next once the 3D terrain model was created. To further connect geo-information with the BIM environment and create what is generally known as GeoBIM, this phase is crucial. Because it allows for a more thorough study and supports predictive maintenance methods based on the spatial relationship between geological conditions and tunnel infrastructure, this integration is an essential component of our workflow.

Table 55. Permeability-Based Grouping of Rock Units in the Study Area

Permeability Score Range	Interpretation	Matching Rock Types & Lithology
0–10	Very tight or sealing rocks (used as caprocks)	**Paleozoic–Precambrian (pCM)** – Crystalline basement (granite, gneiss, schist)
10–30	Low to moderate flow (fractured basement or cemented sandstone)	**Paleozoic–Precambrian (pCM)** – Fractured zones
30–80	Moderately permeable (common reservoir sandstones)	**Triassic** – Clean or moderately sorted sandstones
80–100	Highly permeable (karstified/fractured carbonates or clean sandstones)	**Mesozoic (Mzm)** – Karstified/fractured limestones or clean sandstones

Table 56. Integration of Geo BIM Ring Segments with Geological Units and Risk Classification

<table>
<tr><th colspan="3">Geo BIM</th><th>GEO data</th></tr>
<tr><th>GUID ID</th><th>Type of Ring</th><th>Risk Class</th><th>Type of soil</th></tr>
<tr><td>3mECF5j8D48voEuLfBCjZx</td><td rowspan="4">Tratto A</td><td rowspan="4">Low</td><td rowspan="4">Precambrian (pCm)</td></tr>
<tr><td>3mECF5j8D48voEuLfBCjZt</td></tr>
<tr><td>3mECF5j8D48voEuLfBCjZp</td></tr>
<tr><td>….</td></tr>
<tr><td>32lvXIgLf7hwT$DgK1E1Rq</td><td>Tratto A</td><td rowspan="4">High</td><td rowspan="4">Mesozoic Rocks (Mzm)</td></tr>
<tr><td>32lvXIgLf7hwT$DgK1E1Rm</td><td rowspan="3">Calotta</td></tr>
<tr><td>32lvXIgLf7hwT$DgK1E1Rc</td></tr>
<tr><td>….</td></tr>
<tr><td>3AFPqu$dX74wjRSjIi6Adk</td><td rowspan="4">Tratto A</td><td rowspan="4">Medium-High</td><td rowspan="4">Triassic Rocks</td></tr>
<tr><td>2_ktq9GE10Ieo6V4DNONkm</td></tr>
<tr><td>3AFPqu$dX74wjRSjIi6Adq</td></tr>
<tr><td>....</td></tr>
</table>

Table 57 above helps us understand how different rock types along the tunnel route behave in terms of permeability, essentially how easily fluids like water can pass through them. We grouped the rocks into four categories, from very tight formations (like Precambrian crystalline rocks that barely let anything through) to highly permeable zones (such as karstified limestones or clean sandstones). This classification gives us a clearer picture of which parts of the ground may pose more challenges or risks, such as water pressure or structural stress over time.

Building on that, Table 58 connects the geological data to specific parts of the tunnel using GUIDs from the BIM model. For each ring or tunnel segment, we've included the type of rock it's passing through, the type of structural ring (like "Tratto A" or "Calotta"), and a general risk level low, medium-high, or high. For example, segments in Precambrian rocks are considered low risk because the ground is stable and impermeable. But areas that pass through Triassic formations or karst zones, where the rock is more porous or fractured, are marked as higher risk.

This kind of table is useful because it ties everything together: the tunnel structure, the geology, and the risk. It also sets the stage for predictive maintenance. If we know which areas are geologically more vulnerable, we can focus our monitoring efforts there by placing pressure sensors or other IoT tools to detect early warning signs. This approach not only improves safety but also helps prioritize maintenance resources more efficiently.

To maximize monitoring coverage, we suggest a variable pressure sensor distribution based on each tunnel segment's risk assessment. For basic monitoring, low-risk segments are given a single sensor, but medium-high risk zones are given two sensors to boost dependability. To guarantee early identification of pressure anomalies, high-risk segments particularly those in extremely permeable or geologically complicated zones are outfitted with three sensors. The technology remains cost-effective while improving the predictive maintenance plan because of this precise sensor positioning, as shown in the table below.

Table 57. Integration of BIM Segment IDs with IoT Sensor Deployment Strategy

BIM	IOT
Rings Global ID	Pressure sensor number
3mECF5j8D48voEuLfBCjZx	1
3mECF5j8D48voEuLfBCjZt	1
3mECF5j8D48voEuLfBCjZp	1
….	
32IvXIgLf7hwT$DgK1E1Rq	3
32IvXIgLf7hwT$DgK1E1Rm	3
32IvXIgLf7hwT$DgK1E1Rc	3
….	
3AFPqu$dX74wjRSjIi6Adk	2
2_ktq9GE10Ieo6V4DNONkm	2
3AFPqu$dX74wjRSjIi6Adq	2

....	

Geological data and GeoBIM data are combined to produce a more comprehensive and contextual aware representation of the subterranean environment. We can pinpoint sensor placement, identify important zones, and eventually provide a more accurate and proactive predictive maintenance strategy thanks to this combined methodology. In this sense, BIM turns into a valuable tool for long-term tunnel monitoring and decision-making, rather than only a design or documentation tool.

Following the setup of custom parameters in Revit, we successfully embedded key geotechnical and monitoring-related information within the BIM model. As shown in the figures below, each tunnel ring segment was enriched with attributes such as Attention Class, Permeability Range, Soil Type, Color Code, and the corresponding number of Pressure Sensors. These parameters were manually assigned based on the permeability to-risk-class mapping, as well as the assumed sensor distribution logic discussed in the predictive maintenance framework.

For instance, tunnel segments intersecting Mesozoic rocks with a permeability range of 80–100 was classified as High Attention Class, visualized in red, and assigned three pressure sensors due to their higher monitoring priority. Conversely, segments falling within Precambrian–Paleozoic crystalline formations with low permeability (0–10) were categorized as Low Attention Class, represented in green, and assigned only one sensor. This tiered approach reflects how data-driven risk categorization can be embedded directly into the BIM environment, enabling its export via IFC and subsequent use in GIS-based analysis and visualization.

By integrating these properties at the object level within Revit’s property sets, we ensured that the model is not only geometrically informative but also semantically rich supporting downstream applications like predictive maintenance, automated classification, and risk-aware decision making in tunnel asset management.

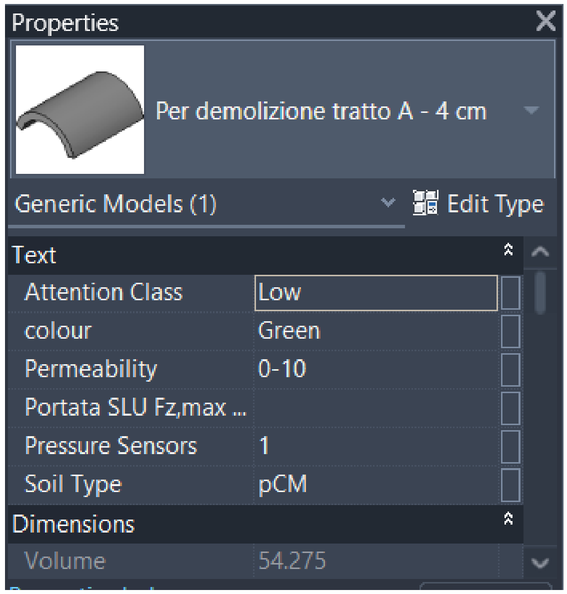


Figure 74. Embedded Pset Parameters for Low-Risk Segment with Precambrian–Paleozoic Rock in Revit BIM Model

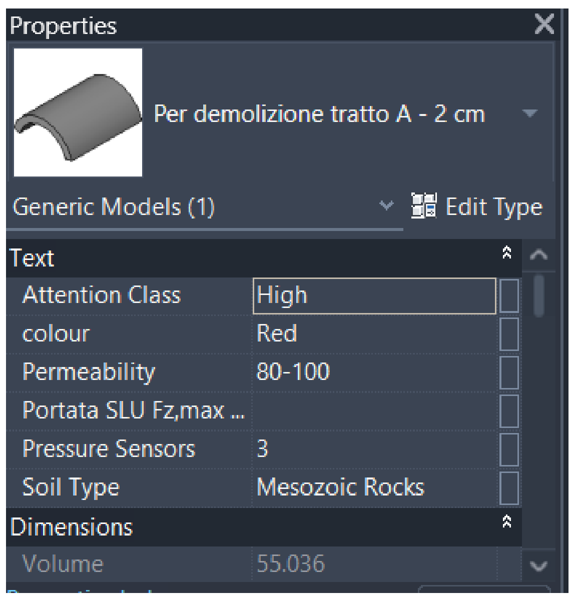


Figure 75.Embedded Pset Parameters for High-Risk Segment with Mesozoic Rock in Revit BIM Model

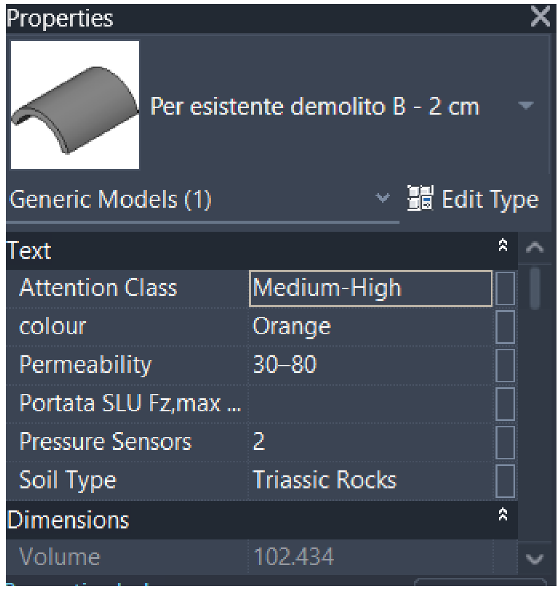


Figure 76.Embedded Pset Parameters for Medium-High Risk Segment with Triassic Rocks in Revit BIM Model

5. Conclusion

Predictive maintenance is a forward-looking approach that aims to identify potential failures before they occur, allowing for timely interventions that reduce costs, extend infrastructure lifespan, and enhance safety. In the context of tunnel engineering, it means anticipating structural or geotechnical issues such as pressure build-up, water ingress, or ground instability before they lead to damage or downtime.

This thesis focused on the role of BIM, GIS, and their integration in achieving predictive maintenance, specifically through the concept of GeoBIM where structural and spatial data are combined with geological intelligence. By bringing together georeferenced BIM models and detailed geological datasets, we explored how this synergy can support more informed decision-making in tunnel management. The goal was to understand how spatial context, geological risk, and structural information can collectively contribute to early detection of maintenance needs.

The 3D tunnel model used in this study was provided by TECNE and served as the structural base for our analysis. Rather than developing the model from scratch, the work involved integrating this existing BIM model with geospatial and geological datasets through platforms such as InfraWorks, ArcGIS Pro, Blender, and Cesium Ion. This integration allowed us to visualize the tunnel in its terrain context and link each ring segment to surrounding soil types, slope, and permeability characteristics.

To move toward predictive maintenance, we proposed a risk classification framework that evaluates tunnel segments based on a combination of geological and geotechnical factors. Each segment was assigned a risk level low, medium-high, or high depending on parameters like soil permeability, geological age, and topographical slope. While the installation of IoT pressure sensors was not carried out in this project, we suggested it as a next step: a practical enhancement to the predictive maintenance approach, where high-risk segments would benefit from targeted sensor deployment to monitor pressure changes in real time.

In conclusion, this study demonstrates that predictive maintenance in tunnel systems can be more precisely planned when BIM and GIS are integrated. The GeoBIM workflow not only supports visualization and spatial analysis but also lays the foundation for advanced monitoring strategies. By combining structural data with geological conditions and proposing ways to assess and monitor risk, this work shows how digital tools can move tunnel management from reactive maintenance to proactive, data-informed intervention.

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