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# Digital tools to enhance design optimization and tunnel construction in the Sotra Link Project

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## Abstract

The Sotra Link Project (SLP), in Western Norway, is the most complex road infrastructure project developed by the Government of Norway within its National Transport Plan 2018-2029. It includes the design, financing, realization and maintenance of several surface and underground structures: among them 11 km of tunnels between Kolltveit and Drotningsvik, 3 pedestrian/bicycle tunnels, 19 underpasses, 23 tunnel portals and 24 kilometers of two-lane access roads. Concerning the underground works, the infrastructure will be established as two parallel one-direction tunnels, each of them with double lanes. This paper focuses on the design solutions for the two main tunnels in Kipledalen, Drotningsvik area. Geotechnical complexities in this area are mainly related to a combination of low overburden, heterogeneous geology, including clayey layers, fault zone with swelling potential and interferences with existing and future nearby viaducts. Updates on the status of the construction works are provided with a focus on digital tools and model-based design to enhance the tunnel excavation and design optimization during the construction. They mainly consist of a comprehensive 3D geological model, created with the support of specialized software, as Leapfrog, allowing a detailed representation of the geological units, as well as the position of boreholes and faults, for each project area. The coordinated model also includes the tunnel, the new and existing viaducts together with the Kiple Lake. The digital model is updated accordingly with data gathered from drillings at the excavation front, updated scanning, and daily observations resulting from the excavation of the tunnel. It also provides the base for the monitoring system adopted within the SLP that, along with the observational approach, represents a fundamental tool to deal with various geo-hazards. It mainly includes an automatic topographic monitoring system, vibration measurements, and piezometers, allowing the definition of proper thresholds.

## Keywords

Geological model, Computational design, BIM, Shallow tunnelling, Underground structures

# 1 Introduction

This paper is intended to provide an outline of the most recent updates of the underground works of the Sotra Link Project (SLP), a complex infrastructure project in the Vestland county, Norway, western Bergen. Together with a description of the up-to-date construction process, the article provides a deeper insight of the adoption of the BIM (Building Information Modelling) approach in the design and management of a challenging underground stretch along the alignment. In recent years, the application of such a methodology has become increasingly essential to ensure the quality of complex civil engineering projects, as well as their manageability over time. Compared with a traditional design process based on 2D drawings and non-integrated project data management, the BIM methodology reveals significant improvements in both the design and construction phases of underground structures. The use of *comprehensive-consistent* three-dimensional, digital models containing both geometric data and information, working as a centralized source of data, is the key element of the BIM approach. A general reduction of design errors, better management of the construction and maintenance phases and better checking of clashes (Barbieri et al., 2023) are just some of the main benefits in adopting BIM approach in complex engineering projects. In the current paper, some of the main design complexities of the tunnelling works are described, and the adopted solutions together with the advantages of BIM in tunnel design and construction are presented.

# 2 General overview of the Sotra Link Project

SLP is the largest and most complex road infrastructure project developed by the Norwegian Government within its National Transport Plan 2018-2029. It is one of Norway's priority infrastructure projects and includes the design, financing, construction, and maintenance of several surface and underground fathe city of Bergen and the island of Sotra in Western Norway, supplying traffic requirements along the existing national Rv. 555 roadway. The overall project comprises 9 km of new motorway and a suspension bridge between the municipalities of Øygarden and Bergen. The road system includes 12.5 km of tunnels, 19 road and pedestrian culverts, 23 tunnel portals, 22 bridges and viaducts, and 14 km of pedestrian and cycle paths. The project includes 4 main tunnels, named from west to east: Kolltveit tunnel, Straume tunnel, Knarrvika tunnel, and Drotningsvik tunnel (Fig. 1). All tunnels are double-tube, one tube per direction, with 2 lanes in each direction. The SLP also involves the design of a suspension bridge “Ny Sotrabrua” (30 m wide, 900 m long, including 144 m high pillars), representing the iconic structure of the project, 3 tunnels for cyclists and pedestrians along the new cycle path running parallel to the main road.

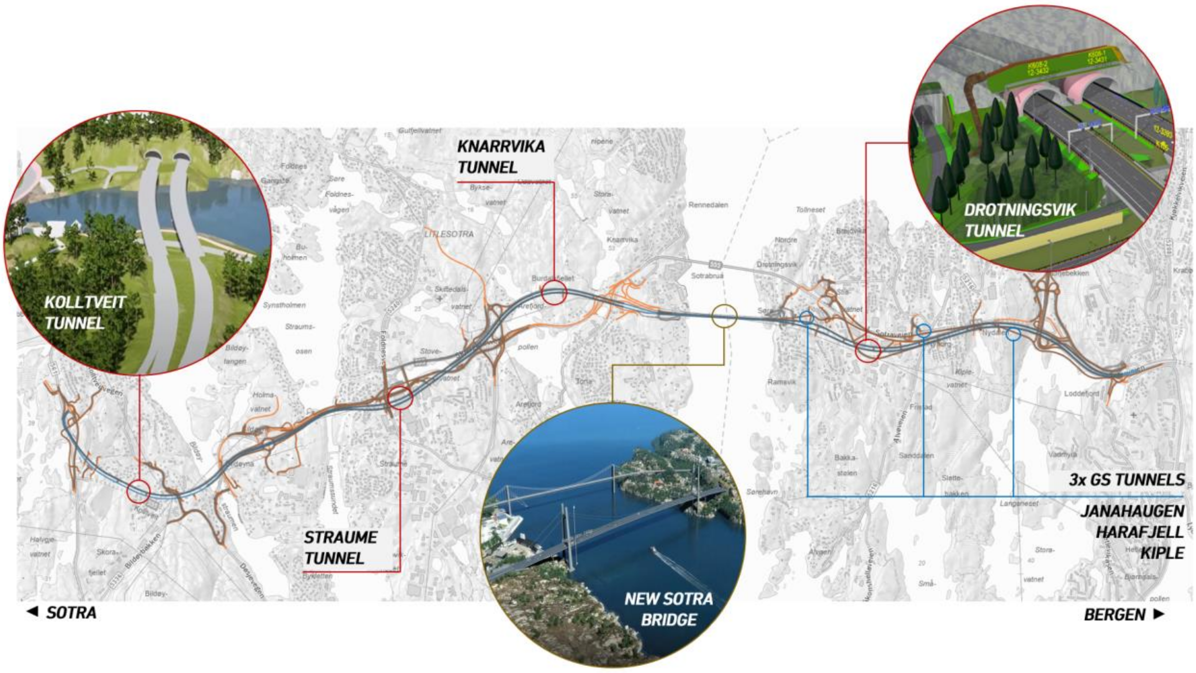


Fig. 1 The Sotra Link Project overview between Bergen and Sotra, Vestland County.

# 3 Updates on construction works

Construction works started in March 2023, and, currently, all the 4 main areas of Kolltveit, Straume, Knarrvika and Drotningsvik include ongoing activities. The excavation of the Kolltveit tunnel started in July 2023 from West to East, and the completion of both North and South tubes was achieved in April 2024. The Drotningsvik tunnel is currently under excavation, and the realization of the tunnel access ramps started during summer 2024. The current advancement is on schedule with the foreseen planning, aiming for the last breakover by June 2026. The excavation of the Straume tunnel began on June 2024, and is scheduled to be completed by July 2025. Following the completion of the Straume tunnel, the excavation of the Knarrvika tunnel will commence, with an estimated completion date of July 2026. All three bicycle and pedestrian tunnel portals are also currently under construction.
Table 1 provides a summary of the excavation status within all the main underground areas as per November 2024.
Concerning the main civil engineering works apart from tunnels, works for the “Ny Sotrabrua” suspended bridge started in March 2023 with the foundations on Knarrvika side – as per Nov.2024 reached almost 90 m - while the works on Drotningsvik side started later (reached almost 45 m in Nov.2024). The completion of the suspended structure is foreseen by September 2026.

Table 1 Statues of the tunnels along Sotrasambandet

| Tunnel | Excavation start | Excavation end | Total length | Excavated Length (status: Nov. 2024) | Typological profile** |
|---|---|---|---|---|---|
| Drotningsvik tunnel | November 2023 | August 2026 * | 1951 m (North tube), 1787 m (South tube) | 33% (North tube), 41% (South tube) | T13 |
| Drotningsvik ramps | September 2024 | June 2026 * | 594 m (North tube), 657 m (South tube) | 13% (North tube), 3% (South tube) | T7.5 |
| Straume tunnel | June 2024 | July 2025 * | 698 m (North tube), 743 m (South tube) | 60% (North tube), 58% (South tube) | T9.5 |
| Knarrvika tunnel | June 2025 * | March 2026 * | 748 m (North tube), 732 m (South tube) | Not started | T9.5 |
| Kolltveit tunnel | July 2023 | April 2024 | 963 m (North tube), 966 m (South tube) | Both tubes completed | T9.5 |

** Expected according to planning  ** Typological profiles defined in agreement with N500 Tunnelling Handbook by SVV*

Fig. 2 Straume tunnel East Portal (upper left); The excavation of Kiple GS tunnel West Portal next to the existing Kiple tunnel along Rv.555 (upper right); Drotningsvik tunnel East Portal (lower left); Tunnel face during the excavation of the Kipledalen section (lower right).

# 4 Kipledalen section: main geotechnical challenges

Drotningsvik is the Eastern area of the worksite, located towards Bergen, and includes the most complex underground alignment, where the systematic tunnelling techniques based on conventional drill & blast advancements needed more robust design studies and currently demands particular attention. A plan view of the Drotningsvik area is given in Figure 3. With its approximately 2 km long stretches, Drotningsvik tunnels are the longest tunnels within the SLP, comprising a wide range of ground overburden, from 6 to about 50 m, 8 cross passages, and 4 underground technical rooms.

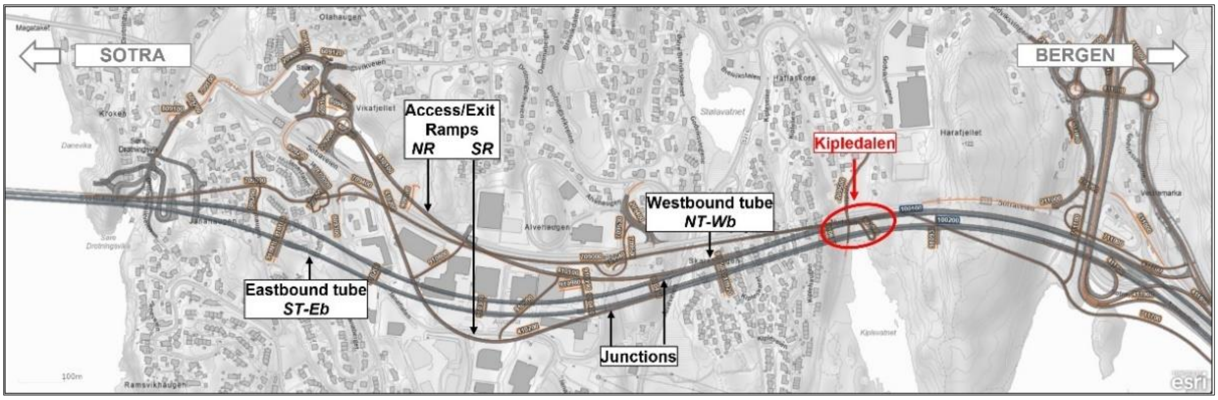


Fig. 3 Plan view of Drotningsvik area and detail of the Kipledalen section location.

Drotningsvik tunnels most complex section, including both the North tube (Westbound, towards Sotra) and the South tube (Eastbound, towards Bergen) was foreseen for a total length of 50 m, confirmed after a last geological campaign including 3 total core drillings, performed in January 2024. The section is located under the current Rv.555, running upwards Kipledalen. Moreover, the new tunnels openings have been excavated in close proximity to a small lake reservoir, Kiplevatnet. With two nearby sections measuring 19 m as maximal span, and 9 m as maximal front height, the following aspects represented the most challenging engineering problems of the section:

- A very low overburden with a minimum 6 m, with geological uncertainties regarding the thickness and quality of the upper rock mass level at the section vaults;
- The upper alignment of the current roadway Rv.555, partially laying on an artificial embankment and partially running on a viaduct deck, which pillar load is founded in the ground upon the North tube vault;
- The pillar of a future pedestrian bridge, which is part of the foreseen bicycle and pedestrian parallel infrastructure, to be built after the tunnel excavation;
- The low quality of the fractured rock mass infillings, which could generate potential swelling phenomena influencing the long-term durability of the permanent structures (Giani et al. 2024).

The presence of loosened surficial deposits at the tunnel vault and the water reservoir demanded the realisation of extensive grouting curtains and crowns around and above the excavations, to improve the effectiveness of the radial bolting and the perimetral waterproofing (Figure 4, left). The longitudinal advancing profile showing the application of the *reinforced ribs of shotcrete* (Barton & Grimstad 2014b, Norwegian Geotechnical Institute NGI 2015, Palmstrom & Broch, 2006) as permanent lining is illustrated in Figure 4, on the right.

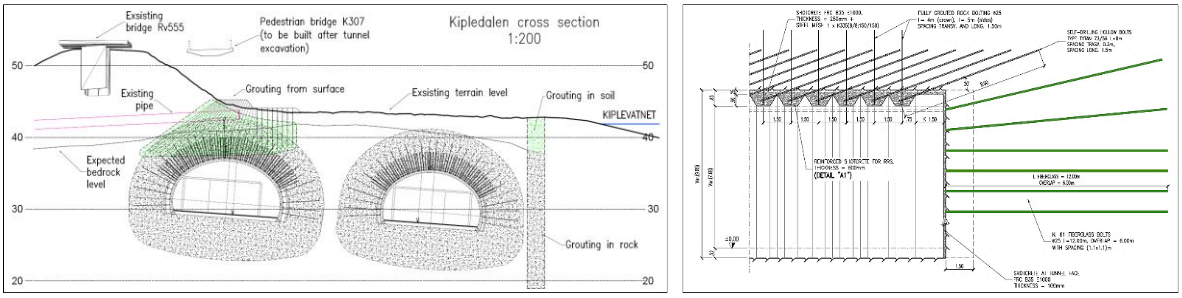


Fig. 4 Section overview of the solution designed for Kipledalen stretch (left); longitudinal section and advancing scheme of Kipledalen stretch (right), with the perimetral application of the *reinforced ribs of shotcrete*.

# 5 Digital tools guiding the design and construction evidences

## 5.1 General description

The adoption of BIM methodology in the SLP is mentioned in the tender documents: they clearly state that the project must be delivered on a BIM-based platform from the Early Design phase to the Detail Design of tunnels (Figure 5). The application of BIM methodology for a complex infrastructure project such as the SLP proved to be beneficial to the overall quality of the design and construction phases. The BIM implementation has proven to bring several improvements over a traditional design process based on different and non-interoperable file types and formats. The integration of all project data into a single *source of truth* represented by the digital model enables immediate verification of clashes and resolution of possible errors, improving understanding of design choices and collaboration between different task teams – e.g. tunnels, roads and landscape designers. The availability of the model to all project stakeholders also improves communication between the design team and the client, making the entire process more transparent and efficient. Finally, the information content implemented in the models allows for constant updating and extraction of project amounts for the bills of quantities and forms the basis for a deeper evaluation of design choices. In conclusion, the adoption of BIM methodology provides significant benefits in terms of more efficient management of design data, increased productivity, and improved communication between parties.

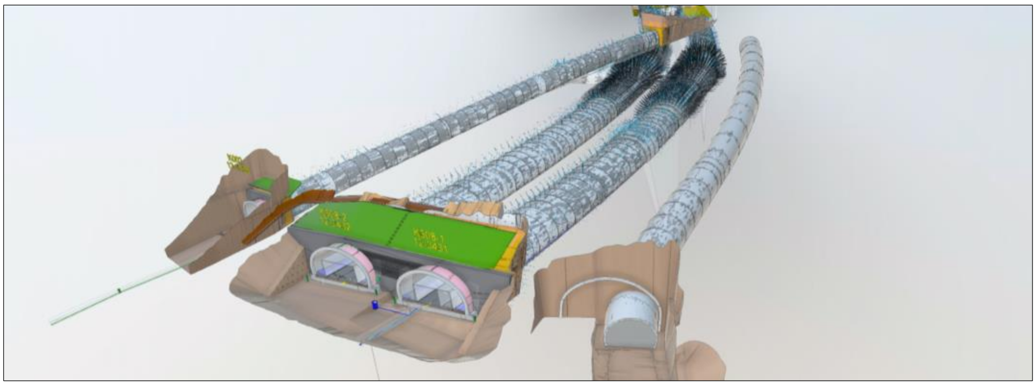

Fig. 5 The multidisciplinary collaboration model, seen from the east portals of the Drotningsvik tunnel.

## 5.2 BIM-based design iteration for Kipledalen area

As detailed in Chapter 3, the tunnel stretch of Kipledalen required specific ground treatment interventions due to its geotechnical complexities and the interference with both existing and foreseen structures. In this context, the adoption of BIM methodology and the availability of project data in an interoperable format enabled the team to guide, verify, and compare different design options in order deliver the most efficient solution, while minimising disruptions during drill and blast activities. To address the geotechnical challenges, the design team relied on a geological model, created using the software LEAPFROG, also available in an interoperable format. This model facilitated a precise analysis of the low overburden and heterogeneous geological conditions. Additionally, bathymetric measurements provided crucial data for designing ground treatments and facilitating comparative evaluations. These data (Figure 6) were instrumental in guiding the direction of design options.

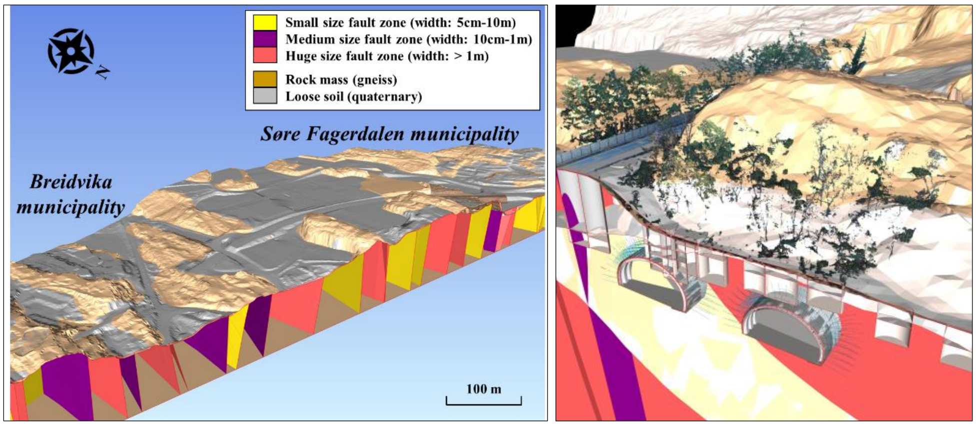


Fig. 6 Geological 3D model of Area 10 (left) and federation with others 3D model and point cloud (right)

In the subsequent phase, the project team developed and validated these options within a framework where geotechnical data were integrated with 3D models of the designed structures and point clouds representing the existing infrastructure. This integration led to the development of two distinct design solutions. The first option (Option 1 in Figure 7, left) involved the construction of a bulkhead of piles downstream of the existing viaduct. This solution included the removal of the existing loose soil and the placement of a lean concrete layer to guarantee a minimum overburden of performing material. From the design point of view, this allowed to justify the adoption of conventional tunnelling excavation instead of external trenching interventions (e.g. cut and cover methodology). In the second option (Option 2 in Figure 7, right), following coordination with the client, the design team proposed an extensive ground improvement, operated through:

- Jet grouting columns from the surface, to improve the low overburden stretch, in particular upon the North tube, and to provide a curtain to counteract seepage phenomena coming from the likely drainage of the Kiplevatnet reservoir to the South;
- Grouting injections around the excavation perimeters, operated from the underground through advancing probe-drillings at regular steps of 9 m.

Both design solutions were thoroughly evaluated for potential interference with existing and future structures.

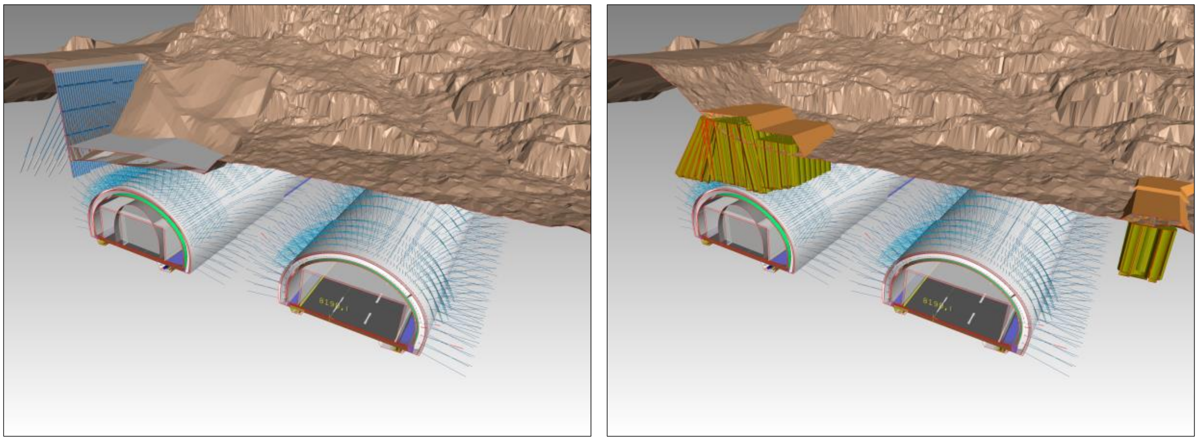

Fig. 7 Developed design options: Option 1 (left) and Option 2 (right)

Once the final solution was agreed, in collaboration with the client (Option 2), BIM models were developed to the Model Maturity Index (MMI) required for construction. This level of detail was further enhanced through the incorporation of additional survey data, which enabled the creation of a more accurate geological model, closely aligned with the actual on-site conditions. The project team placed particular emphasis on structuring the 3D model using parametric elements, ensuring that all necessary information for construction and the preparation of the metric calculations was included.

## 5.3 Monitoring system and observational method updating the construction process

During the excavation activities in Kipledalen, achieved by autumn 2024 for both main tubes, approximately 90% of the stretch was mapped as rock mass class “E1”, according to the NGI characterisation based on *Q*-value (Norwegian Geotechnical Institute *NGI*, 2015). Due to the section's complexity and interference with surrounding infrastructure, during the detailed design phase, a permanent rock support corresponding to a rock mass class “F” was prescribed, including the rigid *reinforced ribs of shotcrete* solution shown in Figure 4.

With the on-site observations and measurements of the rock quality, discussions to reduce the rock support were conducted during each mapping. During the excavation, probe hole drilling was conducted every three meters (every second blasting round) to gather more information about the rock conditions ahead of the face and the overburden. Measurements based on the point-resistance to perforation (MWD) to install the spiling umbrella were gathered, enhancing the construction optimisation process (e.g. Figure 8, left). To foresee overall conditions before entering the stretch, three deeper holes were also drilled at an inclination of 20-40° from the horizontal. The South tube's average *Q*-value equal to 0.5 allowed to optimise the self-drilling spiles initially designed (type TITAN 73/56) with lighter spiles (32 mm of diameter, fully grouted for a total length of 6 m) for most of the stretch. With an average $Q$-value of 0.4 mapped in the North tube, the same spiling system was installed halfway through the section. Nonetheless, a length of 6.5 m was detected, where $RQD \leq 35$ resulted in $Q$-values below 0.1, requiring indeed the rock support class as per detailed design, applying the *reinforced ribs of shotcrete* solution.

Eventually, the effective stretch length where specific solutions, corresponding to the BIM-based design mitigations, had to be adopted resulted, respectively, 31 m long for the North tube and 23.5 m for the South tube.

Fig. 8 MWD rock strength data at chainage 8+132 in the North tube (left) and jet-grouting from the surface before the North tube excavation (right).

## 6 Conclusions

In the context of a *design and build* realisation approach of the Sotra Link Project, this paper described a practical case study for the main aspects of a BIM-based design implementation in the most complex stretch of the new underground infrastructure.

Compared with a traditional design process based on 2D drawings and non-integrated project data management, the BIM approach for underground works proved to bring several significant improvements in both the design and construction phases. Despite the initial effort to implement BIM-based procedures within the design team, the benefits of BIM became evident as the design phase progressed. The creation of a single comprehensive digital model of the project that worked as single "source of truth" allowed for more precise control of clashes between disciplines and more efficient resolution of design issues. Collaborative workflows on the shared digital platform enabled better communication between task teams and between the design team and the client, reducing the possibility of errors and radical construction variations on site. Moreover, the implementation of information in models (LOI) allowed immediate extraction of project quantities from the models, enabling rapid updating of bills of quantities, and formed the basis for accurate analysis. In conclusion, the application of BIM methodology to infrastructure projects, despite the initial investment by all parties in terms of intense training, has proven to create a more integrated and collaborative approach to infrastructure, with benefits in terms of increased productivity, reduction of costs due to errors, and improved communication between the stakeholders of the project.

The design and BIM activities of the SLP are currently on schedule. The design phase is scheduled to be completed in 2025, and the infrastructure is expected to be completed in 2027.

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