BIM-GIS INTEGRATION FOR GEOTECHNICAL RISK MANAGEMENT IN MIDSTREAM PIPELINE INFRASTRUCTURE

PILOT STUDY AT PK 046+550 OF THE OCENSA PIPELINE

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De la emergencia a la eficiencia:
Un nuevo estándar para la ingeniería de ductos?

06 de Noviembre de 2025

PREMISAS

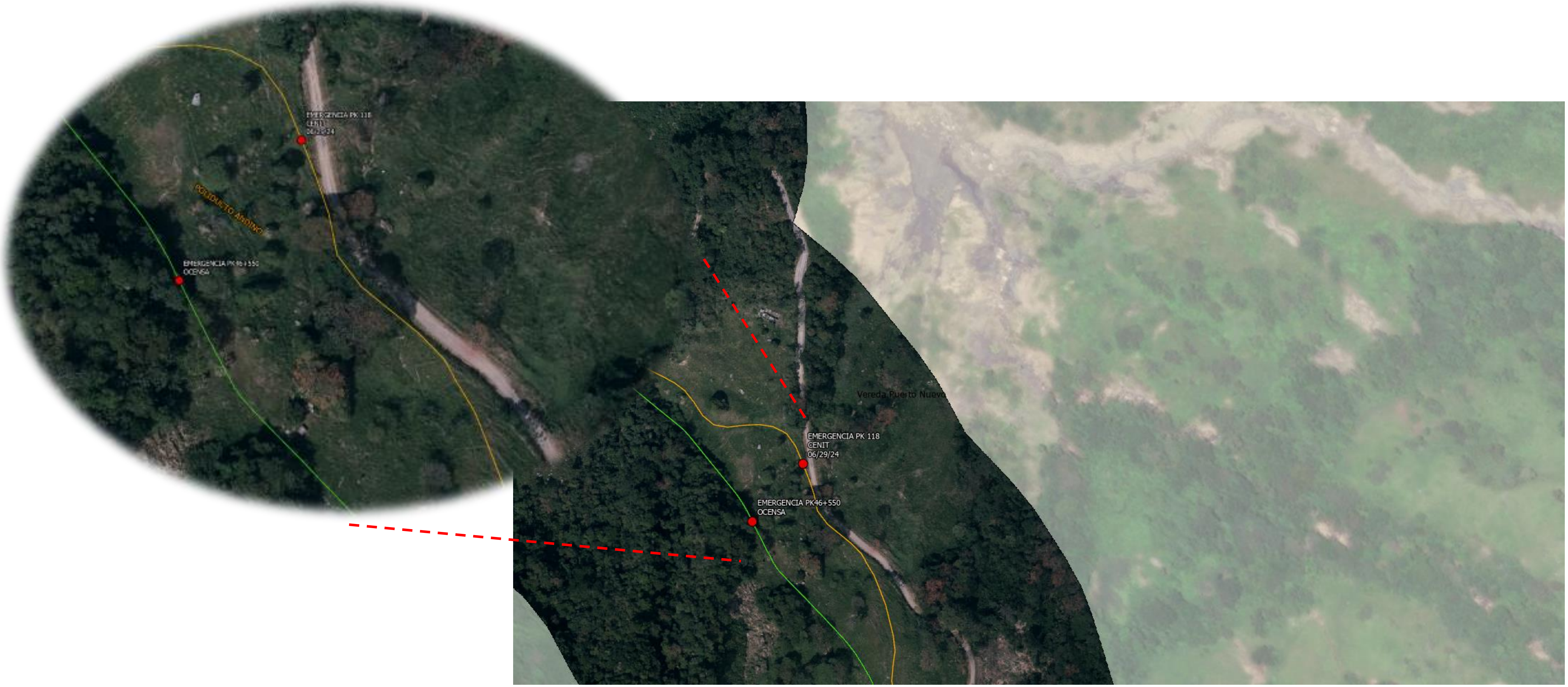
- En Colombia, más del 20% de los riesgos sobre el oleoducto OCENSA están ligados a procesos geodinámicos y climáticos.
- En Junio de 2024 se presentó un deslizamiento en el PK 118+800 del Poliducto Andino que generó pérdida de contención del sistema de Cenit.
- El DDV de Ocensa cuyo ducto trascurre paralelo, se vio afectado en la abscisa que corresponde al PK 46+550

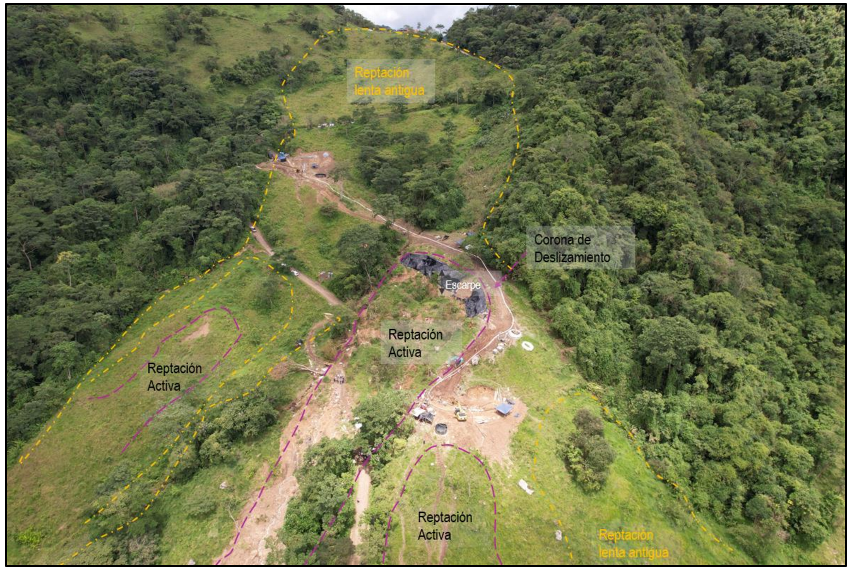
RESULTADO :

A solo 16 metros del ducto, la montaña comenzó a moverse

EMERGENCIA

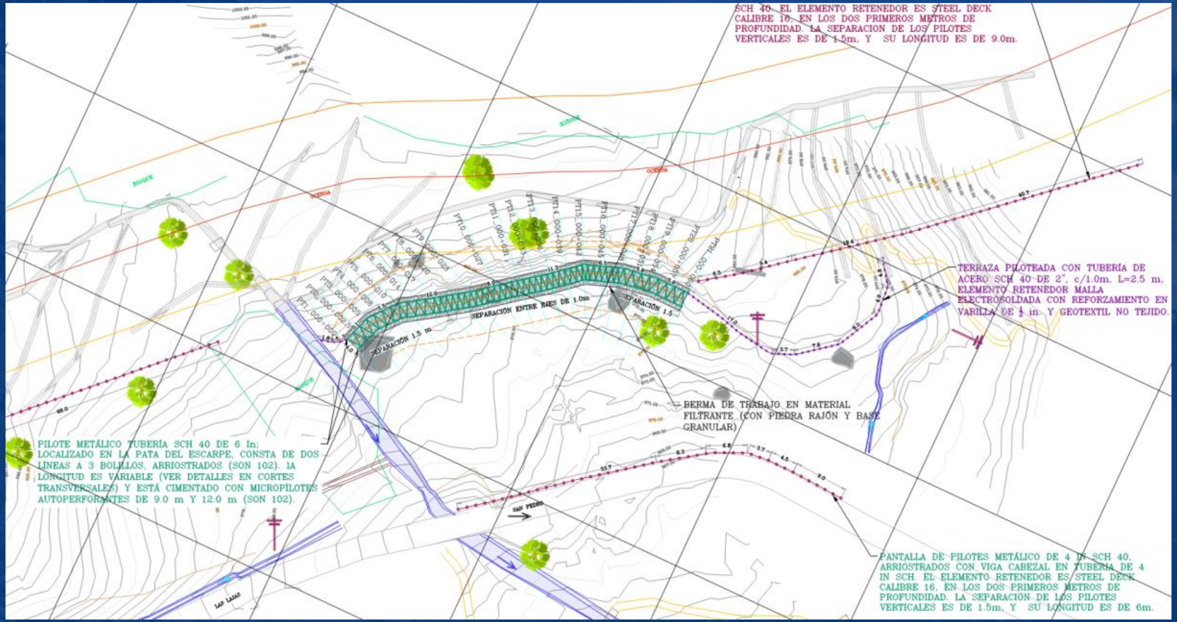
LA CONDICIÓN GEOTÉCNICA

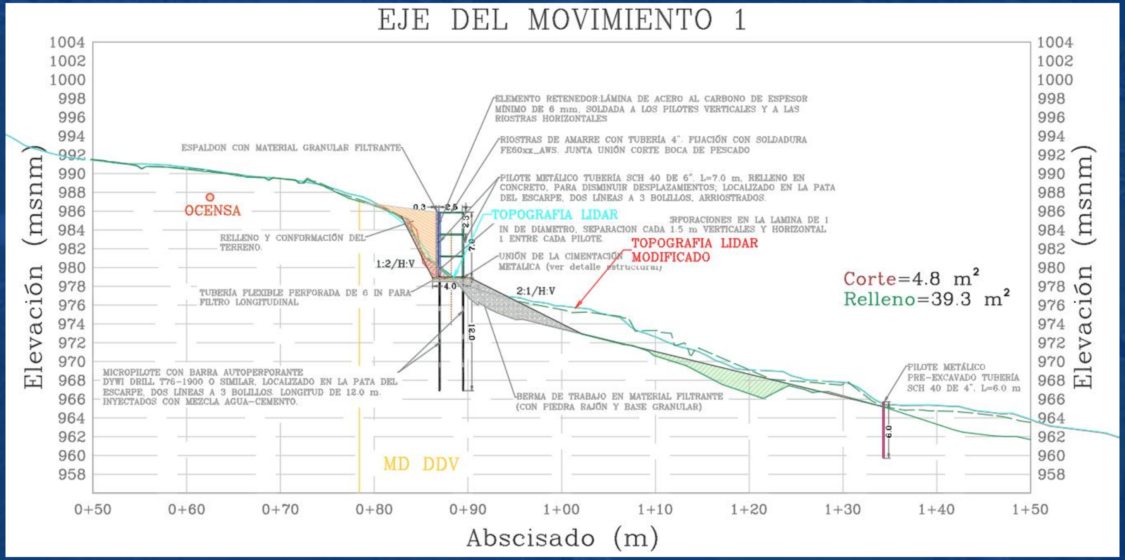




- Deslizamiento activo de tipo compuesto (Rotacional / Planar)
- Mecanismos traslacionales en la parte baja y media, movimientos rotacionales en la parte alta.
- Procesos sucesivos que se dirigen predominantemente hacia el cauce de la quebrada La Volcanera.

EL RETO





- **Obras de alta complejidad:**

Los diseños iniciales incluyeron tres líneas de pantallas piloteadas, micropilotes y una superestructura de contención de hasta 7 metros de alto.

- **Altas precipitaciones**

Media anual por los últimos 10 años de 3619.63 mm IDEAM
En la Cuenca del rio Meta la precipitación varia:
2011.66 mm actual
2226.9 mm cambio climático a 50 años

Las condiciones de extrema y persistente Lluvia empeoraron la condición geotécnica de la zona, manteniendo el sitio bajo alerta (Lluvia diaria media de 2.28 horas)

Saturación de la ladera, aparición de grietas, impedimento de la consolidación del suelo, retardando el progreso en la ejecución de las obras

- **Necesidad de actualizar diseños como respuesta a los cambios del terreno**

Método tradicional = Dificultad para seguirle el ritmo al terreno
Cada cambio de diseño puede generar demoras, sobrecostos y pérdida de trazabilidad.

Integración BIM – GIS

BIM led – GIS Support

Demostrar la innovación técnica y su impacto real.

Entorno digital integrado

BIM

- Simulación de escenarios
- Modelado paramétrico
- Atributos
  - Materiales
  - Proveedores
  - Especificaciones
- Activo: Prototipo, testear y mejorar

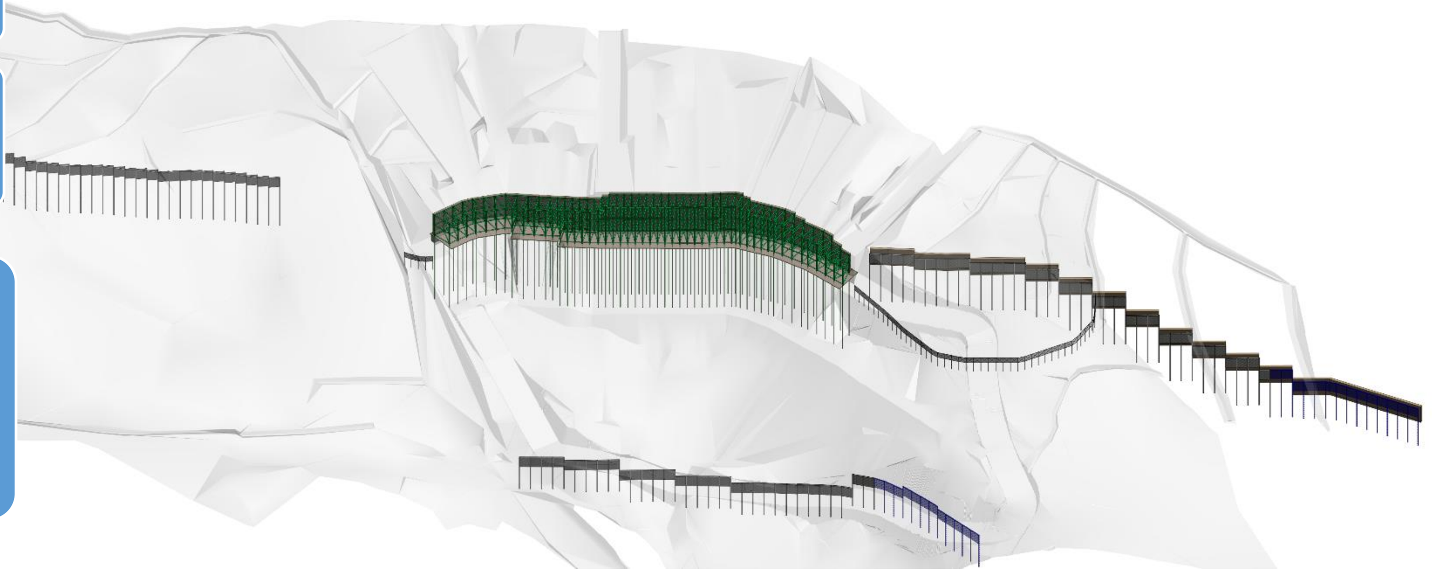
GIS

- Contexto espacial (Georreferenciación)
- Base topográfica
- Base interoperabilidad

Usos clave

- Modelado de condiciones existentes
- Estimación de cantidades y costos
- Planificación de fases
- Planificación de construcción
- Control de construcción

- Modelado 3D (Visualización)
- Simulación 4D (Tiempo)
- Simulación 5D (Costos)

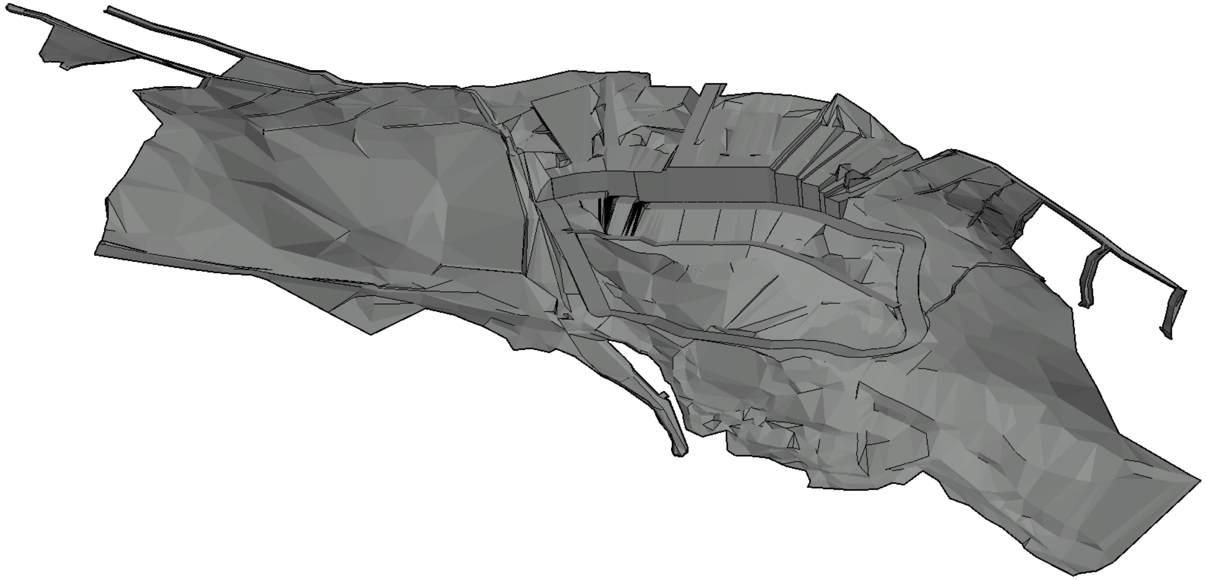


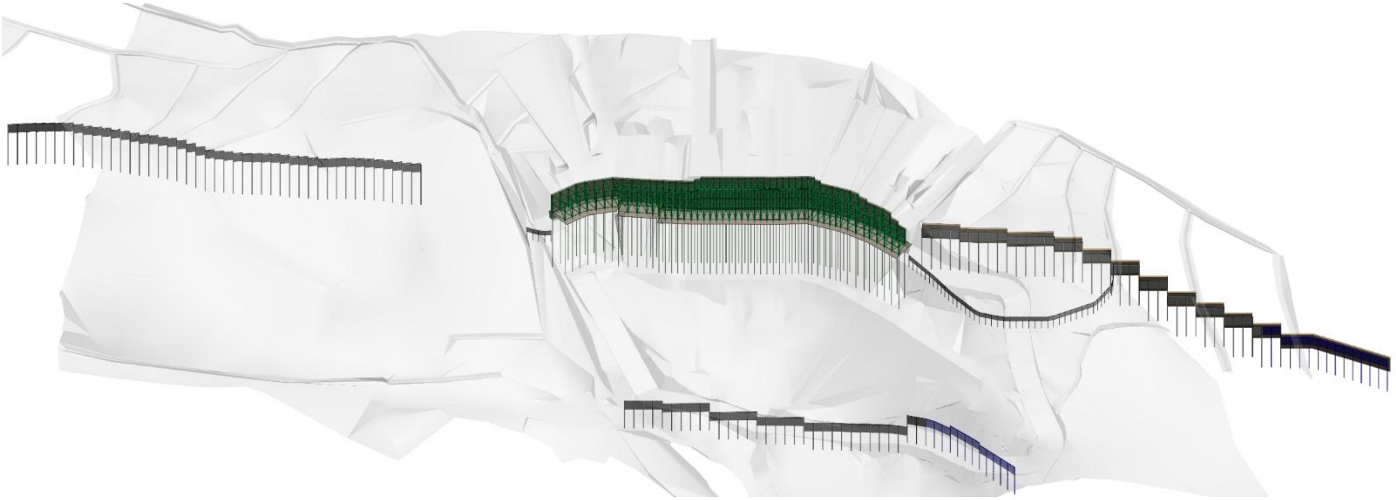
Integración BIM – GIS

BIM led – GIS Support

- Diseños de geotecnia: Pantallas piloteadas, Micropilotes, drenes horizontals, puntos de inyecciones de consolidación y sistemas de anclaje
- Componentes estructurales: Estructura metalica, láminas, estructuras de soporte al Sistema de contención
- Movimientos de tierra: Modelado detallado de los volumenes de tierra, cruciales para el control de costos y la ejecución de las obras

Se desarrolló un modelo 3D detallado, que incluyó:

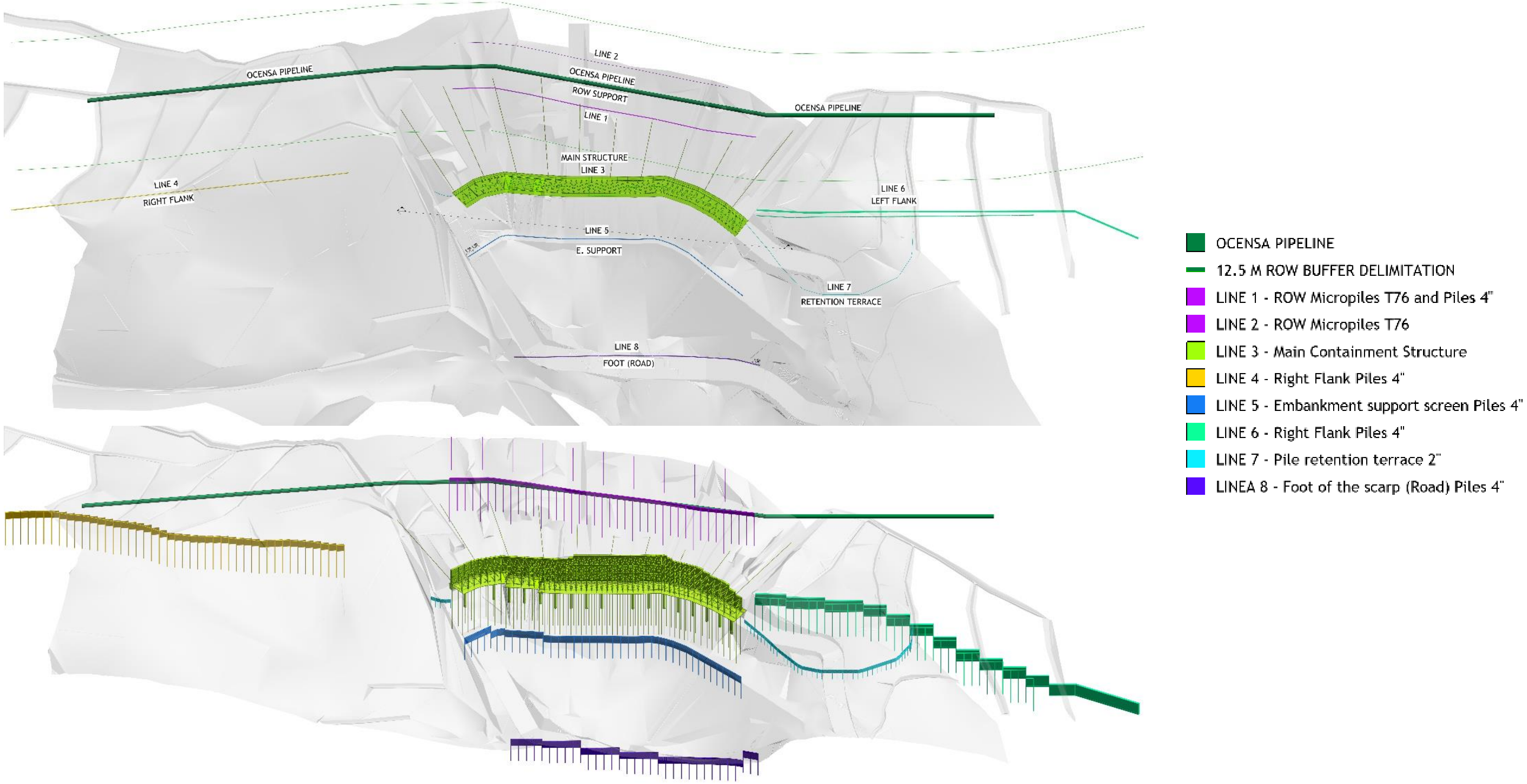




Integración BIM – GIS

BIM led – GIS Support

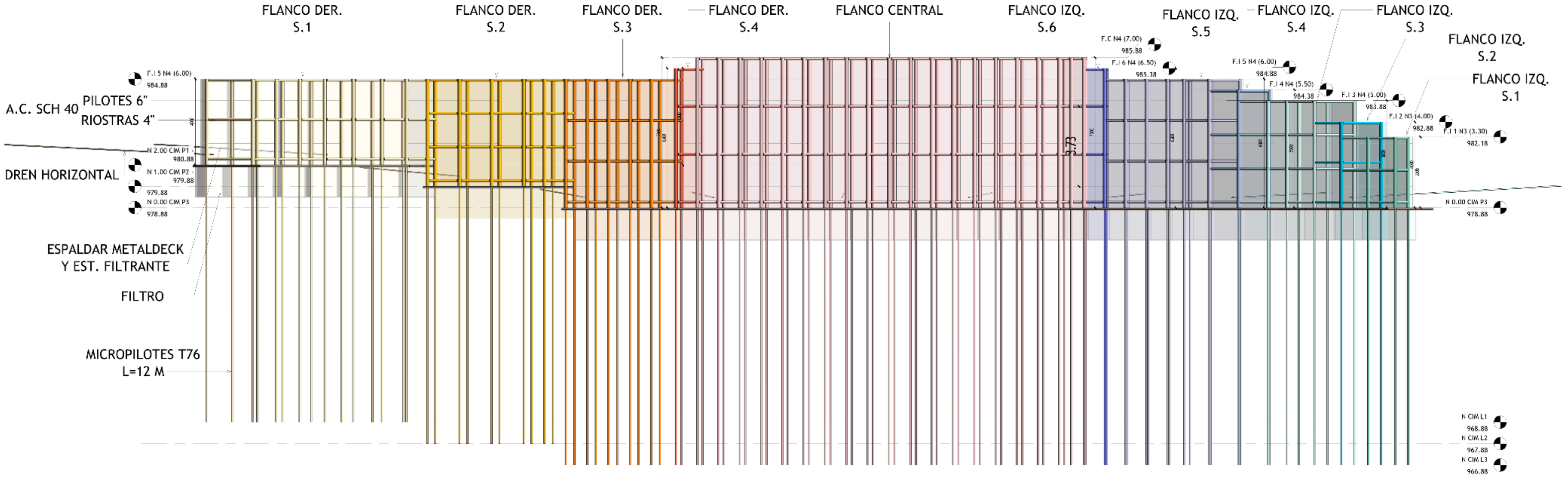
Zonificación y segmentación de cantidades



Integración BIM – GIS

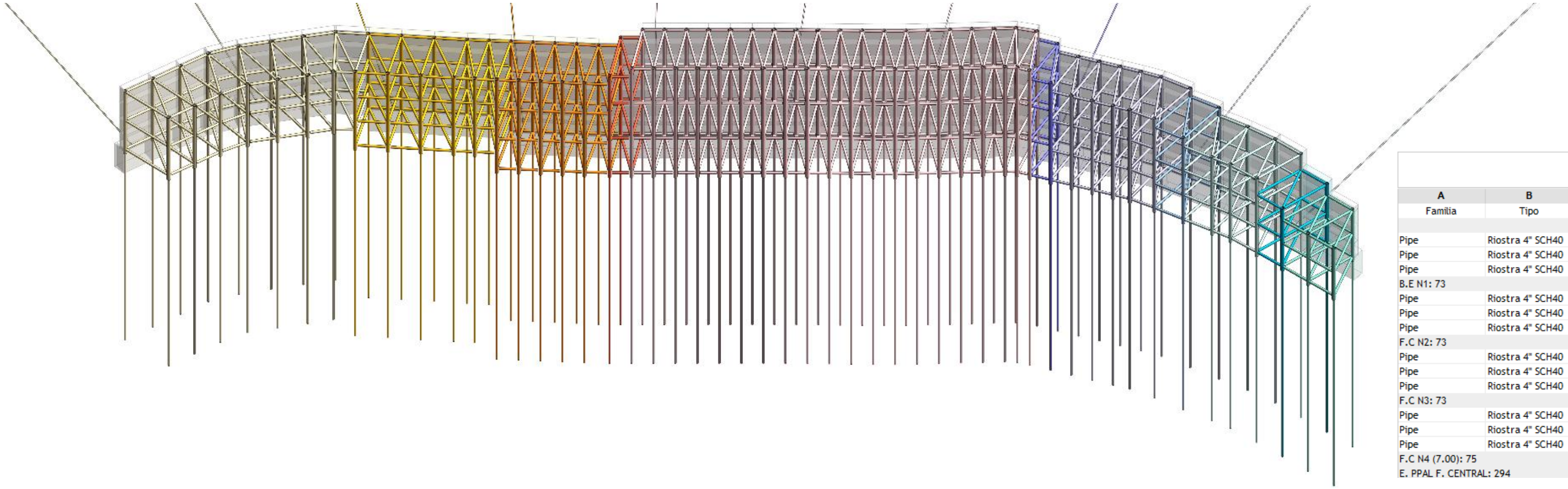
BIM led – GIS Support

Zonificación y segmentación de cantidades



<2.1 SUMINISTRO DE TUBERÍA DE AC Φ= 6">

A	B	C	D	E	F
Familia	Tipo	Longitud	Zone	Linea	Ejecutado
Pipe-Column	Pilote 6" SCH 40	133.00	E. PPAL F. CENTRAL	3.1	☐
Pipe-Column	Pilote 6" SCH 40	140.00	E. PPAL F. CENTRAL	3.2	☐
Pipe-Column	Pilote 6" SCH 40	32.00	E. PPAL F. DER	3.1	☑
Pipe-Column	Pilote 6" SCH 40	28.00	E. PPAL F. DER	3.2	☑
Pipe-Column	Pilote 6" SCH 40	25.00	E. PPAL F. DER 2	3.1	☑
Pipe-Column	Pilote 6" SCH 40	25.00	E. PPAL F. DER 2	3.2	☑
Pipe-Column	Pilote 6" SCH 40	30.00	E. PPAL F. DER 3	3.1	☐
Pipe-Column	Pilote 6" SCH 40	30.00	E. PPAL F. DER 3	3.2	☐
Pipe-Column	Pilote 6" SCH 40	6.50	E. PPAL F. DER 4	3.1	☐
Pipe-Column	Pilote 6" SCH 40	6.50	E. PPAL F. DER 4	3.2	☐
Pipe-Column	Pilote 6" SCH 40	3.30	E. PPAL F. IZQ 1	3.1	☐
Pipe-Column	Pilote 6" SCH 40	6.60	E. PPAL F. IZQ 1	3.2	☐
Pipe-Column	Pilote 6" SCH 40	4.00	E. PPAL F. IZQ 2	3.1	☐
Pipe-Column	Pilote 6" SCH 40	4.00	E. PPAL F. IZQ 2	3.2	☐
Pipe-Column	Pilote 6" SCH 40	15.00	E. PPAL F. IZQ 3	3.1	☐
Pipe-Column	Pilote 6" SCH 40	15.00	E. PPAL F. IZQ 3	3.2	☐
Pipe-Column	Pilote 6" SCH 40	5.50	E. PPAL F. IZQ 4	3.1	☐
Pipe-Column	Pilote 6" SCH 40	5.50	E. PPAL F. IZQ 4	3.2	☐
Pipe-Column	Pilote 6" SCH 40	36.00	E. PPAL F. IZQ 5	3.1	☐
Pipe-Column	Pilote 6" SCH 40	30.00	E. PPAL F. IZQ 5	3.2	☐
Pipe-Column	Pilote 6" SCH 40	6.50	E. PPAL F. IZQ 6	3.1	☐
Pipe-Column	Pilote 6" SCH 40	6.50	E. PPAL F. IZQ 6	3.2	☐
Total general: 102		593.90			



<2.4 SUMINISTRO DE TUBERIA AC DE 4" RIOSTRAS NIVELES>

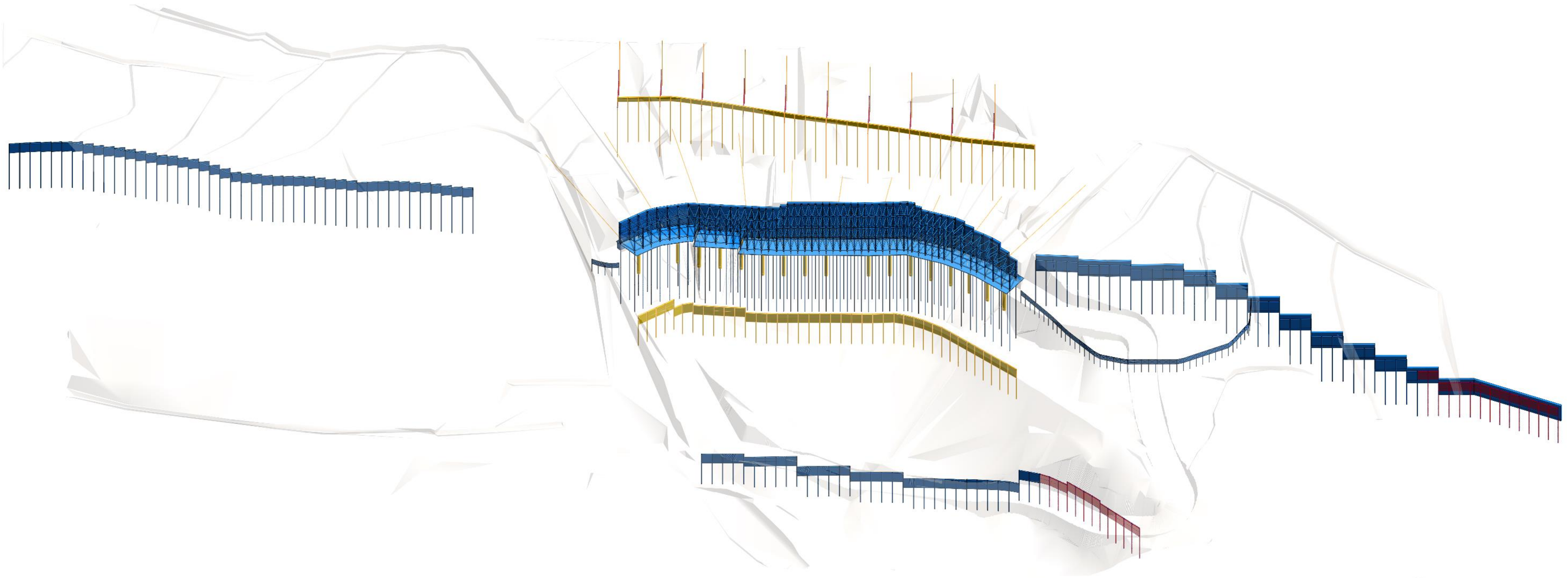
A	B	C	D	E	F	G	H	I	J
Familia	Tipo	Recuento	Longitud	L2	Desfase de nivel fi	Nivel de referenci	Zone	Linea	Ejecutado
Pipe	Riostra 4" SCH40	36	91.79	91.79	0.07	B.E N1	E. PPAL F. CENTRAL	3	☐
Pipe	Riostra 4" SCH40	18	17.99	17.99	0.07	B.E N1	E. PPAL F. CENTRAL	3.1	☐
Pipe	Riostra 4" SCH40	19	18.08	18.08	0.07	B.E N1	E. PPAL F. CENTRAL	3.2	☐
B.E N1: 73			127.86	127.86					
Pipe	Riostra 4" SCH40	36	91.79	91.79	0.06	F.C N2	E. PPAL F. CENTRAL	3	☐
Pipe	Riostra 4" SCH40	18	17.99	17.99	0.06	F.C N2	E. PPAL F. CENTRAL	3.1	☐
Pipe	Riostra 4" SCH40	19	18.08	18.08	0.06	F.C N2	E. PPAL F. CENTRAL	3.2	☐
F.C N2: 73			127.86	127.86					
Pipe	Riostra 4" SCH40	36	91.79	91.79	0.06	F.C N3	E. PPAL F. CENTRAL	3	☐
Pipe	Riostra 4" SCH40	18	17.99	17.99	0.06	F.C N3	E. PPAL F. CENTRAL	3.1	☐
Pipe	Riostra 4" SCH40	19	18.08	18.08	0.06	F.C N3	E. PPAL F. CENTRAL	3.2	☐
F.C N3: 73			127.86	127.86					
Pipe	Riostra 4" SCH40	38	96.89	96.89	0.00	F.C N4 (7.00)	E. PPAL F. CENTRAL	3	☐
Pipe	Riostra 4" SCH40	18	17.99	17.99	0.00	F.C N4 (7.00)	E. PPAL F. CENTRAL	3.1	☐
Pipe	Riostra 4" SCH40	19	18.08	18.08	0.00	F.C N4 (7.00)	E. PPAL F. CENTRAL	3.2	☐
F.C N4 (7.00): 75			132.96	132.96					
E. PPAL F. CENTRAL: 294			516.54	516.54					

ACIEM

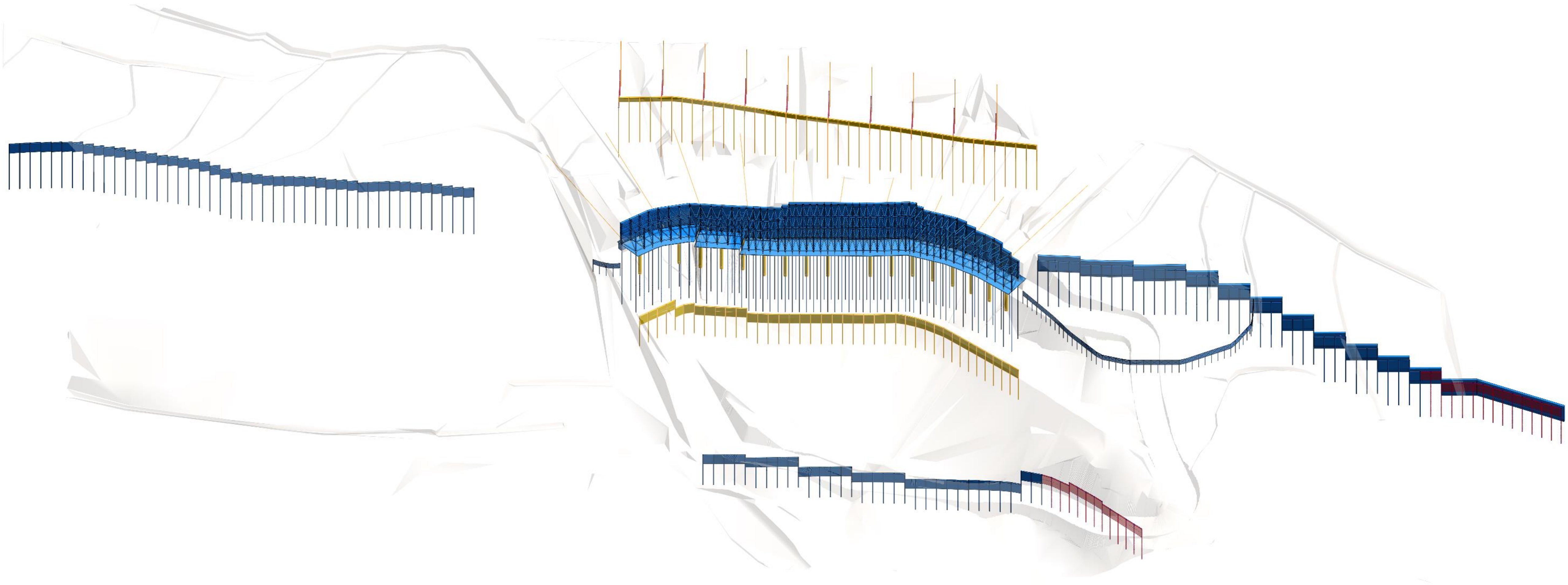
Integración BIM – GIS

BIM led – GIS Support

Control de Cambios

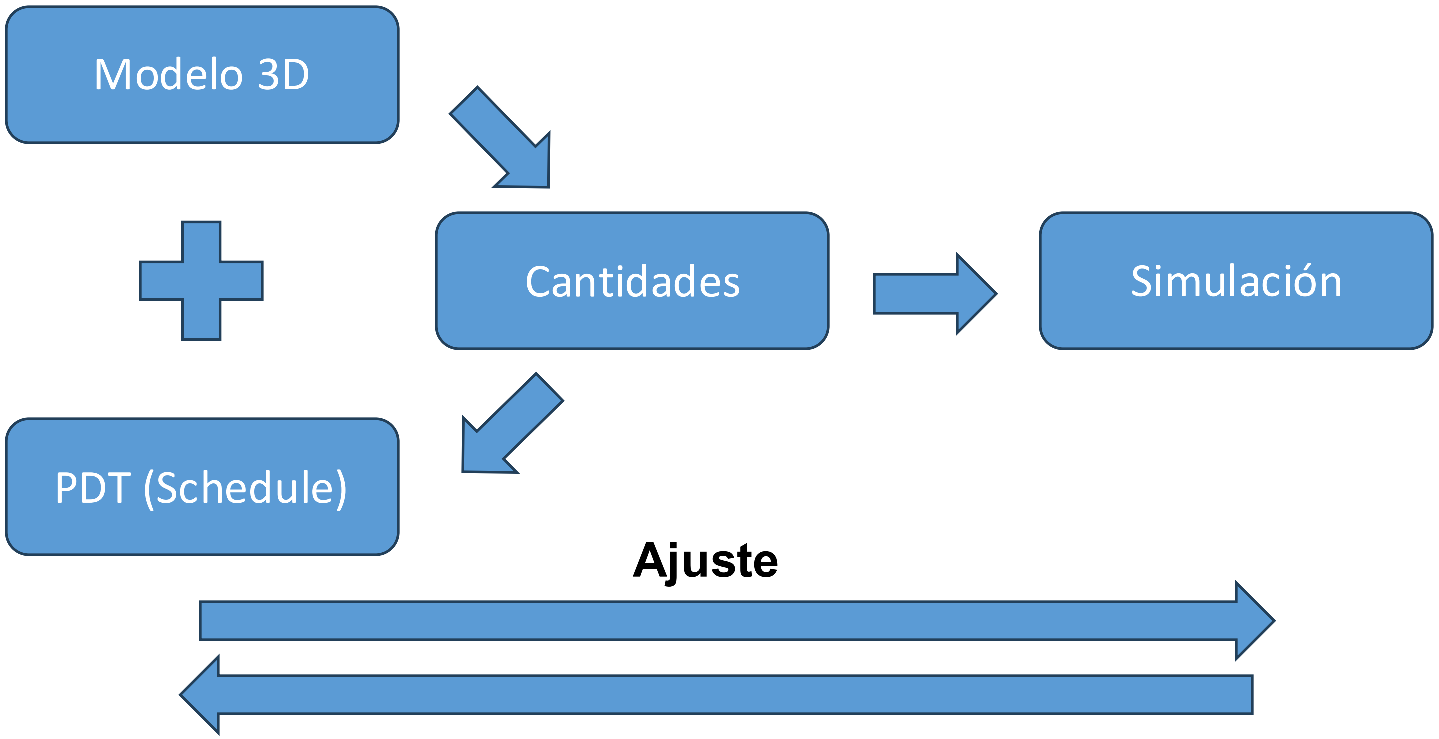


Integración BIM – GIS
BIM led – GIS Support



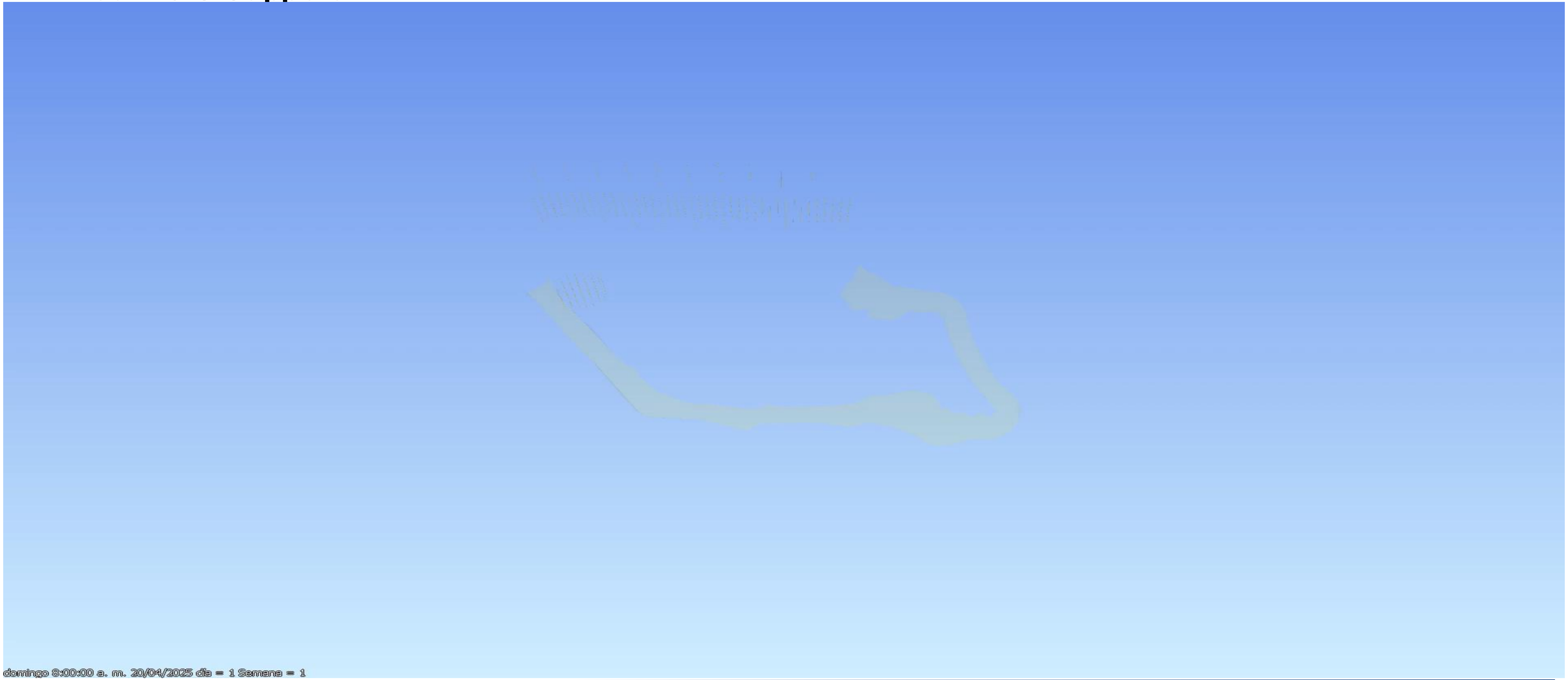
Integración BIM – GIS
BIM led – GIS Support

Planificación y control



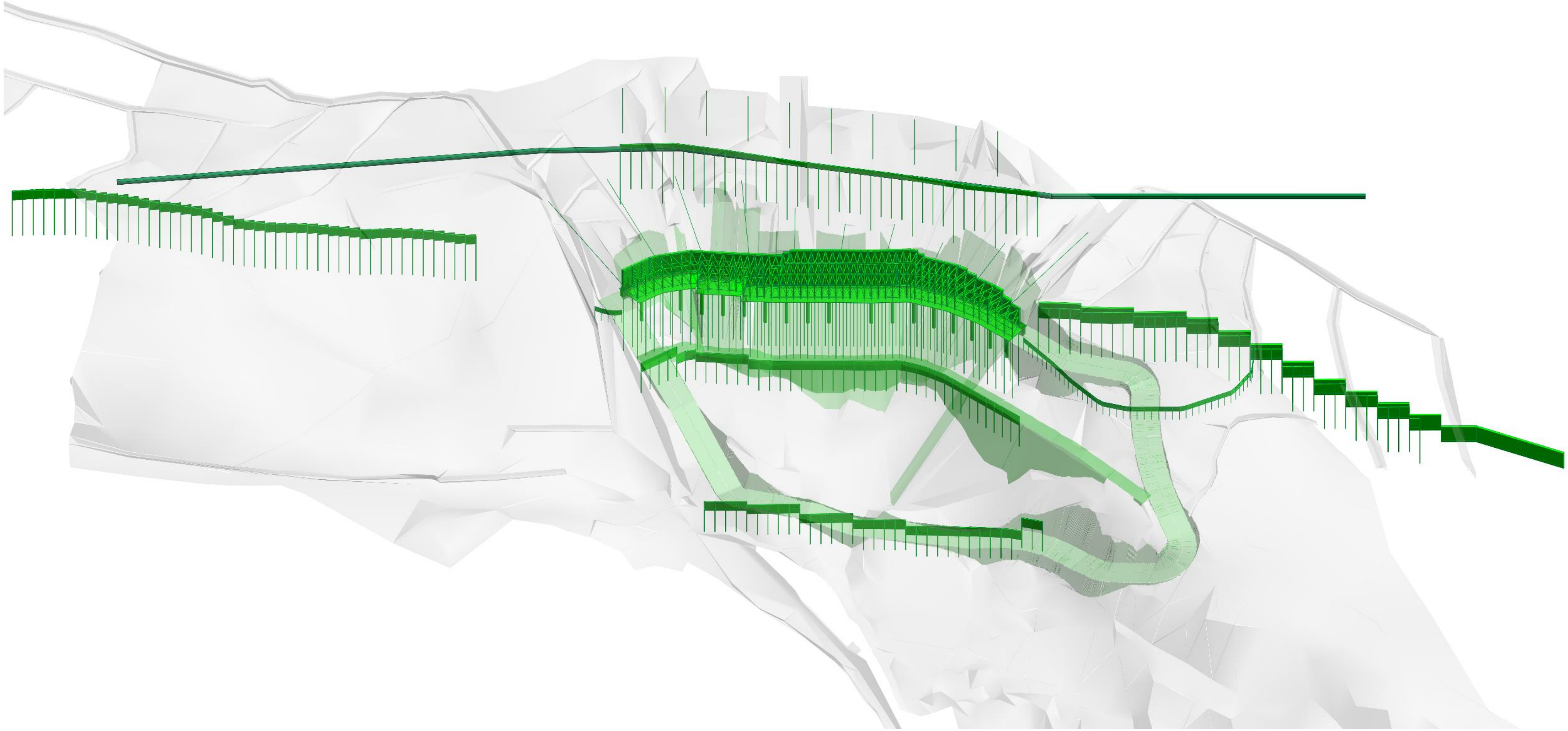
Integración BIM – GIS
BIM led – GIS Support

Planificación y control



Integración BIM – GIS
BIM led – GIS Support

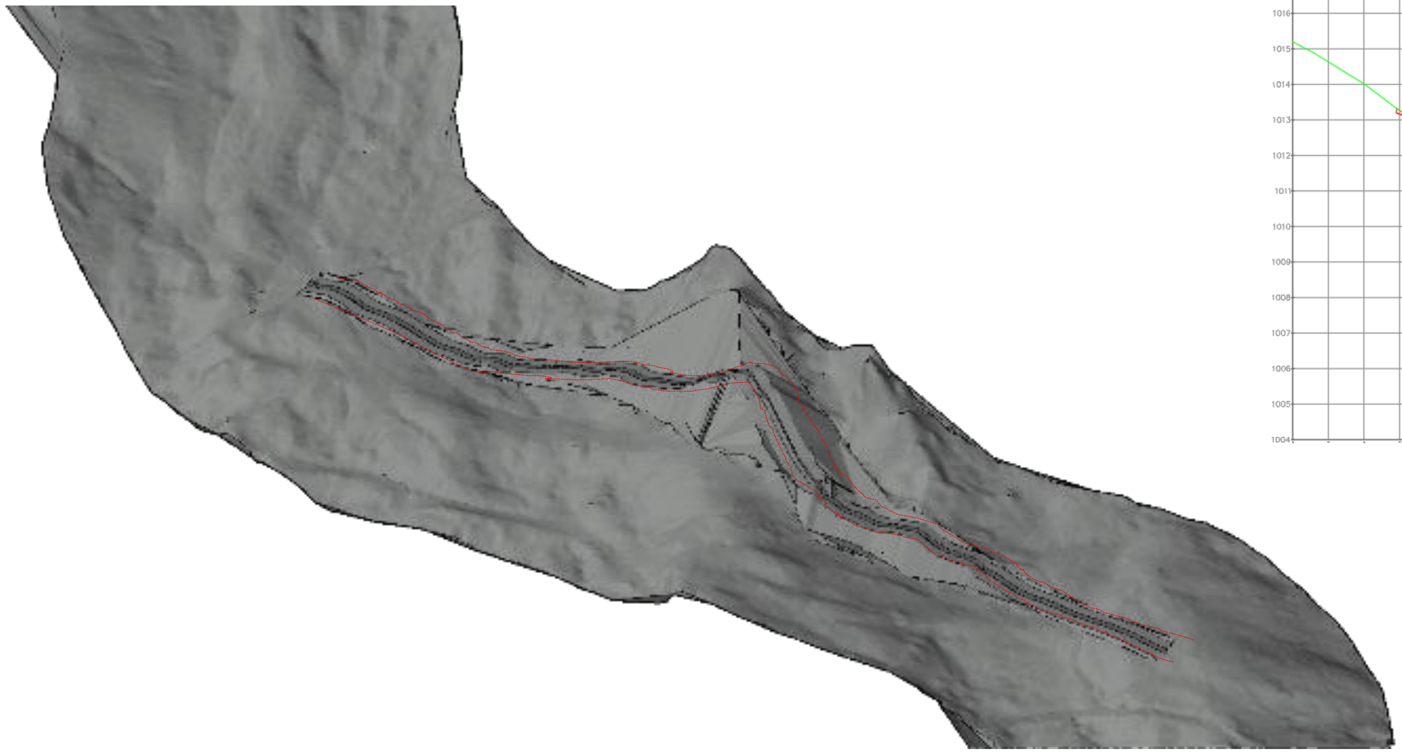
Planificación y control

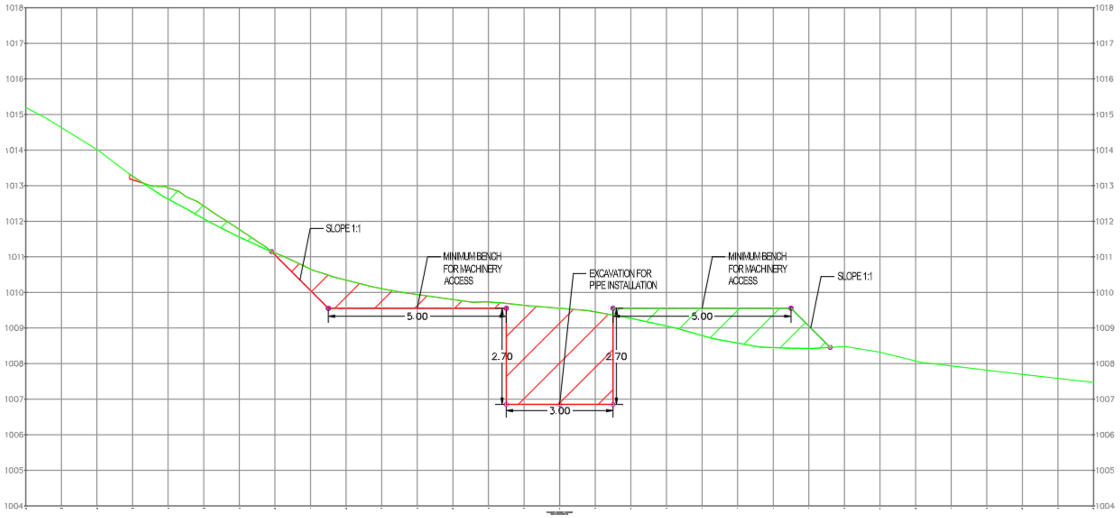


Integración BIM – GIS

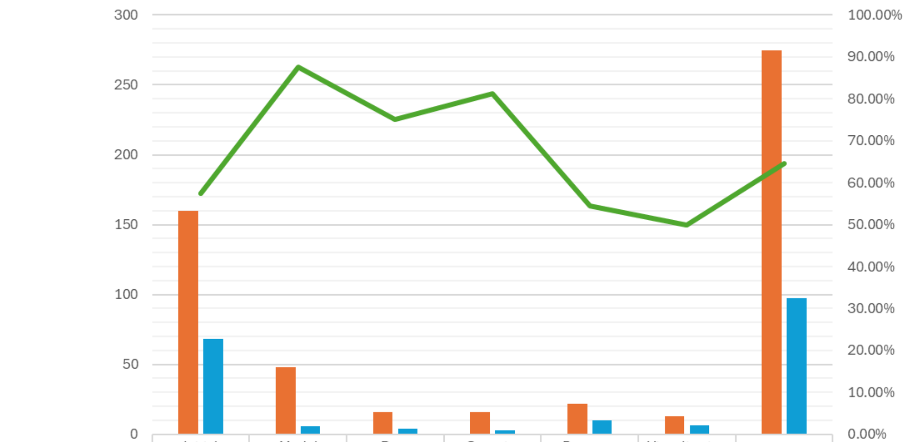
BIM led – GIS Support

GIS: Otras Contribuciones





Resultados



	Initial Modeling	Model Updates	Data Extraction	Quantity Segmentation	Progress Planning (4D)	Visualization & Filters	TOTAL
CAD (hours)	160	48	16	16	22	12.8	274.8
BIM (hours)	68	6	4	3	10	6.4	97.4
% Reduction	57.50%	87.50%	75.00%	81.25%	54.55%	50.00%	64.56%

Resultados tangibles:

Control contractual y presupuestal en tiempo real.
Reducción de errores de campo.
Posibilidad de reducir visitas a campo

Resultados intangibles:

Transparencia, comunicación y confianza.
Digitalización como legado para futuros mantenimientos.

PRINCIPALES AHORROS DE TIEMPO

- Reducción del 57,5 % en el tiempo de dibujo frente al de modelado
- Ciclos de actualización de modelos un 87,5 % más rápidos
- Mejora del 81,25 % en la segmentación de cantidades
- Extracción de datos un 75,0 % más rápida
- Reducción del 54,55 % en el tiempo de planificación del progreso
- Total 177.4 work hours (−64.56%). 22.18 dias de trabajo.

RECURSOS

- Reducción de holguras en cantidades hasta un 5%
- Optimización de cuadrillas de trabajo (Planificación E. ppal)
- Optimización PDT (Ejecución E. Ppal reducida a 8 meses) 8 – 10%
- Detección temprana de interferencias y validación de alternativas,
- Definición más clara del alcance y menos cambios en la etapa de ejecució
- Asignación más eficiente de la fuerza laboral
- Mejor control de las contingencias en el terreno,
- Mayor transparencia en la recuperación contractual y la justificación de co

¡Gracias!

Este piloto no es solo una experiencia exitosa: es una invitación a integrar esta metodología en otros proyectos y compañías, a escalar la innovación y construir una infraestructura más resiliente, trazable y sostenible.

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BIM-GIS INTEGRATION FOR GEOTECHNICAL RISK MANAGEMENT IN MIDSTREAM PIPELINE INFRASTRUCTURE: PILOT STUDY AT PK 046+550 OF THE OCENSA PIPELINE

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ABSTRACT

The OCENSA pipeline, a critical hydrocarbon transport infrastructure in Colombia, traverses geologically complex and unstable terrains, making it vulnerable to significant risks—61% of which are linked to climatic and geodynamic factors. At chainage PK 046+550 in Puerto Nuevo (Casanare), an active landslide currently threatens the pipeline's integrity, requiring urgent intervention under emergency conditions. This paper presents a pilot project evaluating the integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) during the pre-construction and construction phases of remedial works. The objective was to assess the effectiveness of this integrated methodology in optimizing processes and ensuring quality in a highly uncertain geotechnical environment.

Key BIM applications included existing condition surveys, quantity and cost estimation, construction phasing, planning, and execution control. A 3D model was developed enhanced with georeferenced information, creating a comprehensive digital twin. Enabling 4D (schedule-based) and 5D (cost-based) simulations to complement and synchronize construction activities with approved designs and improving data driven decisions and streamlining resource management.

The results show that the integrated BIM-GIS approach significantly enhanced project management, particularly for projects demanding strict quality assurance and resource efficiency—by enabling fast design adjustments, accurate quantity tracking, improved scheduling, budget control, real-time monitoring and fast decision-making. A 64.56% reduction was identified in the total time of the preconstruction phase in contrast with traditional CAD approaches; therefore, it demonstrated how a unified data environment enables more effective risk mitigation and better resource allocation, offering a replicable model for other pipeline infrastructure projects. Highlighting BIM's transformative potential for pipeline infrastructure projects, where its use is still emerging.

Future uses include support for future maintenance, decision making and asset management.

Keywords: BIM, GIS, Infrastructure management, Geotechnical Remediation

Nomenclature

BIM	Building Information Modelling
GIS	Geographic Information systems
ROW	Right-of-way

1. INTRODUCTION

Pipelines are recognized as one of the most efficient and safe modes for large-scale hydrocarbon transportation, as it offers economic, environmental and operational advantages compared to other alternatives [1] The OCENSA pipeline, constructed between 1994 – 1997 and operational since 1998 is one of Colombia's most critical hydrocarbon transportation systems, extending 836 km from Cusiana to Coveñas. As a Critical Infrastructure System (CIS), its failure would result in severe social and economic consequences, requiring resilient design and proactive risk mitigation strategies. Its extensive route navigates diverse and challenging geographical and geotechnical conditions, rendering it susceptible to various hazards. Approximately 61% of geohazards affecting the system are associated with climatic drivers, geodynamic processes and external forces.

At chainage PK 046+550, near Puerto Nuevo (Casanare), a geotechnical event classified as a composite (rotational/planar) slide was identified in June 2024. Triggered by intense rainfall, the event affected a polyduct located 45 m from the OCENSA pipeline axis and posed a direct threat to pipeline integrity. The main scarp was located approximately 11.3 from the pipeline, with a height ranging from 2.5 and 3.0 m, a minimum length of 90 m, and a width of 40 m, The estimated depth of the failure surface was at least 2.5 m. The overall slope of the hillside is approximately 60%, with movement oriented almost orthogonally to the pipeline route. As a result, the upper colluvial deposits mobilized downslope as a flow toward the Volcanera stream.

The materials involved belong to unconsolidated colluvial deposits, deconfined by the scarp, reaching approximately 9.0 m in height. Retrogression of the scarp toward the pipeline is therefore expected. Furthermore, the surface runoff and persistent precipitation have the potential to accelerate movement and increase the extent of the geotechnical event. Consequently, due to the imminent risk of rupturing of the OCENSA pipeline, and the need for expedited procurement and intervention**.** Remediation and stabilization works were prioritized led by the declaration of an emergency status.

According to IDEAM, the annual precipitation at site averages 3619.63 mm for the last 10 years [2]. In addition, based on a recent assessment for the Meta River Basin (which includes Casanare) annual precipitation under current climate scenarios is reported to range from 2011.6 mm to 2226.9 mm for current and 50-years climate change scenarios [3]. Initial mitigation designs included three rows of pile screens, micropiles, and a superstructure reaching up to 7 meters in height. However, the prevailing environmental conditions, characterized by extreme and persistent rainfall, exacerbated the instability and maintained the site under continuous alert status, as well as the average rainfall of 2.28 hours contributed to slope saturation, impeding soil consolidation and delaying construction progress. The high probability of destabilization triggered the need for multiple updates to the designs as a response to changing field conditions, such as the emergence of new fissures along the right-of-way (ROW).

Given these complexities and the critical nature of the infrastructure, a pilot project was proposed to integrate Building Information Modeling (BIM) and Geographic Information Systems (GIS) methodologies. This integration was conceived as a strategic approach to enhance project management, optimize resource allocation, and ensure the quality of remedial works in an environment characterized by high uncertainty and dynamic geotechnical challenges. Traditional methods, which rely heavily on manual estimates and linear planning, often fail to anticipate interdependence and dynamic changes. As highlighted in the literature, these conventional approaches tend to overlook critical scenarios during early planning phases [4] [5].

The conventional design and construction workflows required a lot of operational effort to deal with the rapid changes and interdependencies inherent in this emergency response.

Architecture, Engineering, and Construction (AEC) and Facility Management (FM) industries often face challenges associated with limited or even ineffective digitalization, weak collaboration, and fragmented management process [6]. The integration of BIM and GIS is increasingly recognized as a transformative approach to overcome this barrier, enabling improved data visualization, traceability, and informed decision-making [7] [8]. Nevertheless, the application of BIM in geotechnical projects – particularly those involving dynamic subsurface dynamic conditions such as landslides – remains relatively unexplored in both industry and academia [9]. This gap is linked to the inherent complexity of modelling heterogeneous terrains, the absence of standardized workflows for geotechnical data integration, and persistent technical barriers to interoperability between BIM, GIS and geotechnical software [10].

While BIM and GIS have been widely applied to infrastructure and building projects, their integrated use in midstream oil and gas pipeline systems for emergency risk management is still rare. Most existing studies focus on large-scale infrastructure planning or facility management, often neglecting practical case studies in dynamic risk scenarios. The literature on Geotechnical BIM and midstream pipelines remains scarce compared to general construction or upstream/downstream oil and gas sectors [11] [5].

Pilot initiatives, such as this OCENSA case study, provide valuable insights into the benefits and limitations of BIM-GIS integration for managing complex geotechnical emergencies. Underscoring the need for improved interoperability, standardization, and research focused on automation and multidisciplinary collaboration in pipeline infrastructure.

This paper details the application of this integrated methodology and presents the methodology, key findings, challenges, and recommendations for future implementation in similar critical pipeline infrastructure projects.

2. METHODOLOGY

In line with the nature of the geotechnical mitigation works, the pilot project was structured around the application of BIM methodology, due to its potential benefits related to time designs and adjust optimization, enhanced project management, quality assurance, innovative approach and its interoperability with other tools and even methodologies or systems that enable enhanced efficiency in traditional design and construction environments.

The implementation followed a structured framework leveraging the complementary strengths of BIM and GIS throughout the pre-construction and construction phases. The overarching goal was to create a comprehensive digital representation of the intervention to support planning, visualization, execution, and control.

The core of the methodology relied on a tightly integrated BIM-GIS environment, applied at both conceptual and operational levels. At the fundamental level, data exchange was facilitated through geometric transformations and semantic information mapping between systems [12]. BIM served as the central repository for design and construction data, while GIS provided spatial context and analytical capabilities essential for site-wide assessment and decision-making.

2.1 GIS Integration and Spatial Analysis

Several authors recognize GIS as a precursor to BIM, due to its long-standing capacity to manage spatial data and perform multiscale analysis in digital environments [13], [14]. GIS enables not only visualization of geospatial elements but also integration of attribute data to support technical evaluations and planning. While BIM focuses on detailed as-built elements yet to be constructed, GIS models real-world entities with spatial logic.

Consequently, many experts regard GIS as having laid the conceptual and methodological groundwork for BIM by integrating visual and descriptive data for spatial analysis, planning, and engineering, and essential features of modern infrastructure management.

In this project, GIS played a critical role in providing spatial intelligence and contextual geodata to inform BIM modeling.

This GIS-BIM methodological framework can be classified into three types:

1. **BIM led - GIS supports.** BIM leads the process, focusing on semantic and geometric modeling of the project, while GIS contributes natural terrain and environmental context, enabling integrated modeling [15].
2. **GIS led - BIM supports.** GIS provides foundational spatial data and terrain analysis, enabling preconstruction planning. BIM elements are imported into GIS for simulations, spatial analysis, and safety planning [15].
3. **Balanced Integration.** The aim is to combine the benefits of both BIM and GIS into a single integrated tool, often viewable directly in a web browser without additional software. This approach is particularly useful for tasks like energy modeling at a community scale, blending spatial dimensions from GIS with detailed building information from BIM. Standards like IFC and CityGML facilitate interoperability [15].

In this project, GIS was essential for providing topographic and geotechnical context to inform BIM modeling. The BIM-GIS integration followed the "BIM-led/GIS-supports" approach [8], where GIS provided the foundational spatial data and terrain context upon which the BIM model was developed. This resulted in a more realistic and reliable modeling approach, consistent with site-specific geotechnical conditions. Georeferenced integration ensured seamless interoperability and allowed information to be shared with stakeholders via conventional formats such as CAD or Shapefiles.

Key applications included:

- Topographic Updates: Given the dynamic nature of the landslide, continuous topographic updates were essential. RTK (Real-Time Kinematic) drones were deployed to conduct frequent aerial surveys, providing highly accurate and up-to-date topographic data. This data was then integrated into both the BIM and GIS environments, ensuring that all planning and design modifications were based on the most current ground conditions.
- Alternative Route Analysis: Based on the emergency alert, efforts to mitigate risk included evaluating alternative pipeline routings to bypass the active landslide. Field survey points were integrated with orthophoto imagery and official pipeline cartography within the GIS environment. This allowed for a preliminary spatial analysis of potential new alignments and, through integration with Civil 3D, rapid estimation of earthwork quantities for these alternatives.
- Georeferencing BIM Data: The 3D BIM model was precisely georeferenced and imported into the GIS platform. This integration allowed for the visualization of the proposed geotechnical structures and the pipeline within their real-world context, enabling mechanical engineers to analyze the interaction of support structures with the pipeline on the right-of-way. Accurate spatial alignment also enabled quantity estimates and coordination with contractors using shapefiles and CAD outputs.

2.2 BIM Modeling and Simulation

The BIM implementation focused on five core uses: (1) existing conditions modeling, (2) quantity and cost estimation, (3) phase planning, (4) construction planning, and (5) construction control.

A detailed 3D BIM model was developed, encompassing all proposed geotechnical and structural elements. This included:

- **Geotechnical Works:** Pile screens, micropiles, horizontal drains, consolidation injection points, and slope anchoring systems.
- **Structural Components:** Steel frames, metal deck sheeting, and other support structures for the containment system.
- **Earthworks:** Detailed modeling of earthwork volumes, crucial for cost and schedule control.

A key advantage of BIM is the ability to simulate design scenarios. As noted in prior studies, BIM supports parametric modeling that treats the digital asset as a prototype, improving scenario testing in early stages. Unlike static 3D CAD models, BIM objects include attributes such as materials, suppliers, and specifications [5].

This approach enabled the possibility to incorporate detailed segmentation aligned with construction zones, levels, and contractors. This granularity enabled accurate scheduling, progress tracking, and resource assignments, particularly useful for multi-level structures ranging from 4 to 7 meters in height.

Subsequently, 4D (time) and 5D (cost) simulations were carried out:

- 4D Planning: The 3D model was linked to the construction timeline to simulate activity sequencing; this was critical for staging scaffolded works and ensuring work-at-height safety.
- 5D Estimation: Cost data was analyzed based on the model, allowing for real-time budget updates based on activity progress and quantity tracking. This enabled faster adaptation to design revisions and improved financial oversight.

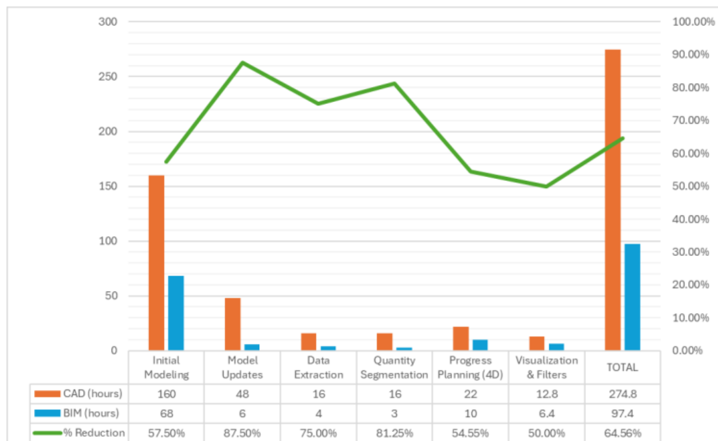
3. RESULTS AND DISCUSSION

The integrated BIM-GIS methodology yielded significant technical and operational benefits throughout the emergency response and construction phases at PK 046+550 including:

3.1 Enhanced Design and Model updates

GIS served not only as the foundational environment for the project but also as the primary interoperability bridge between design tools. While topographic data and earthworks were processed in Autodesk Civil 3D, structural modeling was carried out in Revit and coordinated using Navisworks. The 40 hours required to configure the Civil 3D corridor were offset by just 28 hours for the structural modeling, proving interoperability accelerates complex projects.

However, due to the landslide's active behavior and persistent rainfall (averaging 2.28 hours/day) underscored the need to update the design, which happened 4 to 5 times before finalizing the remediation plan. The contractor provided design adjustments within 48 hours, while updating the BIM model took typically 1 to 3 hours per revision depending on the scale of the updates, averaging 6 hours total. Moreover, the BIM model provided full traceability for changes. Each design iteration, including additions like a new line of piles anchored to bedrock, concrete grout injections, and a new retaining structure, was seamlessly integrated into the model, enabling automatic quantity recalculations and minimizing manual rework.



	Initial Modeling	Model Updates	Data Extraction	Quantity Segmentation	Progress Planning (4D)	Visualization & Filters	TOTAL
CAD (hours)	160	48	16	16	22	12.8	274.8
BIM (hours)	68	6	4	3	10	6.4	97.4
% Reduction	57.50%	87.50%	75.00%	81.25%	54.55%	50.00%	64.56%

Figure 1. Time Efficiency Comparison (Traditional Methods vs. BIM)

*Percentages reflect real project data from a geotechnical case study (earthwork, piles, retaining walls). CAD times include conservative estimates for unreported tasks (e.g., quantity segmentation). BIM workflows used Autodesk Civil 3D, Revit and Navisworks.

As the main result, Total BIM saved 177.4 work hours (−64.56%), equivalent to 22.18 labor-days.

3.2 Improved Construction Quantification, Planning and Control

The BIM model played a critical role in refining construction planning and ensuring accurate field execution through data-driven workflows.

- **Coordinate Generation:** Integration between BIM and GIS enabled the automatic generation of real-world coordinates for structural elements such as pile locations. These coordinates were directly shared with the contractor, improving precision in layout and reducing interpretation errors. The georeferenced model also eliminated redundant data by ensuring consistent spatial referencing across platforms.

- **Structure Zoning and Quantity Segmentation:** As the main philosophy of BIM is the modelling of "Information". Its strength relies on the structured management of information. To maximize its analytical potential and improve design, planification, construction, maintenance and other processes to improve the sustainability of the projects, reduce their impacts in different ways and increase the return of investment (ROI), ensuring higher profits. In that way, data parameters were designed to segment the remedial works into functional and spatial zones that included:

  Zones by description and colors:
  1. Purple: ROW Interventions (2 pile lines)
  2. Lime green: Main containment structure,
  3. Yellow: Right flank
  4. Teal green: Left flank
  5. Blue: Support screen for the main structure
  6. Cyan: Pile retention terrace
  7. Foot of the scarp (Road)

  Pile Lines by number:
  1. ROW line in front of the pipeline
  2. ROW line behind the pipeline
  3. Main structure pile lines
  4. Pile screen on the right flank
  5. Support pile screen for the main structure's embankment
  6. Pile screen on the left flank
  7. Pile retention terrace
  8. Pilot screen on the foot of the scarp

This zoning allowed an organized approach for data extraction and management, supported by the mentioned parameters classification and filtering, enabling and enhancing updates traceability after each design iteration, and improved control over progress tracking and resource allocation.

In addition, a level and section classification was applied to the main structure, following the objective of execute the quantity takeoff with an organized approach that enabled a logical sequence analysis to propose the construction process of the structure, enhanced by the 4D simulation of the project.

Large-scale infrastructure projects frequently experience significant costs overruns and delays. Several studies have shown that cost overruns average between 22 and 45%, with delays affecting more than 70% of such projects worldwide [16]. These inefficiencies correlate strongly with the duration and complexity of projects, highlighting a critical need for improved delivery methods. Digital transformation, which includes the adoption of BIM, has emerged as a key strategy to address these challenges by enhancing workflow efficiency, resource optimization, sustainability outcomes and data driven decision-making. Digital workflows allow to plan and extract data with better precision, reducing material waste and optimizing recourse use, leading to improved return on investment ROI [17].

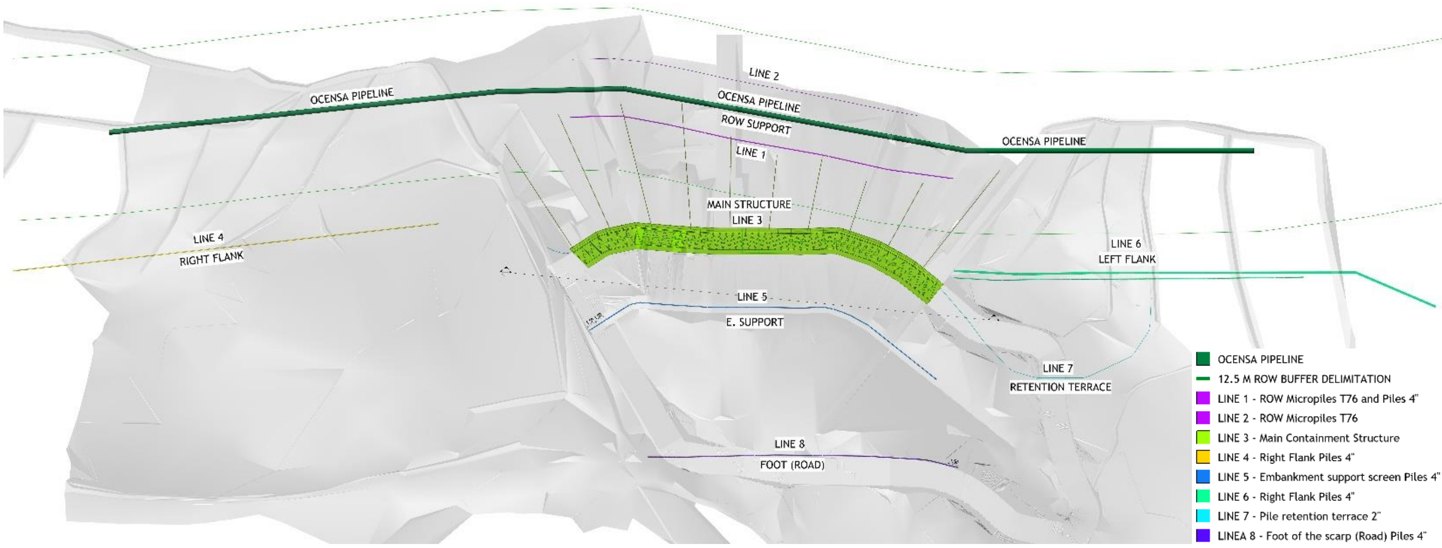


Figure 2. General classification by zones of the remediation works

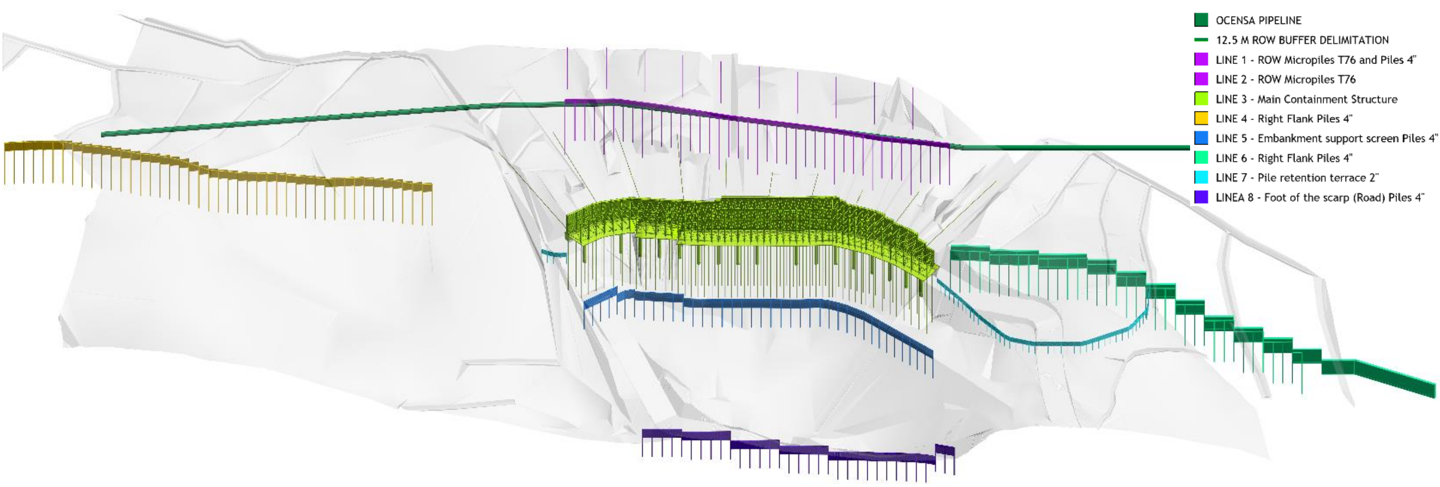


Figure 3. Isometric of general classification by zones of the remediation works

- **Precision in Estimations:** The creation of a detailed digital replica (Digital twin) driven by BIM allowed for highly accurate material quantity estimation, which in turn improved scheduling and budget precision [4] [6]. Initial quantity takeoff using traditional CAD methods took over 16 hours, excluding additional time required for updates, and facing the need to overlay the CAD drawings to identify changes.

  In contrast, BIM-based quantity extraction required only 4 hours. Once classification parameters were defined (a process that took an additional 3 hours), quantities were automatically recalculated whenever the model was updated. This reduced the time and effort by 75% compared to typically required time for manual quantity reassessment and drawing revisions, streamlining the entire design-update cycle and avoiding mistakes due to manual calculations.

- **Waste reduction and early planning:** The BIM-driven workflow significantly contributes to waste reduction and early-stage planning in construction by minimizing material waste through reduced errors, enhanced visualization, and precise material quantification. Studies indicate that BIM application can reduce construction waste by approximately 10–20% compared to traditional methods [18] [19], this is enabled by the early error detection, better coordination and optimization in the use and ordering of materials. As BIM encourages greater rigor during the design phase by ensuring all necessary elements are integrated comprehensively from the outset, substantially reducing improvisation and the rework that often leads to additional material waste during construction. For instance, integrated BIM workflows combined with digital twin technologies have shown to maximize economic benefits in waste management by continuously monitoring material flows and supporting real-time decision-making. [20]

In this specific case, the quantities of materials were obtained directly from the BIM model, enabling highly precise procurement and installation. This accuracy ensured that material orders closely matched actual site needs, significantly reducing the typical contingency or "slack" usually allowed for unforeseen conditions. As a result, the material allowance was minimized to only 5%, justified by unavoidable field uncertainties such as site variability and unforeseen installation conditions.

- **Construction Sequence Analysis:** The model facilitated a critical analysis of the construction sequence for the 4m to 7m high superstructure. By segmenting the structure into sections by height and bracing levels, it was identified that construction could proceed in 1m to 2m height increments, as well as by section, optimizing the use of available space, equipment and resources; and enabling a clear visualization of the execution works to the stakeholders to enhance planning and decision-making processes. This optimized workflow addressed the contractor's limited experience with such complex steel constructions in challenging weather conditions, directly impacting productivity and HSE considerations.

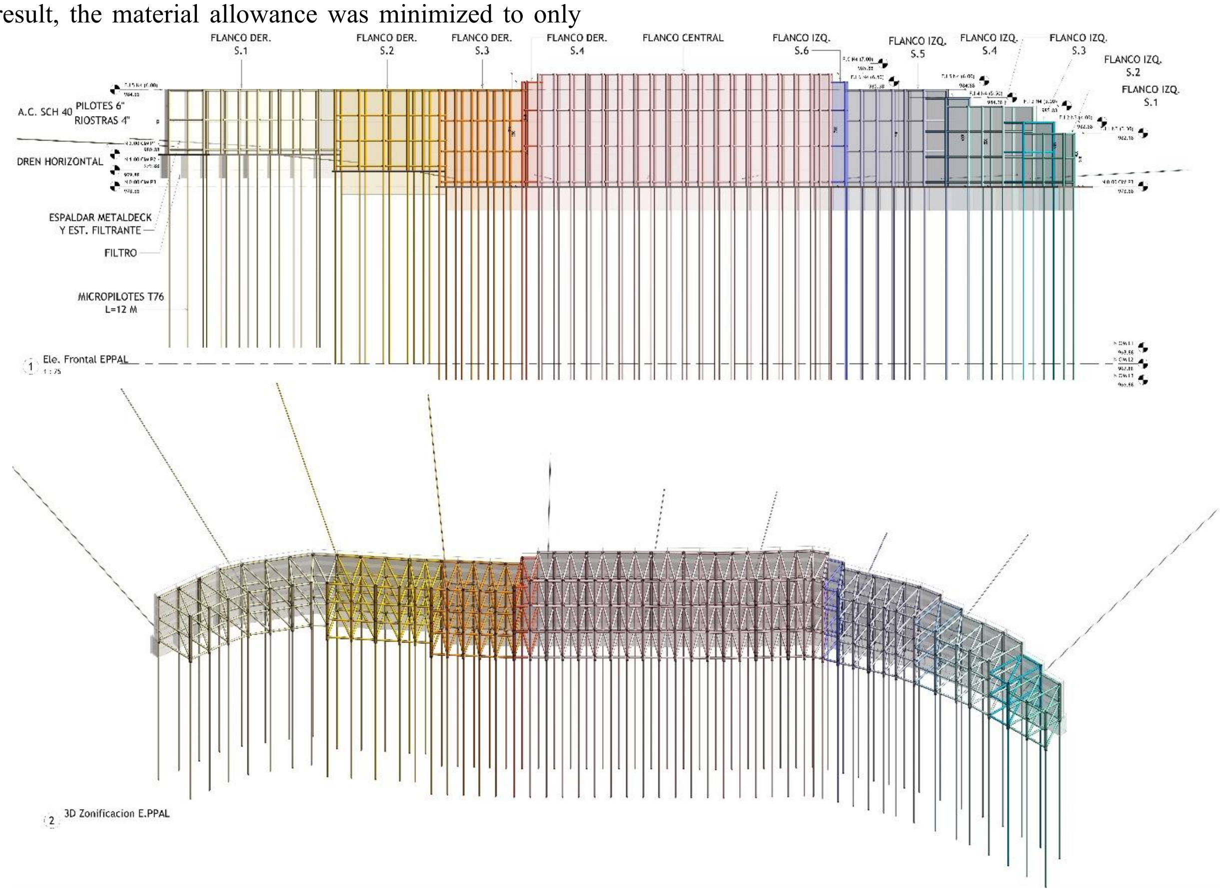


Figure 4. Classification by zones of the main contention structure

- **Construction Simulation:** Studies confirm that 4D BIM simulations improve coordination, reduce costly rework, and enhance decision-making by integrating time and spatial data in a single model. The segmented BIM model enabled the generation of a detailed construction simulation that visually demonstrated the planned sequence of activities [21]. This simulation proved to be a powerful communication tool that clarified execution doubts among stakeholders and facilitated real-time schedule adjustments based on collaborative feedback. BIM integration provides an ideal environment for digital simulation of the construction process, allowing project teams to evaluate alternative scenarios and anticipate potential conflicts or delays before physical work begins [22]. Thus, digital construction simulation supports proactive project management and risk mitigation by enabling virtual rehearsals of workflows and facilitating dynamic schedule optimization during execution.

Workforce Optimization: The BIM model supported an analysis that resulted in optimizing the number of welding crews, leading to a more efficient execution of cutting, alignment, installation, welding, and grinding tasks for the steel structure. According to recent studies, BIM-based workforce planning can improve labor productivity by approximately 8 to 10% in steel structures [23], reducing redundant efforts and enhancing crew utilization. In this case, an optimized allocation of welding crews was carried out by assigning two crews to the construction of the main structure and one additional for the outside welding works around the structure. This enhanced the possibility of avoiding waste due to hiring excess teams, according to the availability of contract resources, and decreased execution time by 50% (8 months) as it was estimated to be around 14 months.

3.3. Support for Contractual Recoveries and Cost Control

The segmentation of the BIM model by milestones, execution zones, and pile lines enabled precise alignment with the contractual structure of the project. This facilitated accurate calculation of executed quantities per contract section. When model-derived quantities were compared against manually recorded data, several discrepancies were identified and corrected—improving the precision of the recovery process, especially in the context of cost overruns related to the emergency declaration.

Furthermore, given the project's emergency status, it was essential to provide clear documentation and justification to support the design adjustments to stakeholders and insurers. However, communicating these changes using traditional 2D plans, elevations or tables proved inefficient or hard to understand, particularly for non-technical audiences. In this case, the classified 3D BIM model served as a powerful visual tool to illustrate design modifications and quantity increases. It also supported weekly construction progress tracking and functioned as a verifiable basis for contractor payment approvals. These visualizations improved transparency and were instrumental in administrative claims related to scope adjustments and budget extensions.

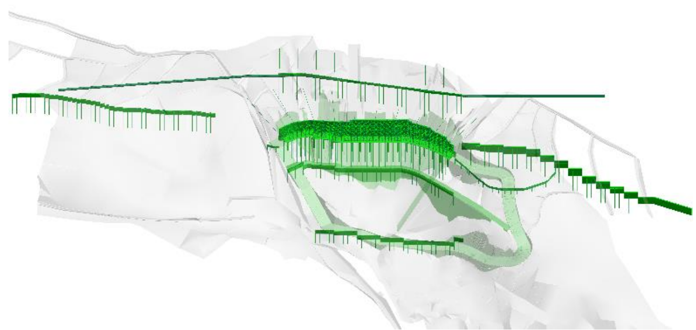


Figure 5. Isometric view of the completed interventions

3.4. Decision-Making and Digital Twin Development

The integrated BIM-GIS environment acted as a comprehensive decision-support system throughout the project execution and that will be functional for its life cycle. Simulation tools enabled the team to visually analyze execution alternatives and identify potential risks early in the planning stages, thereby reducing uncertainties and improving risk mitigation strategies [21] [22] [24]. The consolidation of design, cost, and spatial data within a unified model facilitated the creation of a high-fidelity digital twin of the asset, which serves as a dynamic digital replica, reflecting the current state of the infrastructure project.

This digital twin supports long-term monitoring and forecasting maintenance needs by offering stakeholders. It facilitates early detection of deterioration patterns, prediction of future needs, and informed planning of interventions. The ability to perform segmented analyses of quantities and costs by zones and sections significantly accelerates budget control and decision-making processes, offering a level of granularity and accuracy unattainable through manual methods [22]

In the post-construction phase, the model supports infrastructure lifecycle management by:

- Organizing multimodal field data (including point clouds and sensor data)
- Visualizing maintenance requirements
- Structuring "meta-data" for asset integrity assessment
- Enabling interactive dashboards that improve inspection, reporting, and stakeholder communication

This centralized, intuitive visualization platform improves oversight and facilitates informed, timely decisions across all project stakeholders.

3.5. GIS Contributions and Drone Integration

GIS played a critical role in the initial assessment of terrain conditions and the evaluation of alternative design options. A potential pipeline rerouting was initially considered, using geospatial data of the ROW, which was captured from an aerial survey, complemented by field survey points that considered the actual route of the pipeline, and the potential rerouting. This data was consolidated in the GIS environment and then exported to the design software (Civil 3D) to analyze the characteristics of the alternative and its potential viability. A total of 3 alternative routes were designed and analyzed following the minimum requirements for bringing in machinery and installing the necessary piping but ultimately discarded due to excessive earthwork requirements. However, GIS tools integrated with design and BIM software enabled rapid feasibility analyses, accelerating early-stage decision-making, reducing project uncertainty and improving cost-effectiveness [24].

Figure 6. Example of one rerouting alternative developed with Geospatial data, field survey points and Civil 3D.

*The figure illustrates the planned access roadway highlighted in red, for pipeline installation machinery crossing the mountain, as well as the slope stabilization works intended to secure its alignment.

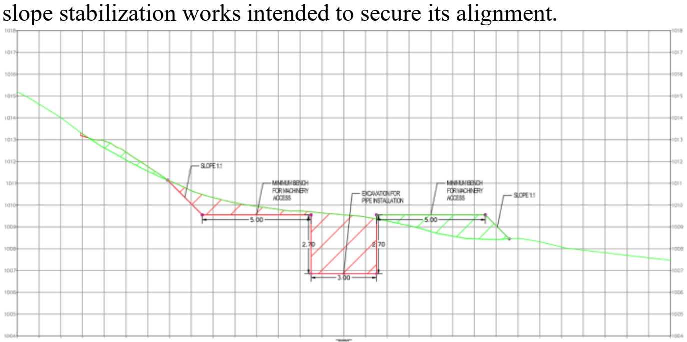


Figure 7. Components considered for the design of the rerouting alternative.

The integration of a georeferenced BIM model within the GIS environment provided mechanical and geotechnical teams with a spatially accurate context for evaluating support structures, thereby assuring the integrity of the existing pipeline under dynamic conditions. This spatial linkage allowed stakeholders to analyze design alternatives not only from a structural standpoint but also in relation to environmental, hydrological, and topographical constraints, enhancing risk-informed decision-making.

The use of UAVs significantly strengthened the monitoring and design adaptation process. RTK-enabled drones were deployed to obtain continuous topographic updates, which allowed engineers to adjust geotechnical and structural designs to the evolving conditions of the landslide. UAV-mounted LiDAR and laser scanning technologies can generate high-density point cloud models with centimeter-level geometric accuracy, which, when integrated into the BIM environment, support deviation detection, validation of earthwork quantities, and refinement of structural geometry [25] [26]

Recent studies demonstrate that UAVs have become a cornerstone in landslide research, particularly for detection, mapping, monitoring, and forecasting of slope instabilities. Applications range from manual visual inventories to semi-automatic methods based on Object-Based Image Analysis (OBIA), and more recently to machine learning and deep learning approaches such as Random Forests, k-Nearest Neighbors, and Convolutional Neural Networks (CNNs), which enable rapid identification of failure surfaces and kinematic parameters [25]. In this context, the integration of UAV outputs into a BIM–GIS framework provides a systematic way to overcome some of these barriers, ensuring traceability, multi-stakeholder accessibility, and a structured workflow for decision-making in emergency contexts.

By incorporating UAV-derived datasets into the OCENSA case study, the project aligned with global best practices in landslide monitoring while advancing the state of practice in pipeline risk management. The resulting BIM–GIS–UAV integration not only enhanced spatial and temporal accuracy in the characterization of the slope failure at PK 046+550 but also facilitated data-driven updates to geotechnical designs, streamlined construction supervision, and supported proactive asset management strategies. This case illustrates how the adoption of UAV-enabled GIS workflows can substantially reinforce the resilience of pipeline infrastructure against geohazards, providing a replicable model for similar projects in complex terrains.

3.6. BIM–GIS Integration: Potentials and Limitations

BIM and GIS have matured in parallel, with increasing overlap but persistent gaps in semantic integration. While BIM provides geometric and semantic information GIS offers a spatially comprehensive framework for contextual analysis. Their integration has proven valuable for applications such as site selection, environmental impact assessments, and safety management [5]

Nevertheless, the translation of geometric and semantic information between BIM (IFC) and GIS (CityGML) remains problematic. Information mismatches arise from different coordinate systems, levels of detail (LODs), scales, and development purposes.

Despite the substantial benefits, The OCENSA case study provided a valuable testbed for understanding the opportunities and constraints of BIM–GIS integration in emergency geotechnical contexts. Several insights emerged:

- **Estimations Discrepancies:** Due to the high uncertainty related with the conventional way of execution related with earthworks, and linked to the unstable geotechnical conditions, manual excavation estimates were prioritized over model-derived quantities as a critical scenario approach to mitigate budget risks. However, drone-based topographic data provided critical validation and a reliable baseline to monitor and update the field conditions and designs.

  This highlights the need of workflows for automation on quantities estimations based on geospatial data, Likewise, due to the dynamic conditions of the terrain, it is important to carry out an exhaustive analysis, in which quantity takeoff is the most reliable depending on the complexity of the project, analyzing the most accurate quantities, the same affected by a safety factor or those calculated manually.

- **Workflow Automation:** Although the pilot demonstrated efficient integration between tools, significant manual effort was required to transfer and update data across software. Automation of data pipelines, particularly between UAV surveys, BIM updates, and GIS dashboards, would have reduced latency and improved decision-making. It remains as an area for further development, particularly in contexts requiring continuous design updates.

- **Organizational Barriers:** Internal communication structures limited direct, real-time collaboration between design, HSE, and construction teams [27]. This highlights the critical need for cultural change and sustained investment in collaborative digital environments to enable shared decision-making across disciplines to reduce uncertainty. Additionally, a significant portion of the infrastructure industry still relies on traditional CAD-based workflows due to limited training and reluctance to adopt new technologies [27]. Incomplete BIM implementations often result in misalignment between project expectations and outcomes damping productivity and interoperability [28]. In Colombia, varying BIM maturity levels across disciplines continue to limit integration and collaboration, reducing interoperability and productivity, while outsourcing BIM modeling in some areas increases project costs and weakens team cohesion and communication [4] [28].

In the geotechnical engineering area, the application of BIM remains limited and predominantly auxiliary, mainly supporting planning and documentation rather than fully enabling geotechnical analysis and data exchange between platforms. However, the adoption of BIM technologies in geotechnical engineering is expected to expand, offering significant opportunities to improve project resilience and decision making under certain ground conditions.

As mentioned, one of the key challenges related with Geotechnical BIM implementation is the seamless exchange of data between BIM platforms and specialized geotechnical software (e.g., PLAXIS, GeoStudio) as one of the foremost obstacles. Divergent standards and file formats hinder integration, while semantic mismatches—such as representing soil stratigraphy in IFC or CityGML—introduce loss of meaning and accuracy [10] [11]. Furthermore, Geotechnical data is inherently complex, heterogeneous, and scale-dependent, often characterized by variability in soil behavior, discontinuities, and incomplete subsurface information. Current BIM platforms struggle to represent this uncertainty, resulting in oversimplified models that may not reflect dynamic field conditions [10]. Therefore, integrating terrain as topography is a practical approach, while geotechnical data supports designs.

- **Cost of Adoption:** High initial costs—associated with software acquisition, hardware upgrades, staff training, and hiring qualified BIM specialists remain as key barriers to wider BIM implementation [27]. Although the long-term return on investment (ROI) for BIM adoption is well documented, early adopters often face negative short-term impacts, including disruptions to existing workflows and budget overruns, which may discourage broader investment. Research indicates that BIM implementation can reduce project costs by up to 50%, shorten construction schedules by over 20–30%, and improve overall productivity, which leads to a positive return on investment (ROI) within a few years post-adoption [21] [29].

  Overcoming these financial hurdles requires supportive policies and incentives, along with clear communication of BIM's tangible benefits to stakeholders

- **Recommendations for Implementation:** Considering international and national BIM strategies roadmap aiming for mandatory BIM adoption in public projects and encouraging its use in private ones by 2030, strategic implementation led by leaderships is imperative. Priorities should focus on strengthening technical training and internal modeling capabilities within organizations, which remains a key challenge for digital maturity. Furthermore, fostering interdisciplinary collaboration is crucial to bridge disciplinary silos and improve integrated project delivery

4. CONCLUSION

The pilot implementation at PK 046+550 of the OCENSA pipeline successfully demonstrated the transformative potential of integrating Building Information Modeling (BIM) with Geographic Information Systems (GIS) for managing geotechnical risk in complex critical infrastructure. This integrated approach enhanced design traceability, improved planning and construction control, accelerated model update cycles and strengthened decision-making and contract management processes culminating in the development of a functional digital twin.

Quantifiable efficiency gains were achieved throughout the project lifecycle. Key time savings included:

- 57.5% reduction in drawing vs. modeling time
- 87.5% faster model update cycles
- 81.25% improvement in quantity segmentation
- 75.0% faster data extraction
- 54.55% reduction in progress planning time

In total, project time was reduced by 64.56%, equivalent to 177.4 saved hours, primarily through the automation of repetitive tasks such as model updates and quantity extraction. The main quantitative benefits of the BIM-GIS integration are summarized in **Table 1**, which consolidates efficiency indicators related to design, planning, workforce optimization, and cost control.

The 3D model became the central tool for technical supervision, enabling an integrated understanding of engineering solutions, supporting interdisciplinary reviews, and serving as a visual checkpoint for quality control. Additionally, 4D simulations improved clarity on construction sequencing, allowing teams to detect clashes, execute robust schedule validation, and optimize planning. The digital twin remains available for post-construction activities, such as maintenance planning, technical audits, and asset management

A critical added value was Workforce optimization where the BIM-driven analysis determined the optimal number of welding crews required for cutting, alignment, installation, welding, and grinding tasks of the steel superstructure. Considering the prevailing rainfall conditions, with an average of 2.28 hours of precipitation per day, productivity was inherently constrained. Nevertheless, by leveraging the digital model for real-time planning and crew reallocation, an estimated 8–10% improvement in workforce efficiency was achieved. This was possible due to the great analytical capacity that the software allows by taking each of the elements of the model, breaking down each of the activities to be carried out and allowing the planning of a very complete schedule that was estimated to complete the welding activities in approximately 8 months. This gain directly impacted on both schedule reliability and budget control, as welding and assembly crews were better coordinated to operate within available work windows, minimizing idle time and rework.

From a stakeholder perspective, the integrated approach enabled:

- Early detection of interferences and validation of alternatives,
- Clearer scope definition and fewer execution-stage changes,
- More efficient workforce allocation and improved control of field contingencies, and
- Greater transparency in contractual recovery and cost justification.

Ultimately, this pilot project underscores that the adoption of BIM–GIS integration in geotechnical pipeline projects is no longer a question of if, but when. With targeted investments in digital workflows, interdisciplinary collaboration, and data standardization, BIM–GIS integration can evolve from a project-specific innovation into a sector-wide practice, enabling more resilient, sustainable, and cost-effective infrastructure delivery.

Table 1. Quantitative Results and Impacts of BIM-GIS Integration in the PK 046+550 Case Study.

Category	Indicator / Value	Impact on Schedule / Budget
Design & Modeling Efficiency	57.5% reduction in drawing vs. modeling time	Faster design phase, less design overhead
	87.5% faster model update cycles (1–3 h vs. >24 h)	Enabled rapid iterations and adaptation to rainfall conditions
	177.4 saved work hours (−64.56%), ≈ 22.175 labor-days	Direct schedule impact
Quantity Takeoff & Segmentation	81.25% improvement in quantity segmentation	Reduced manual rework, better accuracy and budget control.
	75.0% faster data extraction	Improved reporting and coordination
	54.55% reduction in progress planning time	Improved schedule reliability
	Traditional CAD takeoff: >16 h vs. BIM: 4 h (+3 h setup)	Budget accuracy and responsiveness
Waste Reduction	Early-stage planning + automatic recalculations	Material waste reduction (qualitative) As the project enhanced the quantity takeoff and human resources with accuracy
	Estimated savings equivalent to 5% material optimization	Lower direct costs
Workforce Optimization	Welding crews optimized through segmentation	8 - 10% efficiency gain in welding-related tasks
	Adjusted for daily rainfall (avg. 2.28 h/day rain): 8–10% improvement	Mitigated weather-related delays
Contractual Recoveries	Model-based vs. manual quantities identified discrepancies	Prevented budget overruns, supported claims
Decision-Making	Digital twin enabled lifecycle data consolidation	Faster decision-making, reduced uncertainty
Drone & GIS Integration	RTK UAV + BIM coordination ensured accurate updates	Enhanced terrain monitoring, design and model updates

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