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INDIANA DEPARTMENT OF TRANSPORTATION
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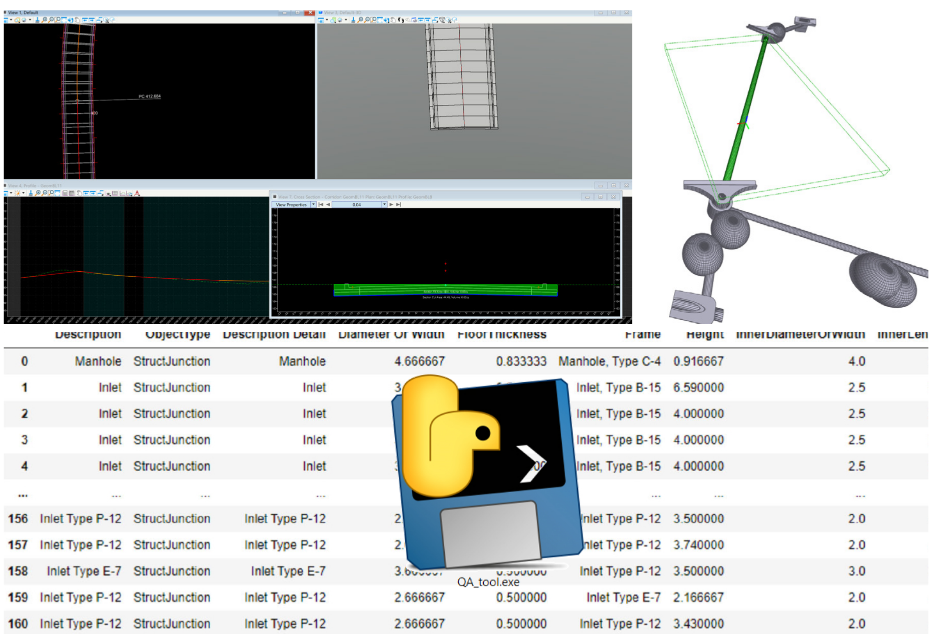
BIM Standards for Roads and Related Transportation Assets



Hang Li, Hosam Hegazy, Xiaorui Xue, Jiansong Zhang, Yunfeng Chen

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AUTHORS

Hang Li
Graduate Teaching Assistant
School of Construction Management Technology
Purdue University

Hosam Hegazy
Visiting Scholar
School of Construction Management Technology
Purdue University

Xiaorui Xue
Graduate Teaching Assistant
School of Construction Management Technology
Purdue University

Jiansong Zhang, PhD
Associate Professor
School of Construction Management Technology
Purdue University
(765) 494-1574
zhan3062@purdue.edu
Corresponding Author

Yunfeng Chen, PhD
Associate Professor
School of Construction Management Technology
Purdue University

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16. Abstract

With the industry foundation classes (IFC) building information modeling (BIM) standard (ISO 16739) being adopted by AASHTO as the national standard for modeling bridge and road infrastructure projects, there comes a great opportunity to upgrade the INDOT model development standard of roads and related assets to 2D+3D BIM. This upgrade complies with the national standard and creates a solid foundation for preserving accurate asset information for lifecycle data needs. This study reviewed the current modeling standards for drainage and pavement at different state DOTs and investigated the interoperability between state-of-the-art design modeling software and IFC. It was found that while the latest modeling software is capable of supporting interoperability with IFC, there remain gaps that must be addressed to achieve smooth interoperability for supporting life cycle asset data management. Specifically, the prevalent use of *IfcBuildingElementProxy* and *IfcCourse* led to a lack of differentiation in the use of IFC entities for the representations of different components, such as inlets, outfalls, conduits, and different concrete pavement layers. This, in turn, caused challenges in the quality assurance (QA) of IFC models and rendered the conventional model view definition (MVD)-based model checking insufficient. To address these gaps and push forward BIM for infrastructure at INDOT, efforts were made in this project to initially create model development instruction manuals that can serve as the foundation for further development and the eventual establishment of consistent and comprehensive IFC-based modeling standards and protocols. In addition, automated object classification leveraging invariant signatures of architecture, engineering, and construction (AEC) objects was investigated. Correspondingly, a QA method and tool was developed to check and identify the different components in an IFC model. The developed tool achieved 91% accuracy on drainage and 100% accuracy in concrete pavement in its tested performance. These solutions aim to support the life cycle management of INDOT transportation infrastructure projects using BIM and IFC.

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EXECUTIVE SUMMARY

Introduction

With the Industry Foundation Classes (IFC) Building Information Modeling (BIM) standard (ISO16739) being adopted by the American Association of State Highway and Transportation Officials (AASHTO) as the national standard for modeling bridge and road infrastructure projects (AASHTO, 2019), there is an urgent need to upgrade the model development standard of roads and related assets to 2D+3D BIM to fulfill the integration of infrastructure projects data to comply with national requirements. Example benefits of IFC-based modeling of roads and related transportation assets include preserving accurate and up-to-date asset information for lifecycle data needs, easier collaborations between different stakeholders, and easier quality assurance (QA).

Efforts have been made by different states to create BIM-based model development standards such as the *Ohio DOT Standards for InRoads/CAD* (Ohio DOT, 2021), the *Utah DOT Model Development Standards Manual* (UDOT, 2023), and the *Virginia 3D Model Development Manual* (VDOT, 2020). However, the BIM frameworks from other states cannot be directly applied to the business at INDOT without testing, analysis, and customization. A practical and implementable standard needs to be customized to the current business practice and asset types of INDOT. Furthermore, transitioning to a new model development standard should be based on the existing project practice at INDOT and take shape gradually. Therefore, how to build the INDOT model development standard of roads and related assets to reap the benefits of BIM technology while minimizing or preventing potential business disruptions at INDOT is the question to be addressed.

INDOT has recognized the need for integrating IFC-based BIM into the life cycle management of roadway projects and related transportation assets. In the previous *SPR-4421 Life Cycle Integration of Infrastructure Information Modeling* project (Guo et al., 2021a, b), several identified challenges in the current INDOT process could benefit from BIM-based life cycle project information management. Some examples of this include the challenges in conflicting opinions about submitting 3D models as legal documents, providing digital as-builts without disclaimer, and the need for a better way to convert 3D models and geographic data between different formats (Guo et al., 2021b). Follow-up discussions with INDOT led to the identification of an immediate need for BIM-based model development standards for drainage and concrete pavement. Correspondingly, specific objectives of this study include the following.

1. Develop BIM-based model development standards for drainage.
2. Develop BIM-based model development standards for selected pavement components.
3. Develop an IFC-based QA method and tool.

Findings and Implementation

- An investigation of interoperability between OpenRoads Designer, Civil 3D, respectively, and IFC was conducted. It was found that all the tools could transform drainage and concrete pavement models to IFC following certain paths. All the drainage and concrete pavement components and their properties could be converted without error.
- Even though OpenRoads Designer and Civil 3D could transform drainage models to IFC successfully with different approaches, the transformed IFC heavily used *IfcBuilding ElementProxy and IfcCourse* at the time of the test. To better distinguish drainage and concrete pavement components for asset management or QA purposes, a new IFC modeling standard needs to be established. The standard should include all types of drainage and concrete pavement components. For example, curb inlet, outfall, and conduit may need to be represented by designated entities such as *IfcCurbInlet*, *IfcOutFall*, and *IfcConduit*, respectively.
- To facilitate the development of the above-mentioned standard, in this project, we initially drafted a *Model Development Instruction Manual for Drainage Inlet* (Appendix A) and a *Model Development Instruction Manual for Concrete Pavement* (Appendix B).
- Until the above-mentioned standard is well established and enforced, during the transition period, automated classification algorithms can be used to help with QA. In our initial development, invariant signatures-based automated object classification algorithms achieved 91% accuracy in classifying drainage components and 100% accuracy in classifying concrete pavement components. Error analysis revealed that improvement towards 100% accuracy will require more balanced training data.
- The IFC-based drainage and concrete pavement models can facilitate INDOT's advancement/transition toward BIM-based practice and support better asset management of drainage and concrete pavement in the dimensions of interoperability, collaboration, and asset data management.

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1. INTRODUCTION

With the Industry Foundation Classes (IFC) Building Information Modeling (BIM) standard (ISO16739) adopted by the American Association of State Highway and Transportation Officials (AASHTO) as the national standard for modeling bridge and road infrastructure projects, there is an urgent need of upgrading the model development standard of roads and related assets to 2D+3D BIM to fulfill the integration of infrastructure projects data to comply with the national requirements (Alexa & Williges, 2022). Example benefits of IFC-based modeling of roads and related transportation assets include preserving accurate and up-to-date asset information for lifecycle data needs, easier collaborations between different stakeholders, and easier quality assurance (QA) (Lombardo, 2019).

Challenges for integrating BIM in infrastructure projects have been identified in a previous *SPR-4421 Life Cycle Integration of Infrastructure Information Modeling* project (Guo et al., 2021a, b) and corresponding solutions are proposed. For example, there are varieties of choices in software or tools on the market to use for infrastructure modeling in design, construction, or asset management, which may create interoperability issues and the isolation of data transmission among different stakeholders. To address it, an IFC-based approach is proposed, which can provide a neutral, open, transparent, and as a result more accessible workflow throughout the life cycle of a project (Guo et al., 2021a, b; Li et al., 2022). As promising as it is, the IFC standard can still be adopted in different ways, which, in turn, may hinder its support in BIM interoperability between different software/processes, because IFC schemas allow certain flexibility such as in the use of *IfcPropertySet* to represent different types of properties. To overcome such limitations of IFC in supporting BIM interoperability, a scientific-based and empirical data driven approach was used to discover invariant signatures of AEC objects, which was defined as "a set of intrinsic properties of the object that distinguish it from others and that do not change with data schema, software implementation, modeling decisions, and/or language/cultural contexts." (Wu et al., 2021). The invariant signatures of AEC objects are used together with IFC to help achieve the objectives in this project.

2. PROBLEM STATEMENT

Efforts have been made at different states to create BIM-based model development standards such as the Ohio DOT standards for InRoads/CAD (Ohio DOT, 2021), the *Utah DOT Model Development Standards Manual* (Draft final 7/17/2023) (UDOT, 2023), and the *Virginia 3D Model Development Manual* (VDOT, 2020). However, the BIM frameworks from other states cannot be directly applied to the business at INDOT without customization; a practical and implementable standard needs to be customized to the current business practice and asset types of INDOT. Furthermore, transition to a new model development standard should be based on the existing project practice at INDOT and taking shape gradually. Therefore, how to build the INDOT model development standard of roads and related assets to reap the benefits of BIM technology whereas minimizing or preventing potential business disruptions at INDOT is the question to be addressed. Correspondingly, this research will answer the following questions.

1. How to develop BIM standards for drainage at INDOT?
2. How to develop BIM standards for concrete pavement components at INDOT?
3. How to QA BIM models submitted by stakeholders?

3. RESEARCH OBJECTIVES

INDOT has recognized the need of integrating IFC-based BIM into the life cycle management of roadway projects and related transportation assets. In the previous *SPR-4421 Life Cycle Integration of Infrastructure Information Modeling* project (Guo et al., 2021a, b), several identified challenges in the current INDOT process could benefit from a BIM-based life cycle project information management, such as the challenges in contrasting opinions about submitting 3D models as legal documents, contrasting opinions about providing digital as-builts without disclaimer, and needs of a better way to convert 3D models and geographic data between different formats (Guo et al., 2021b). Specific objectives of this study include the following.

1. Develop INDOT BIM-based model development standards for drainage.
2. Develop INDOT BIM-based model development standards for selected pavement components.
3. Develop IFC-based QA method and tool.

3.1 Business Process

The highway design at INDOT has already been utilizing design software with BIM support (e.g., the ability to export to IFC formats). What is missing is the BIM standard to guide the creation of the design model in a way that will facilitate its usage in construction and storage in asset management. For example, the type of material and type of lining for pipe culvert are important information that could be specified at the design stage and/or collected during the construction stage and stored in IFC data for future use. However, current practice does not formally store this information. Site surveying or observation would need to be conducted when this information is needed later down the road, the effort of which could have been saved if the standard for storing this information was in place. This need is even more evident for things that go underground. With the IFC being established as the national standard for bridges and roadway, IFC-based BIM standard could be developed to support the life cycle information storage and satisfy information need of roadway and related transportation assets.

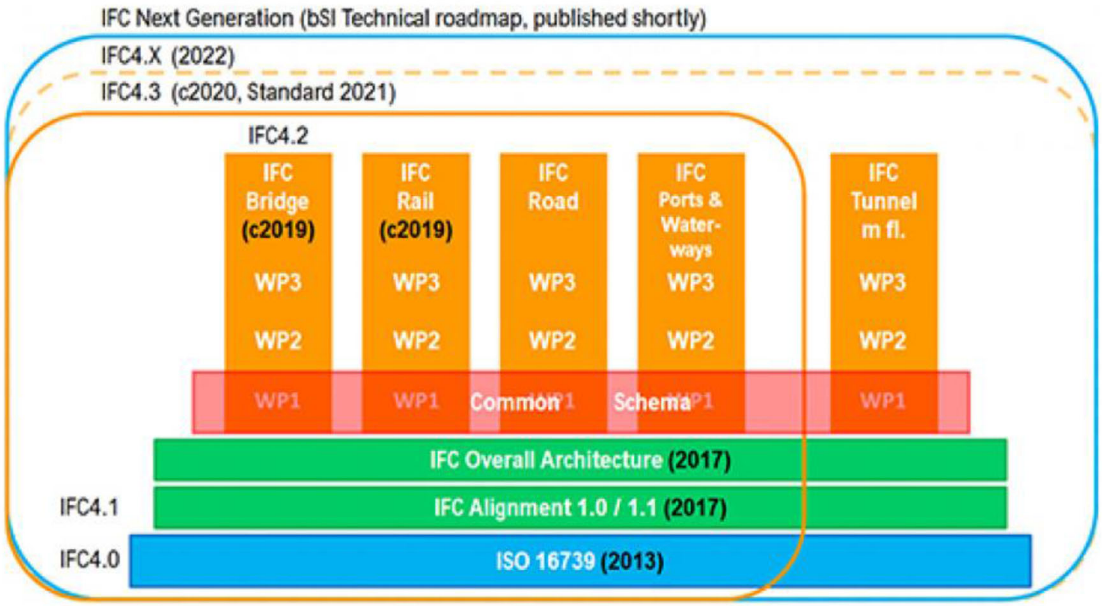


Figure 3.1 IFC infrastructure extensions (BuildingSMART, 2020).

3.2 Technical Rationale

"To evaluate whether BIM data fulfills data exchange requirements, MVD-based checking should be adopted to validate the accuracy of the IFC file (Lee et al., 2018). An MVD consists of a sequence of specification units referred to as concept, which includes a blueprint of IFC entities, their attributes, relationships, and properties (Venugopal et al., 2012). MVDs pinpoint portions of an IFC data structure supported within a particular model view (See et al., 2012). One of the main characteristics of an MVD is its reusability, allowing these concepts to be continuously applied in developing other specifications across several domains (Lee et al., 2018). An MVD allows a user to declare the necessary attributes and entity relationships for the specific use of the IFC file such as quantity takeoff" (Akanbi et al., 2020) and structural analysis (Ren & Zhang, 2021). In this project, we started with potential use of MVDs to check compliance with INDOT IFC-based BIM model development standards. Standards and specifications for roadway and related assets' construction drawings are well defined. For example, it is required that a plan view of the structure showing "details for the installation of structure drainage features, including strip, sheet, edge, blanket, and underdrain systems, and associated piping" be submitted at least 90 days before starting construction (FHWA, 2014). These served as useful input when developing the BIM model development standard at INDOT (e.g., serving construction). Another important source of information is existing BIM or CAD model development standards at other states. For example, UDOT model development standard manuals stated that 3D solid needs to be provided to represent drainage pipe (UDOT, 2023). Starting from these information resources and considering specific needs at INDOT, an initial BIM model development standard for drainage pipe was drafted at INDOT. For example, the drainage pipe model at INDOT should include not only a 3D solid, but material types for the pipe and its lining. Drainage pipe models that follow these standards could then be created in different design software such as Bentley OpenRoads and Autodesk Civil3D to investigate their imports into IFC data, especially which IFC version will be most suitable to enforce at INDOT projects (Figure 3.1).

Although MVDs could potentially be used for enforcing the BIM model development standards (e.g., MVD for drainage construction) with INDOT project stakeholders (e.g., designers, consultants, contractors, asset management office), based on our evaluation, the standard MVD checking tool IfcDoc was insufficient for the needed QA purpose at INDOT, customized computer tool was therefore developed to ensure the specific needs of INDOT are satisfied using a method similar to that in (Ren & Zhang, 2021). With the BIM model development standards for drainage and pavement components drafted in this project, a computer program was developed to automatically extract needed information from IFC-based BIM models to help with QA of the models.

4. METHODOLOGY

According to the nature of highway and roads projects, we divided the research into two parts (drainage and concrete pavement) and worked on each part step by step to achieve the research objectives, as shown in Figure 4.1.

4.1 Part 1: Drainage

We first studied the current practices of drainage modeling standards from different states' Departments

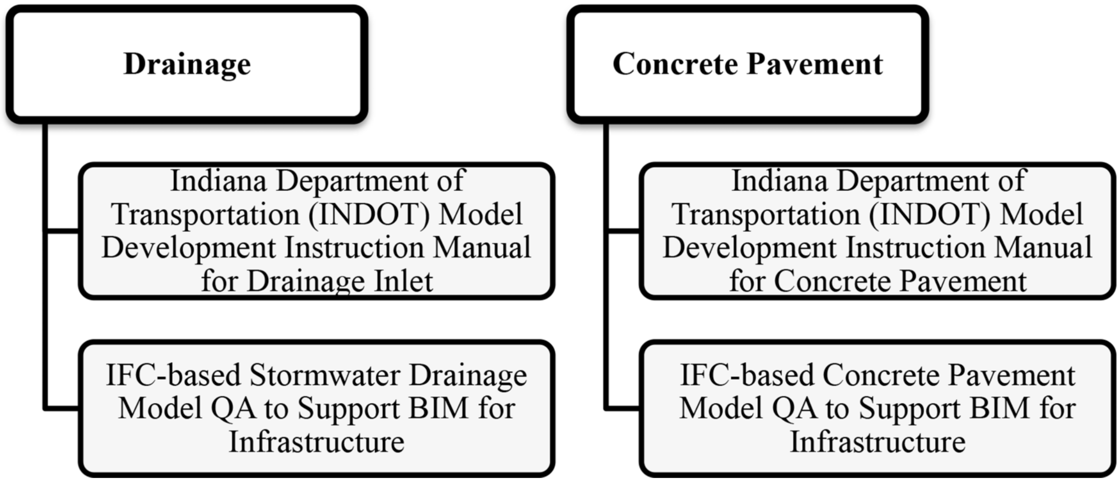


Figure 4.1 Structure and strategy of the research divided into two main parts—drainage and concrete pavement—to achieve research objectives.

TABLE 4.1
Practices of drainage modeling standards from different state DOTs (Li, Xue et al., 2023)

State DOT	Text	Visual Illustration	LOD	Software
Utah DOT (UDOT, 2023)	Yes	Yes	Yes	NA
Virginia DOT (VDOT, 2020)	Yes	Yes	Yes	InRoads
California DOT (California DOT, 2020)	Yes	No	Yes	Civil 3D, MicroStation
Delaware DOT (Del DOT, 2020)	Yes	No	No	InRoads
Illinois DOT (Illinois DOT, 2022)	Yes	No	No	GEOPAK
Iowa DOT (Iowa DOT, 2022)	Yes	No	No	GEOPAK
Oregon DOT (ODOT, 2022)	Yes	No	No	InRoads
South Dakota DOT (SDDOT, 2022)	Yes	No	No	InRoads
Connecticut DOT (CTDOT, 2023)	Yes	No	No	InRoads
New York State DOT (NYSDOT, 2022a)	Yes	No	No	InRoads

of Transportation (DOTs) through a literature review. After that, the drainage modeling design process was investigated using current drainage modeling software in the market. And utilities in the software for drainage modeling standards were investigated. Following that, the interoperability between typical drainage modeling software and IFC was studied. A portion of this section was previously published in Li, H., Xue, X., Zhang, J., & Chen, Y. (2023a). IFC-based stormwater drainage modeling to support BIM for infrastructure. *2023 ASCE International Conference on Computing in Civil Engineering (i3CE 2023)*, ASCE, Reston, VA. Republished here with permission from the American Society of Civil Engineers and content updates.

4.1.1 Study of Current Practices

The current practices of drainage modeling standards from different state Departments of Transportation (DOTs) were studied through a literature review (Table 4.1) (Li, Xue et al., 2023). Ten out of ten reviewed State DOTs provided textual description, while only two out of ten provided visual illustrations, and three out of ten provided Level of Details (LOD) requirements. State DOTs may also provide workspaces/templates for specific software. For example, the Utah DOT describes its requirements for 3D drainage models in textual documents with visual illustration (UDOT, 2022). The Virginia DOT's 3D drainage model requirement is similar to that of the Utah DOT. However, it also explicitly describes the use of InRoads in creating the 3D model (VDOT, 2020). The review shows that different state DOTs are at different stages of adopting BIM and IFC and have different requirements on 3D models of drainages.

The visual illustration is helpful for providing more detailed and vivid demonstrations about the requirement on 3D drainages. However, the majority of the reviewed state DOTs do not provide visual illustrations on 3D drainage models in their requirements. This could be caused by concerns of unintended consequences when conveying information or ideas that was not intended to convey and/or putting unnecessary constraints on contractors (Li, Xue, et al., 2023).

4.1.2 Drainage Modeling Workflow Analysis

4.1.2.1 Design workflow. Typical drainage modeling software was investigated in terms of its workflow for creating a drainage model and utilities for creating modeling standards. Although InRoads, GEOPAK and Civil 3D were mentioned the most by state DOTs' drainage modeling standards, OpenRoads Designer includes all of the capabilities of InRoads and GEOPAK (CTDOT, 2023). It combines InRoads and GEOPAK by providing a new 3D parametric modeling environment with the capabilities for roadway, drainage, subsurface utilities, and site design (CTDOT, 2023). Therefore, OpenRoads Designer 2021 and AutoDesk Civil 3D 2021 were selected as the modeling software for investigating drainage modeling workflow in this report.

It was found OpenRoads Designer 2021 and AutoDesk Civil 3D 2021 follow very similar modeling rules and workflows. There are five main components of a storm drainage system, including curb inlet, outfall, conduit, gutter, and catchment.

The drainage design process is usually carried out following five steps: (1) set terrain, (2) place node, (3) place conduit, (4) place gutter, and (5) place catchment (FDOT, 2021a). The first step is to set the active terrain on which the drainage model is to be built, which is usually done by attaching a reference file to the model. Then, nodes are placed to define drainage structure points within the drainage network (FDOT, 2021a). These nodes serve as placeholders to create drainage components including the inlets, junctions, and outfalls in the drainage systems accordingly (FDOT, 2021a). The third step is to create conduits. A conduit is a linear component representing a path connecting two nodes. Following that, gutters are created to simulate bypass flow along the surface between nodes (FDOT, 2021a). Finally, the catchments are created, which can be used to compute peak discharges. The computed discharge values will then be attached to the nodes (FDOT, 2021a). The design processes from OpenRoads 2021 and Civil 3D 2021 were found to be very similar based on the authors' investigation. Figure 4.2 shows the detailed workflow of drainage design in Civil 3D 2021.

An example drainage model was then created in OpenRoads 2021 following the previous five steps. The overview of the model is shown in Figure 4.3.

4.1.2.2 Model validation. OpenRoads 2021 has its internal model validation functionality. For example, Figure 4.4 shows the validation results of the example model. A conduit was found not to meet minimum cover constraints by hydraulic validation. And a link was found to have an adverse slope from hydraulic results. These validation results can help the designer correct input data (FDOT, 2021b).

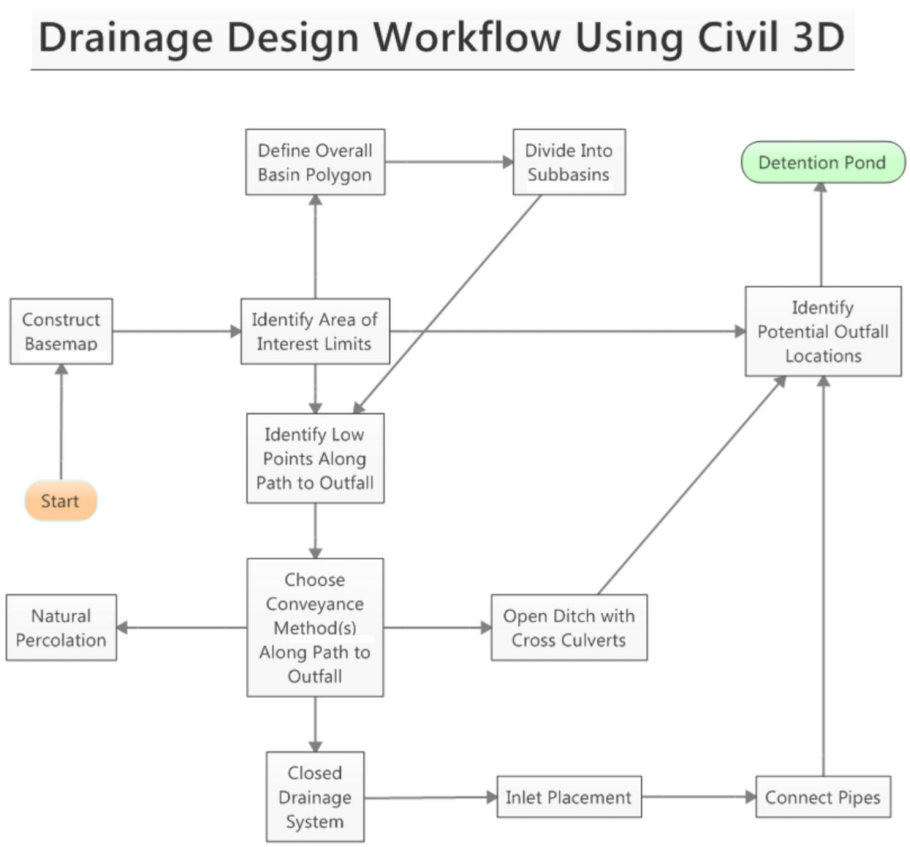


Figure 4.2 Drainage design workflow using Civil 3D 2021 (FDOT, 2021a).

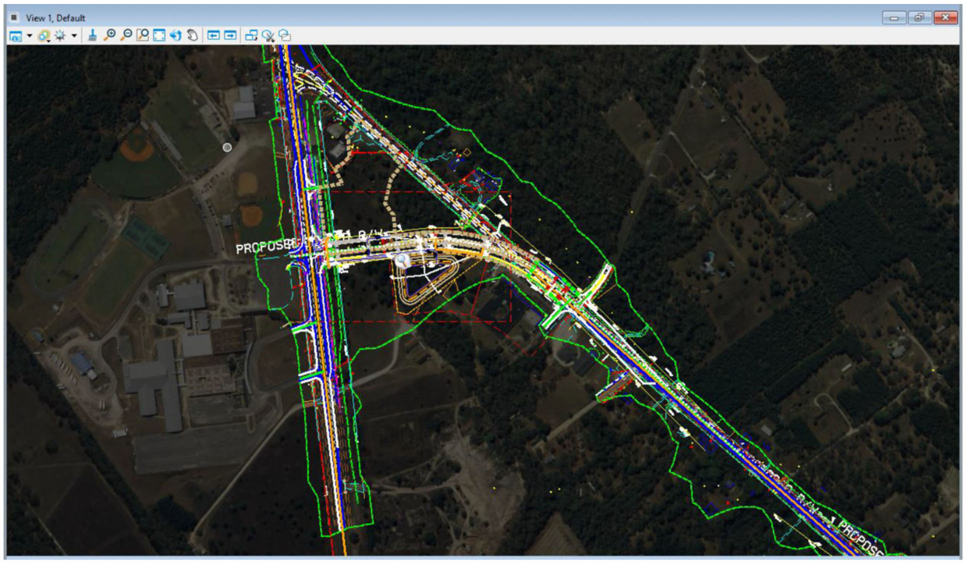
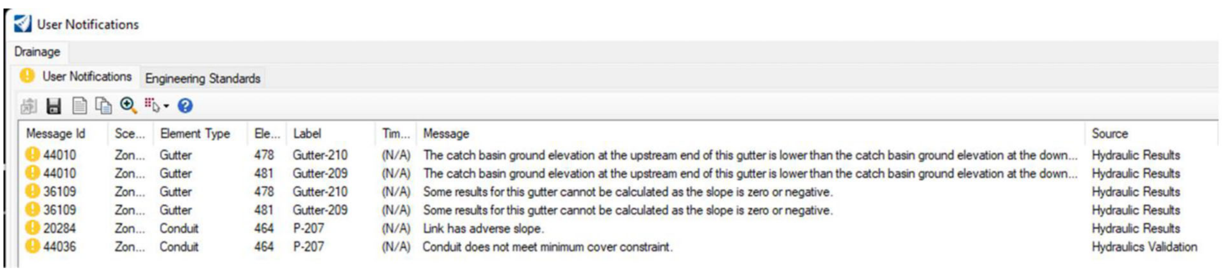


Figure 4.3 Overview of example drainage model created in OpenRoads 2021 (FDOT, 2021b).



Message Id	Sce...	Element Type	Ele...	Label	Tim...	Message	Source
44010	Zon...	Gutter	478	Gutter-210	(N/A)	The catch basin ground elevation at the upstream end of this gutter is lower than the catch basin ground elevation at the down...	Hydraulic Results
44010	Zon...	Gutter	481	Gutter-209	(N/A)	The catch basin ground elevation at the upstream end of this gutter is lower than the catch basin ground elevation at the down...	Hydraulic Results
36109	Zon...	Gutter	478	Gutter-210	(N/A)	Some results for this gutter cannot be calculated as the slope is zero or negative.	Hydraulic Results
36109	Zon...	Gutter	481	Gutter-209	(N/A)	Some results for this gutter cannot be calculated as the slope is zero or negative.	Hydraulic Results
20284	Zon...	Conduit	464	P-207	(N/A)	Link has adverse slope.	Hydraulic Results
44036	Zon...	Conduit	464	P-207	(N/A)	Conduit does not meet minimum cover constraint.	Hydraulics Validation

Figure 4.4 Validation results on the example model.

One advantage of OpenRoads 2021 is that it has the functionality of creating customized engineering standards for model checking and validation (FDOT, 2021b). Figure 4.5 shows an example of an engineering standard created in OpenRoads 2021. It checks all the conduits with diameters less than or equal to 18 feet. Any conduits satisfying this precondition in the model with construction length greater than 100 feet will prompt a warning in the user notification as shown in Figure 4.6. This customized engineering standard functionality can potentially be used in creating modeling requirements in different standards for OpenRoads models.

4.1.2.3 Simulation. Figure 4.7 shows profile run results of Node S-203 to Node S-208 for the example model created in OpenRoads 2021. The detailed simulation results including the link length, rise (inch), material, flow (CFS), slope (%), etc. for each conduit are shown in Figure 4.7. Designers could use these output data for drainage system component sizing and developing flood control strategies.

4.1.3 Research on Interoperability

Interoperability between state-of-the-art drainage design software (i.e., AutoDesk Civil 3D, 2021; Bentley, 2021) and IFC data schema was explored.

4.1.3.1 Bentley OpenRoads Designer. OpenRoads 2021 has its internal utility for exporting to IFC. However, according to the authors' test (and at the time of test), it only allows exporting civil elements (i.e., the terrain model and corridor where the drainage model is built upon) without exporting drainage model. Figure 4.8 shows an example of OpenRoads model and corresponding IFC model exported through the built-in export utility. It can be seen that while stormwater management facilities and civil elements were successfully transformed, the drainage system (highlighted in the yellow bounding box in Figure 4.8(a)) was missing from the transformed IFC model (Figure 4.8(b)).

To export the drainage system from OpenRoads 2021 to IFC, the authors investigated other intermediate data formats and tools (FDOT, 2021b). It was found that the conversion from Bentley OpenRoads Designer drainage model to IFC can be done in four steps with the support of iTwin Design Review platform and iModel: Step 1. export as iModel from OpenRoads Designer; Step 2. upload iModel to iTwin Design Review platform (Figure 4.9); Step 3. select IFC schema (supported version at the time of test: IFC 4.3 RC1, IFC 2×3, IFC 2×3 CV 2.0, IFC 4); and Step 4. wait for processing and download the exported IFC file from iTwin Design Review platform. Figure 4.10 shows an OpenRoads drainage model and the corresponding

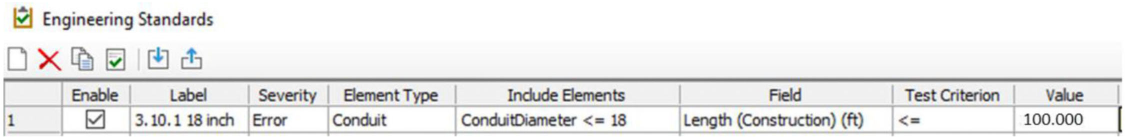


Figure 4.5 An example engineering standard created in OpenRoads 2021.

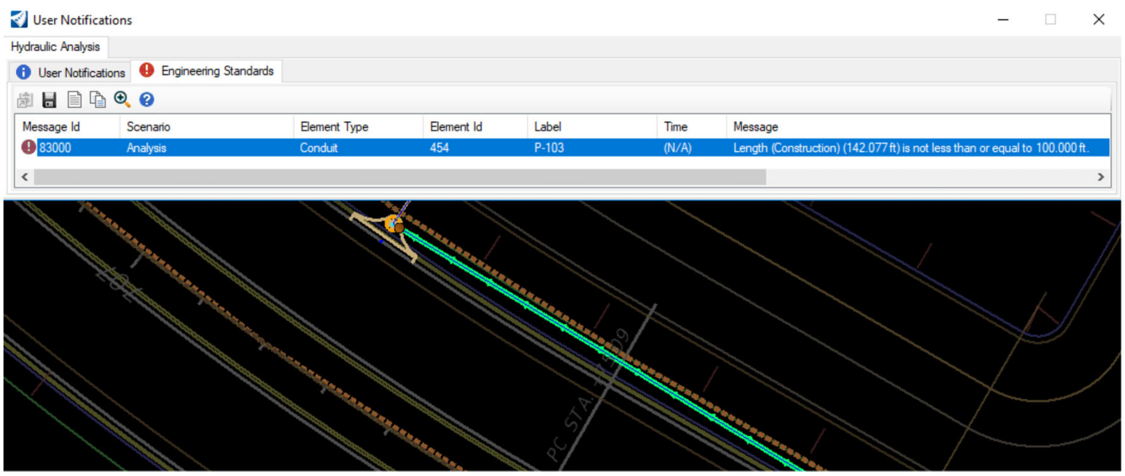


Figure 4.6 Example validation results for the created engineering standard in OpenRoads 2021.

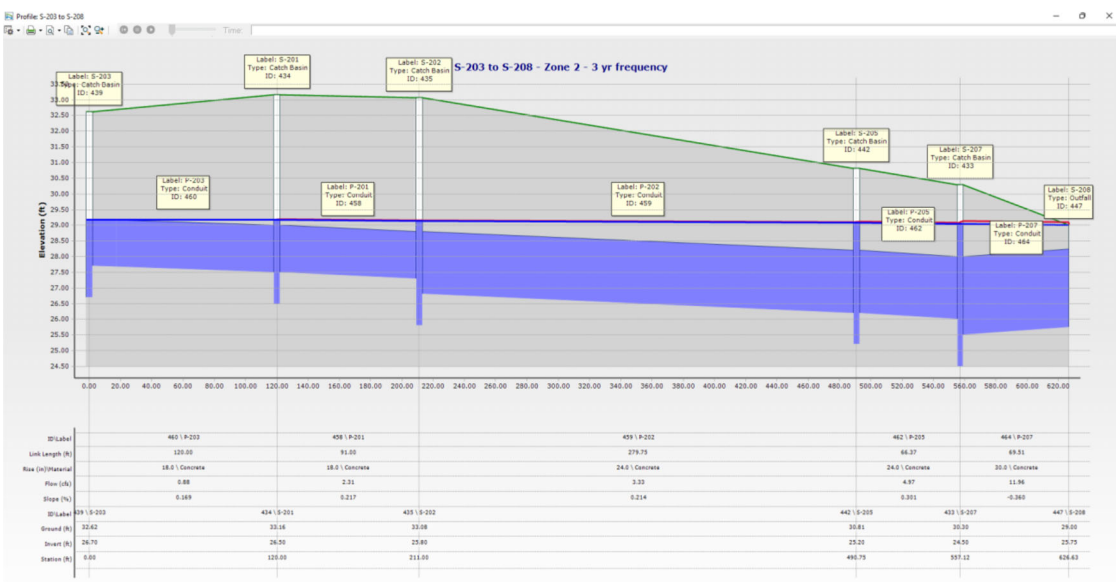
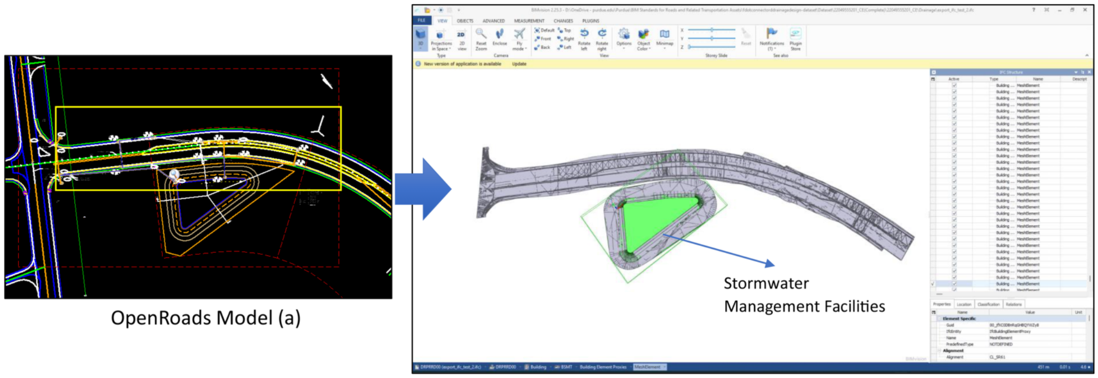


Figure 4.7 Profile run results of Node S-203 to Node S-208 for the example model created in OpenRoads 2021.

transformed IFC drainage model. All the drainage components were transformed correctly. In addition, the attributes and feature definitions under each element were also transformed to IFC without error.

4.1.3.2 AutoDesk Civil 3D. Then, the interoperability between AutoDesk Civil 3D 2021 and IFC was also investigated. It was found the transformation takes four steps: Step 1. convert to 3D Solid by extracting solid object through Civil 3D surfaces; Step 2. add property sets; Step 3. select IFC version and export options; and Step 4. export to IFC. Figure 4.11 shows the interface for converting drainage model to 3D Solid objects in Civil 3D. Figure 4.12 shows the converted 3D Solid model.

The second step is to add property sets to the drainage elements. According to the authors' test, attributes of elements in Civil 3D could not be transformed into IFC without creating property sets. There were two approaches to create property sets. The first one was to create property sets manually in Civil 3D. Figure 4.13



OpenRoads Model (a)

IFC Model (b)

Figure 4.8 Example of exporting OpenRoads model (a) to IFC model (b).

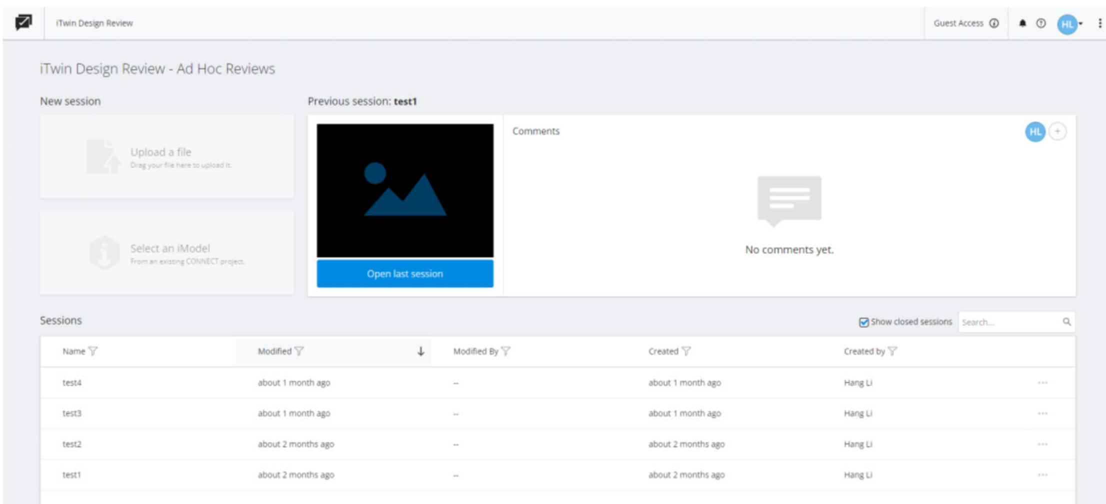
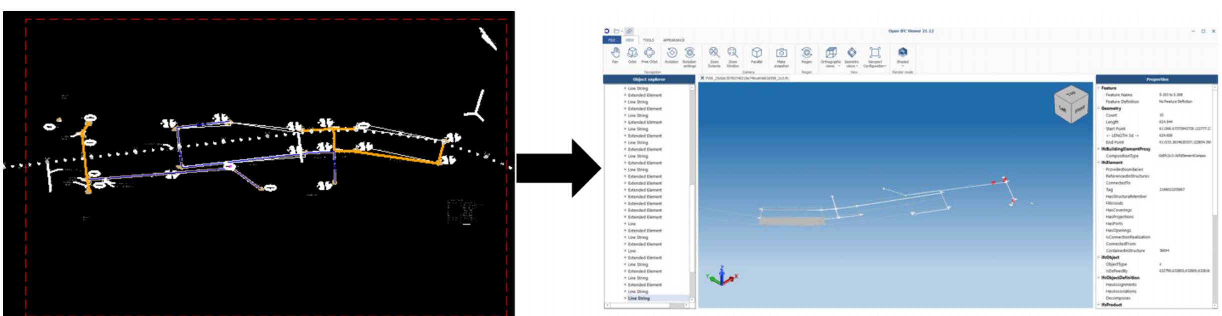


Figure 4.9 Interface of iTwin design review.



OpenRoads Model (a)

IFC Model (b)

Figure 4.10 OpenRoads drainage model (a) and transformed IFC drainage model (b).

shows the interface for creating property sets in Civil 3D manually. The second approach was to create property sets through programming and applications such as using VB scripts.

Figure 4.14(a) shows the property sets of a drainage component in Civil 3D and Figure 4.14(b) shows the transformed property sets in IFC. It can be seen that all the attributes in the property sets were transformed correctly.

The next step was to select the IFC version and export options as shown in Figure 4.15. At the time of test, the available IFC versions included IFC 4×1, IFC 2×3, and IFC 4. By selecting the Solid 3D objects in the export options and IFC 4×1 for the IFC schema, the drainage model can be successfully exported from Civil 3D to IFC.

Finally, the exported IFC model from the example model created in Civil 3D 2021 is shown in Figure 4.16.

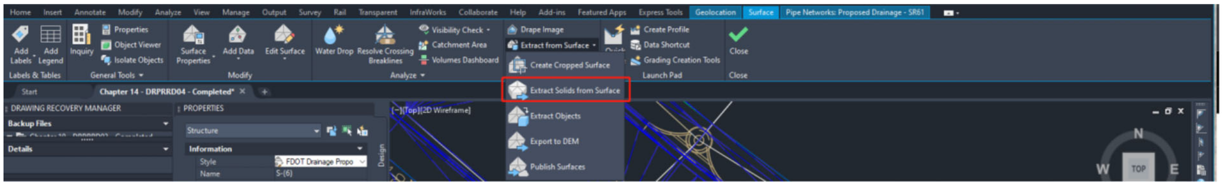


Figure 4.11 Interface for converting model to 3D solid in Civil 3D.

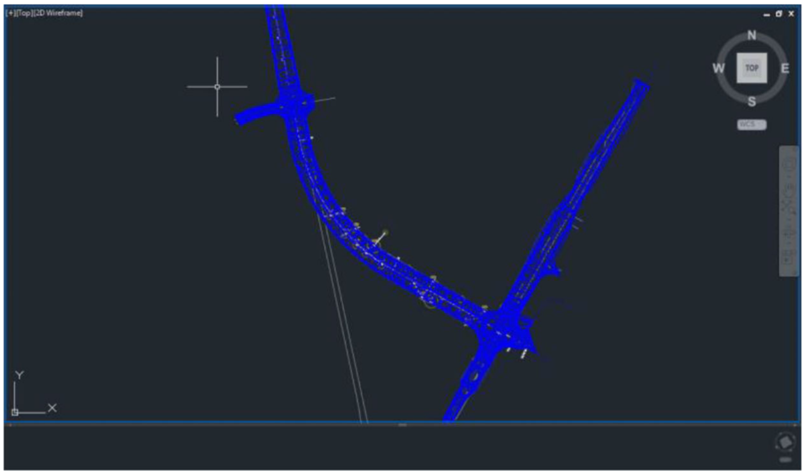


Figure 4.12 Converted 3D solid model.

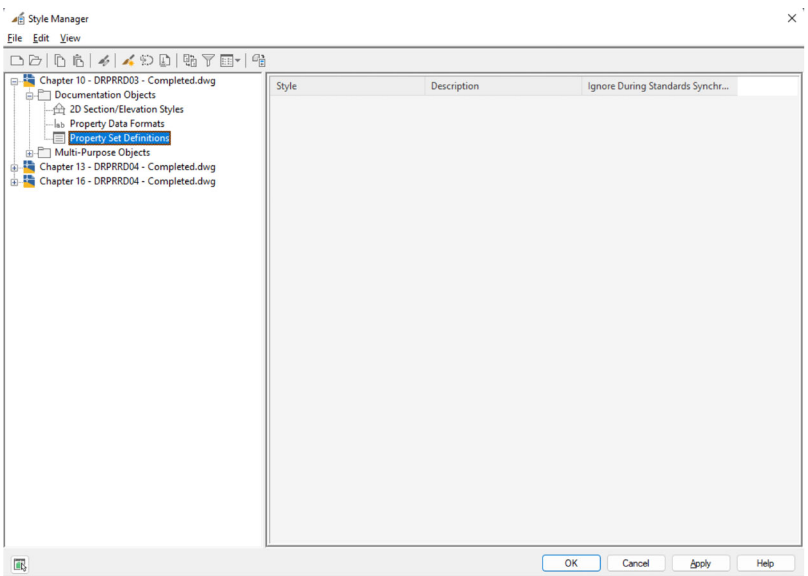


Figure 4.13 Interface for creating property sets in Civil 3D.

Table 4.2 summarized the interoperability between state-of-the-art drainage modeling software and IFC. Both Bentley OpenRoads Designer 2021 and AutoDesk Civil 3D 2021 can transform the storm drainage model to IFC. At the time of test, OpenRoads Designer relied on iTwin Design Review platform using iModel, Civil 3D needed to convert drainage model to Solid 3D objects first then exported it as IFC. OpenRoads could convert all the attributes associated with each drainage component directly without error. While Civil 3D could not convert attributes directly, it relied on property sets for transforming attributes. Both OpenRoads Designer and Civil 3D converted drainage models to IFC without distinguishing IFC entity representations. All the drainage components were transformed and represented as *Ifc BuildingElementProxy* as highlighted in the red box in Figure 4.17.

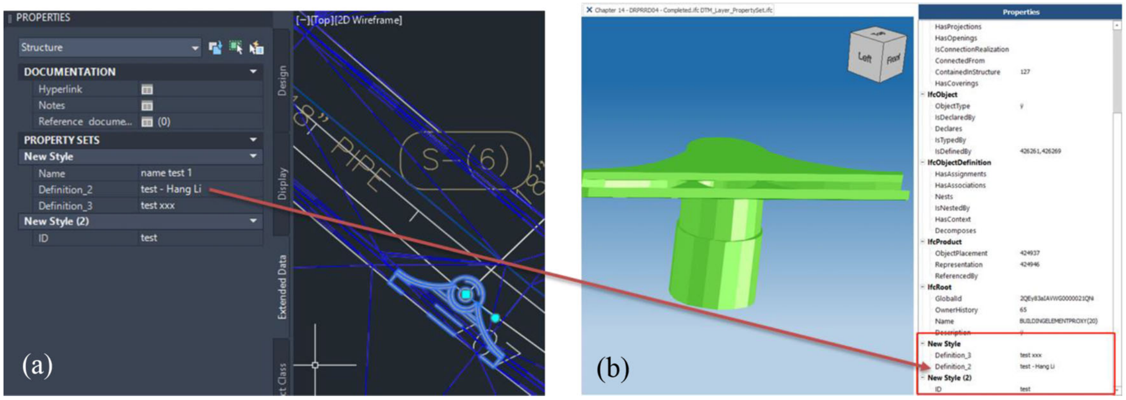


Figure 4.14 Property sets of drainage component in Civil 3D (a) and property sets of drainage component in IFC (b).

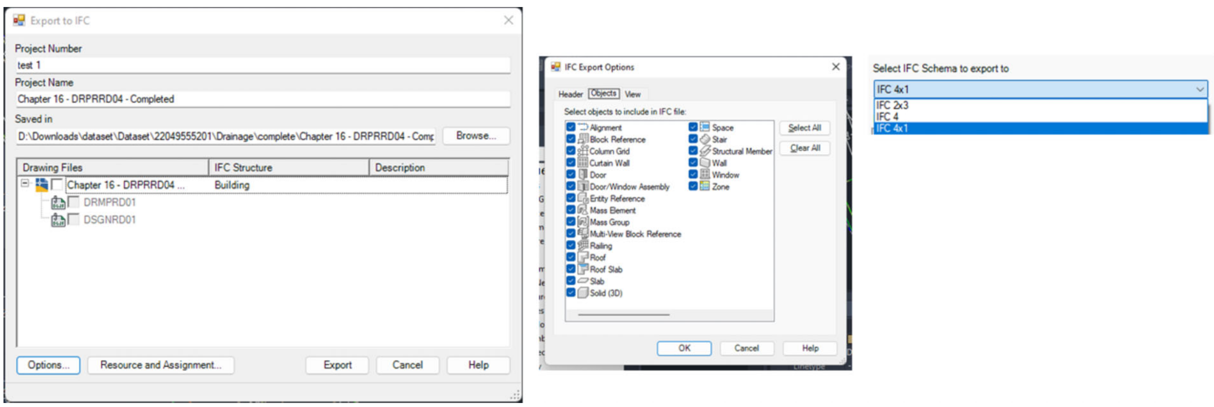


Figure 4.15 Interface for exporting Civil 3D to IFC.

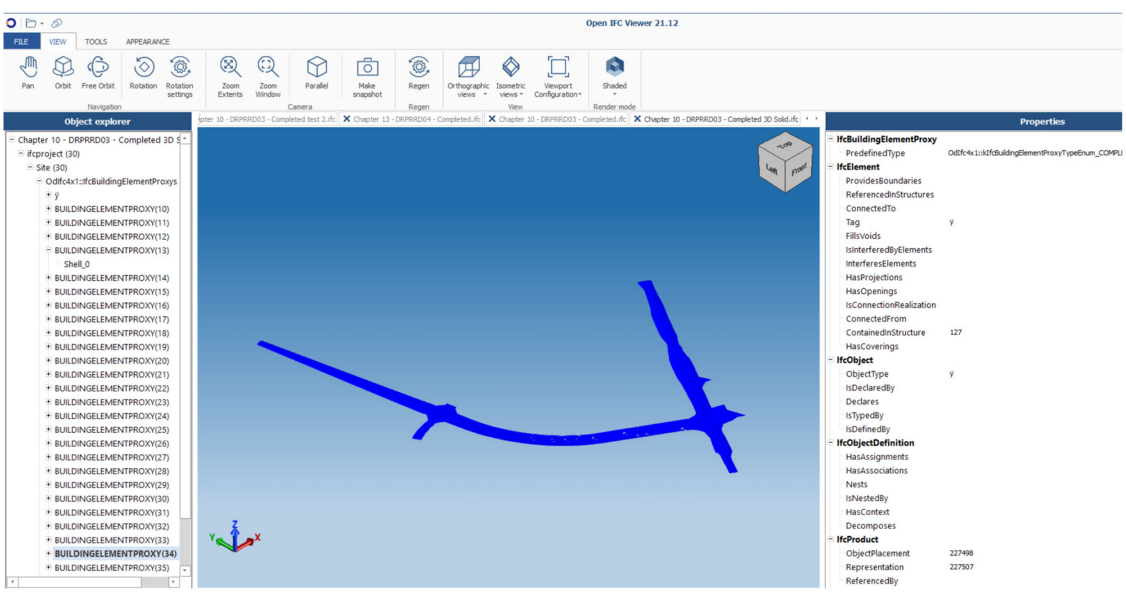


Figure 4.16 Exported IFC model from Civil 3D 2021.

TABLE 4.2
Tested interoperability between drainage modeling software and IFC

Software Platform	Bentley OpenRoads Designer 2021	AutoDesk Civil 3D 2021
Transforming Process	Relied on iTwin Design Review platform and iModel	Needed to create Solid 3D objects for the drainage model to be transformed
Component Attributes	Could convert all the attributes directly without error	Could not convert attributes directly. Relied on property sets for transforming attributes
IFC Entity Representation	No distinction in IFC representation of drainage components. All the components were represented as *IfcBuildingElementProxy*	No distinction in IFC representation of drainage components. All the components were represented as *IfcBuildingElementProxy*

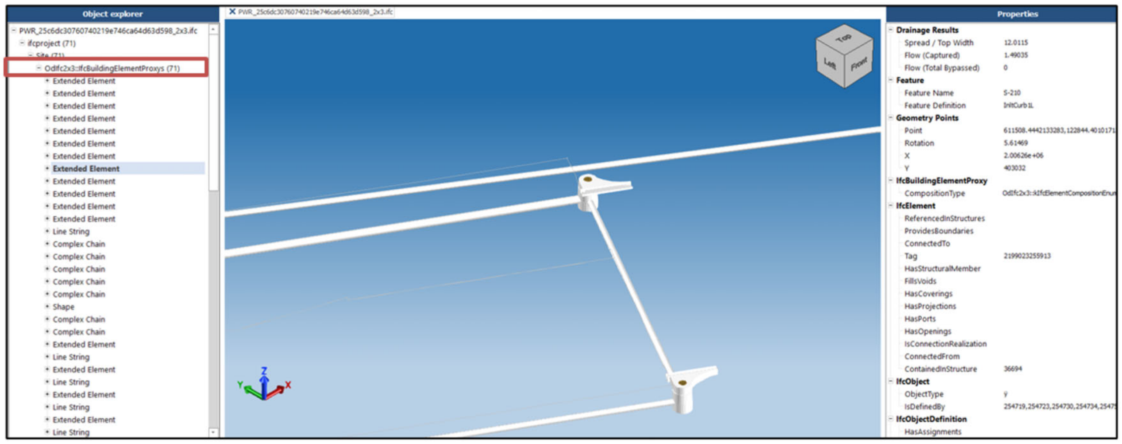


Figure 4.17 Exported IFC drainage model with IFC entities.

Figure 4.18 Research method for investigating the concrete pavement components.

4.1.4 Indiana Department of Transportation (INDOT) Model Development Instruction Manual for Drainage Inlet (Draft)

Based on results from previous tasks and extensive discussions with study advisory committee (SAC), it was decided the first component of INDOT model development standards should be an instruction manual for drainage inlet, which was then drafted as detailed in Appendix A.

4.2 Part 2: Concrete Pavement

Figure 4.18 summarized the overall research approach for the concrete pavement part. For concrete pavement, through a literature review, we first studied the current practices of concrete pavement components standards from different state DOTs (as shown in Table 4.3). After that, the concrete pavement modeling design process and software interoperability with IFC was investigated using a current road modeling software in the market (Bentley, n.d.). The functions in the software for concrete pavement components' modeling standards were investigated based upon which a draft model development instruction manual for concrete pavement was created.

4.2.1 Study of Current Practices

According to (INDOT, 2022c), INDOT Pavement Design Process - INDOT Projects Flowchart contained details regarding the pavement design process, as shown in Figure 4.19.

4.2.2 Research on Interoperability

IfcBuildingElementProxy is an Entity, as shown in Figure 4.20 and Figure 4.21, that was defined as "a proxy definition that provides the same functionality as subtypes of *IfcBuildingElement*, but without having

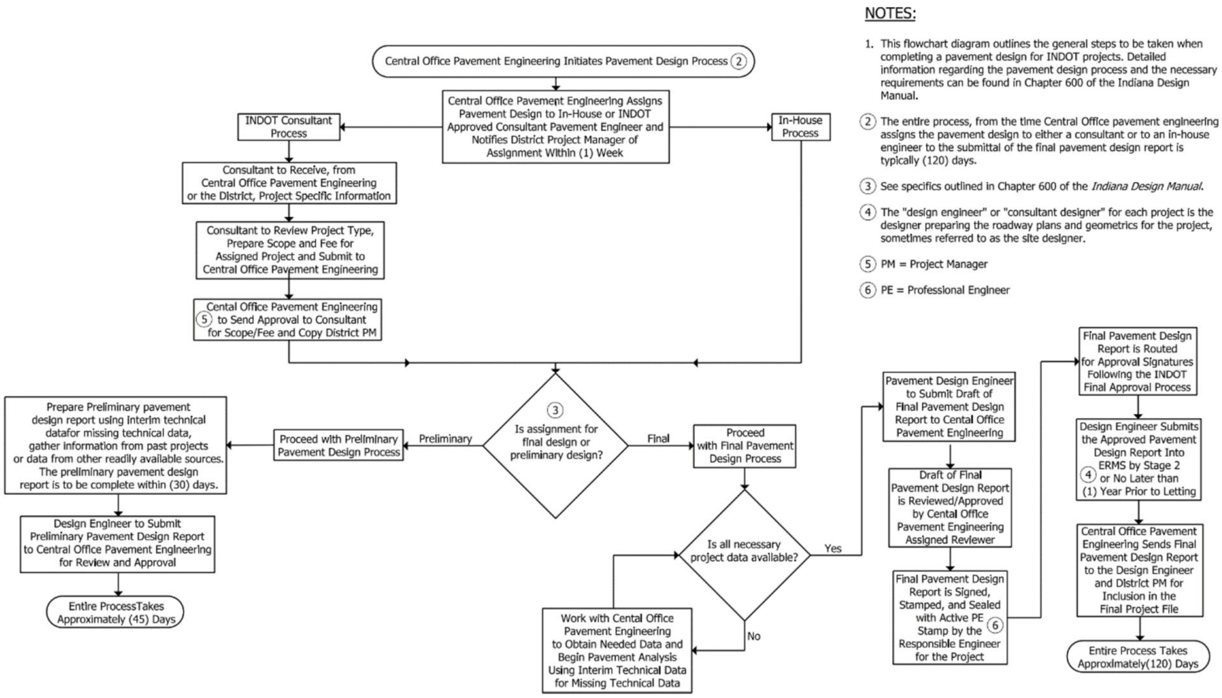


Figure 4.19 INDOT pavement design process—projects flowchart (INDOT, 2022c).

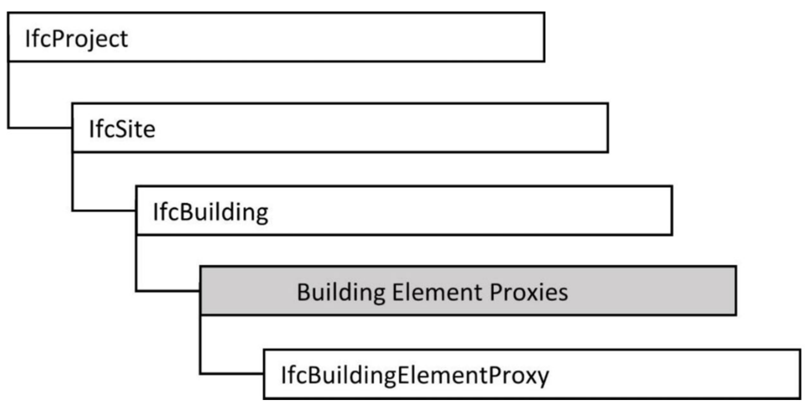


Figure 4.20 IfcEntity for IFC2 $\times$ 3 version.

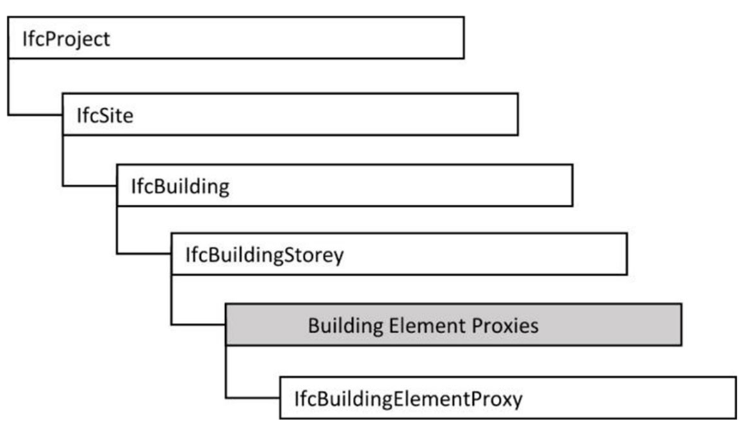


Figure 4.21 IfcEntity for IFC4 version.

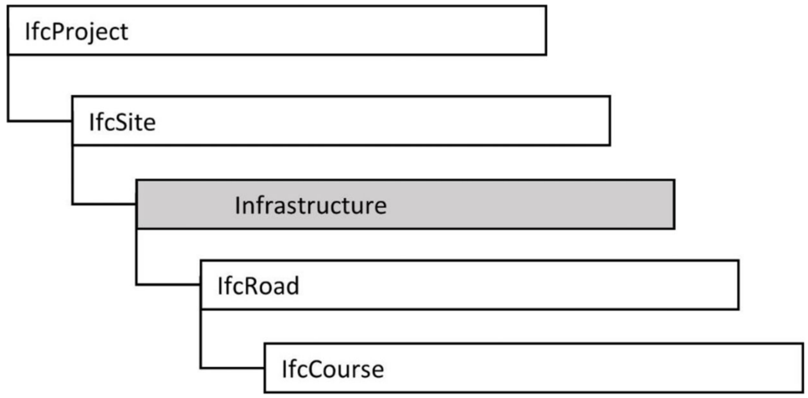


Figure 4.22 IfcEntity for IFC4 $\times$ 3 version.

a predefined meaning of the special type of building element, it represents." (buildingSMART, n.d.a). Also, *IfcBuildingElementProxy* can be for other usages that include (buildingSMART, n.d.a) the following.

- "The *IfcBuildingElementProxy* can be used to exchange special types of building elements for which the current specification does not yet provide a semantic definition.
- The *IfcBuildingElementProxy* can also be used to represent building elements for which the participating applications cannot provide a semantic definition."

IfcCourse is an Entity, as shown in Figure 4.22, that was defined as "a built element whose length greatly exceeds its thickness and often also its width, usually of a single material laid on site on top of another horizontal or nearly horizontal built element." (buildingSMART, n.d.b).

More detailed breakdowns of entities for representing objects in the different versions of the IFC schema are shown in Figures 4.23–4.29.

4.2.3 Indiana Department of Transportation (INDOT) Model Development Instruction Manual for Concrete Pavement (Draft)

Similar to the *Model Development Instruction Manual for Drainage Inlet*, a *Model Development Instruction Manual for Concrete Pavement* was drafted, as detailed in Appendix B.

4.3 QA Method and Tool Development

Based on extensive discussions with study advisory committee (SAC), the primary goal of the QA is to check and identify the different components in a model.

4.3.1 Drainage

For drainage model depicting a storm drainage system, drainage components can be classified into two main types: node elements and conduits. Node elements include inlets, outfalls, grates, and junctions. Conduits include pipes and gutters.

Based on the results from Section 4.1.3, there is a prevalent use of *IfcBuildingElementProxy* entity to represent different types of drainage components in IFC models, which caused the direct MVD-based approach ineffective in performing the needed QA on IFC-based drainage models in this context. To address this challenge, the authors took a cutting-edge invariant signature-based approach. The invariant signature of an architecture, engineering, and construction (AEC) object is "a set of intrinsic properties of the object that distinguish it from others and that do not change with data schema, software implementation, modeling decisions, and/or language/cultural contexts." (Wu et al., 2021). The invariant signatures include two main types—geometric signatures and material signatures (Wu, Akanbi, & Zhang, 2021), which have been successfully tested and demonstrated in supporting different BIM-based applications such as automated quantity takeoff from IFC-based BIM (Wu, Akanbi, & Zhang, 2022), automated BIM-based building code compliance checking (Wu et al., 2023; Wu & Zhang, 2022; Wu, Akanbi, & Zhang, 2022), and building energy modeling and simulations (Li, Zhang et al., 2023; Li & Zhang, 2023; Li & Zhang, 2022).

Stormwater node elements include curb inlet, grate, outfall, and junction. Geometric signatures of stormwater node elements including invert elevation, ground elevation, structure depth, etc. are summarized in Table 4.4. Examples of outfall, curb inlet and grate are shown in Figure 4.30, Figure 4.31, and Figure 4.32, respectively. Figure 4.33 shows the feature definition of a grate and an inlet in Bentley OpenRoads.

"Conduits connect and convey intercepted runoff from the various Nodes within a network to the Outfall, and may consist of pipes, boxes, or ditches. A multitude of options for sizing, and profiling Conduits are supported. A Conduit represents a linear feature depicting a path connecting two Nodes. The path may be a straight line, line string, curvilinear, or a combination" (FDOT, 2021b). "Gutters are required to model bypass flow along the surface between nodes. Typical applications of gutters in designs are Curb & Gutter, median and adjacent barriers, and shoulder gutter" (FDOT, 2021b). Conduits include drainage pipes and gutters.

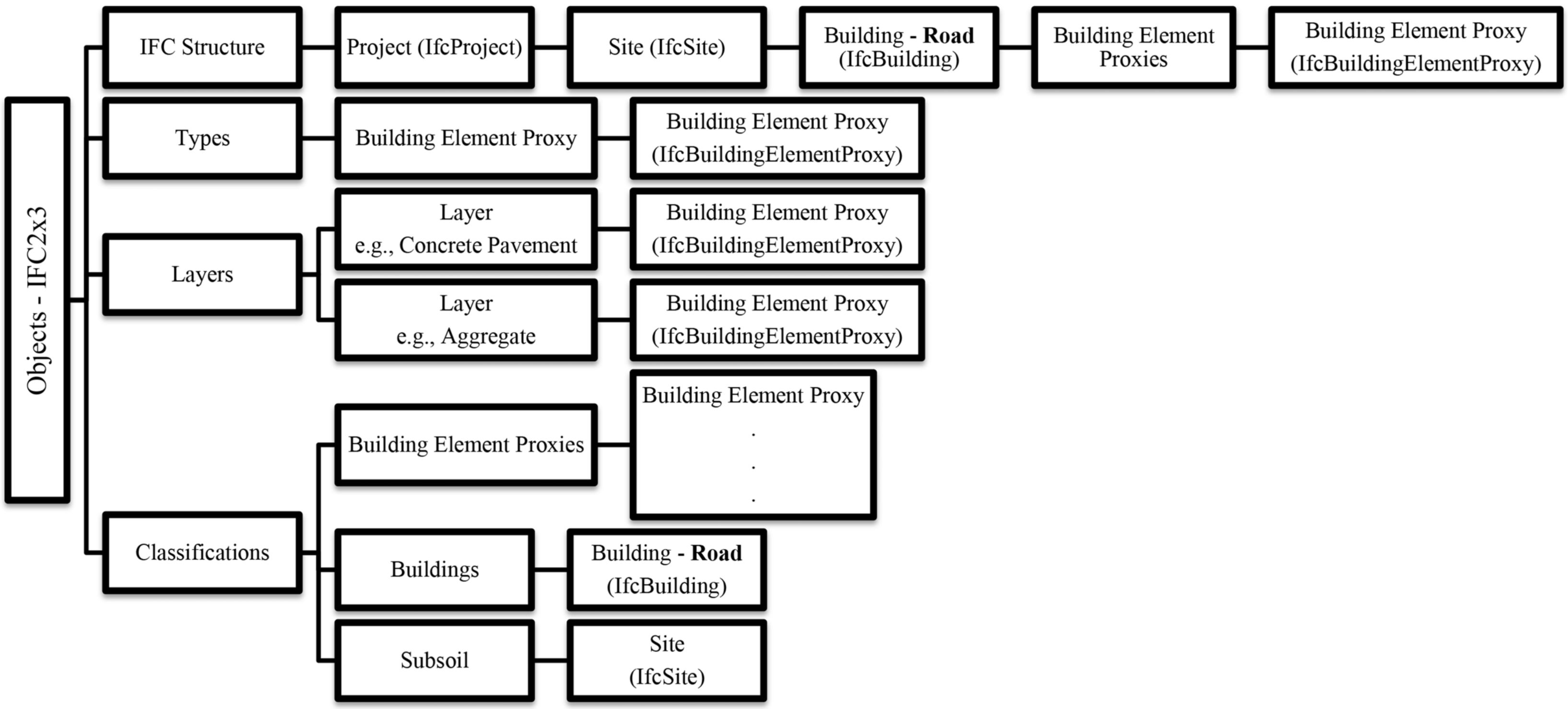


Figure 4.23 Breakdown of the "Objects" for the IFC2 × 3 version.

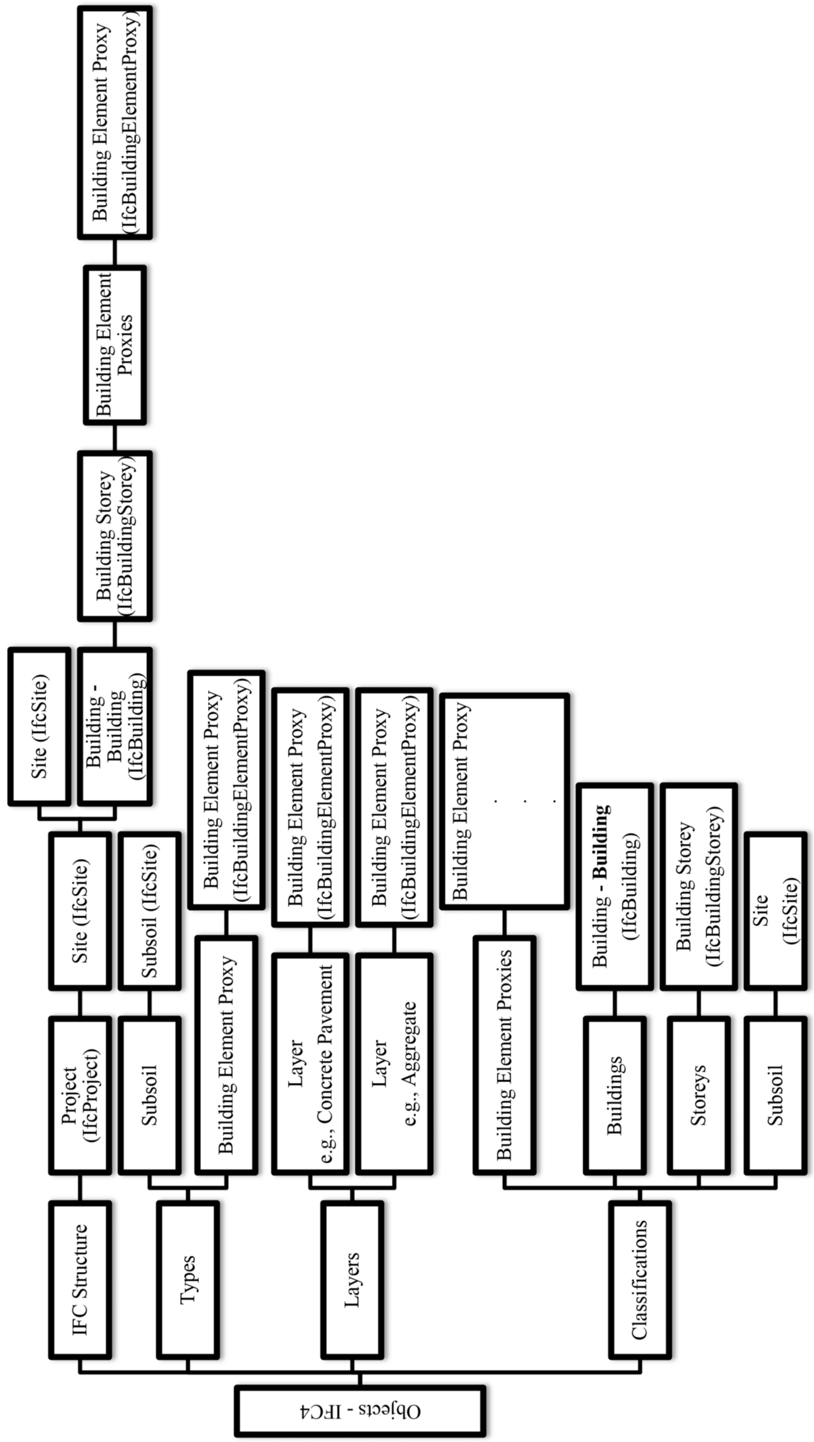


Figure 4.24 Breakdown of the "Objects" for the IFC4 version.

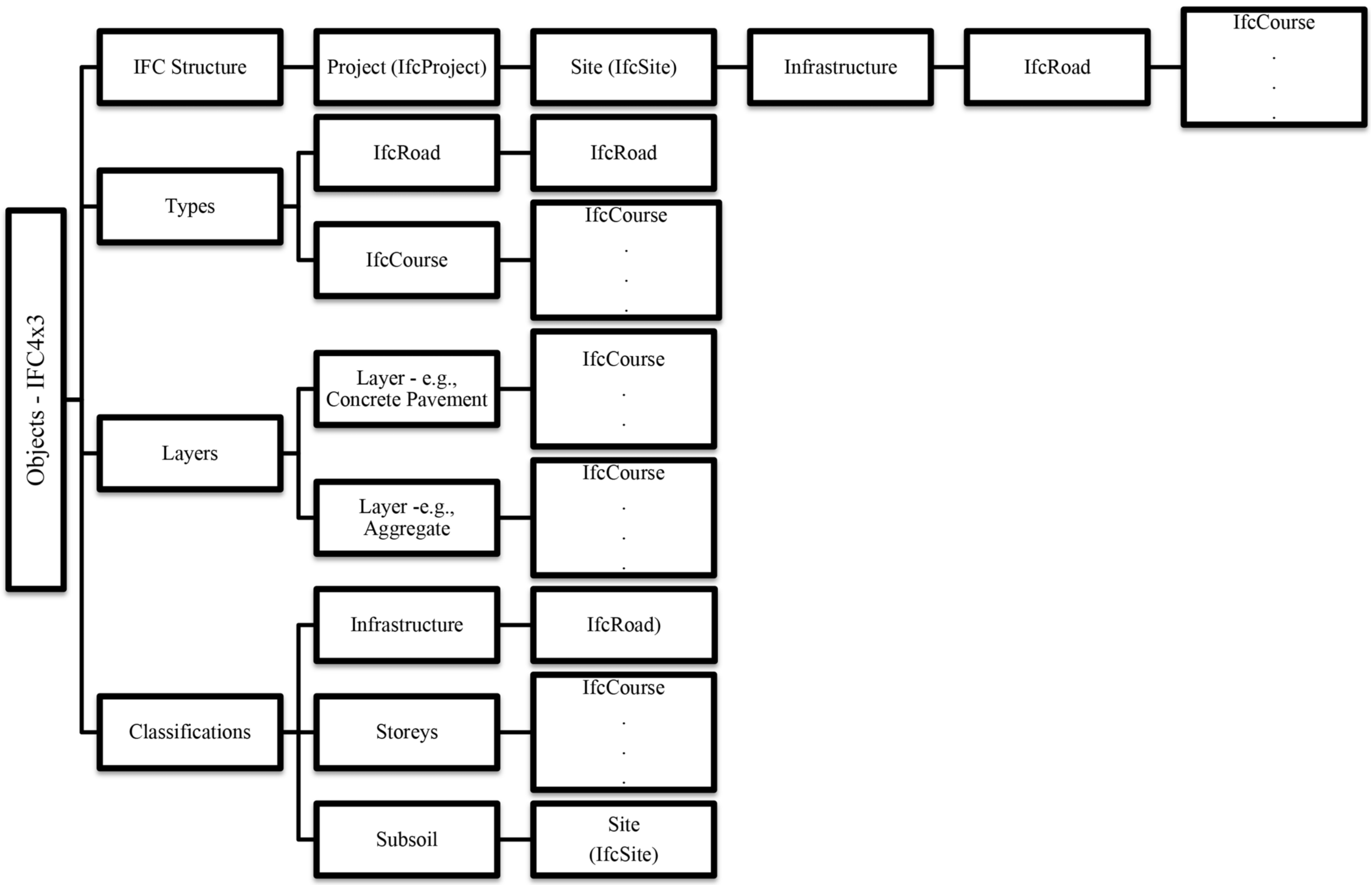


Figure 4.25 Breakdown of the “Objects” for the IFC4 × 3 version.

(a) *IFC4×3 version*

(b) *IFC4 version*

(c) *IFC2×3 version*

Figure 4.26 Interface for the breakdown of the "structure."

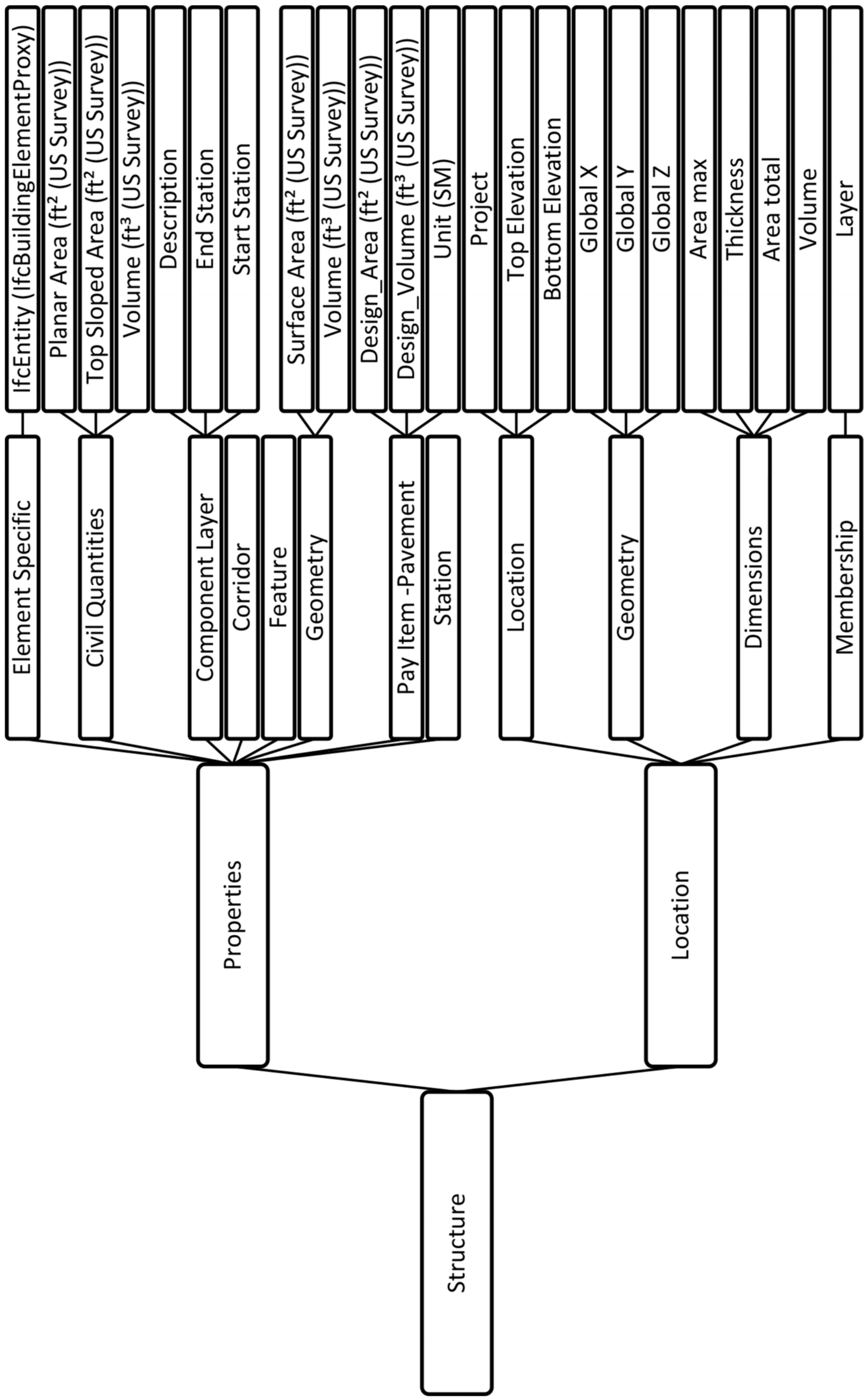


Figure 4.27 Structure of the IFC2 × 3 version.

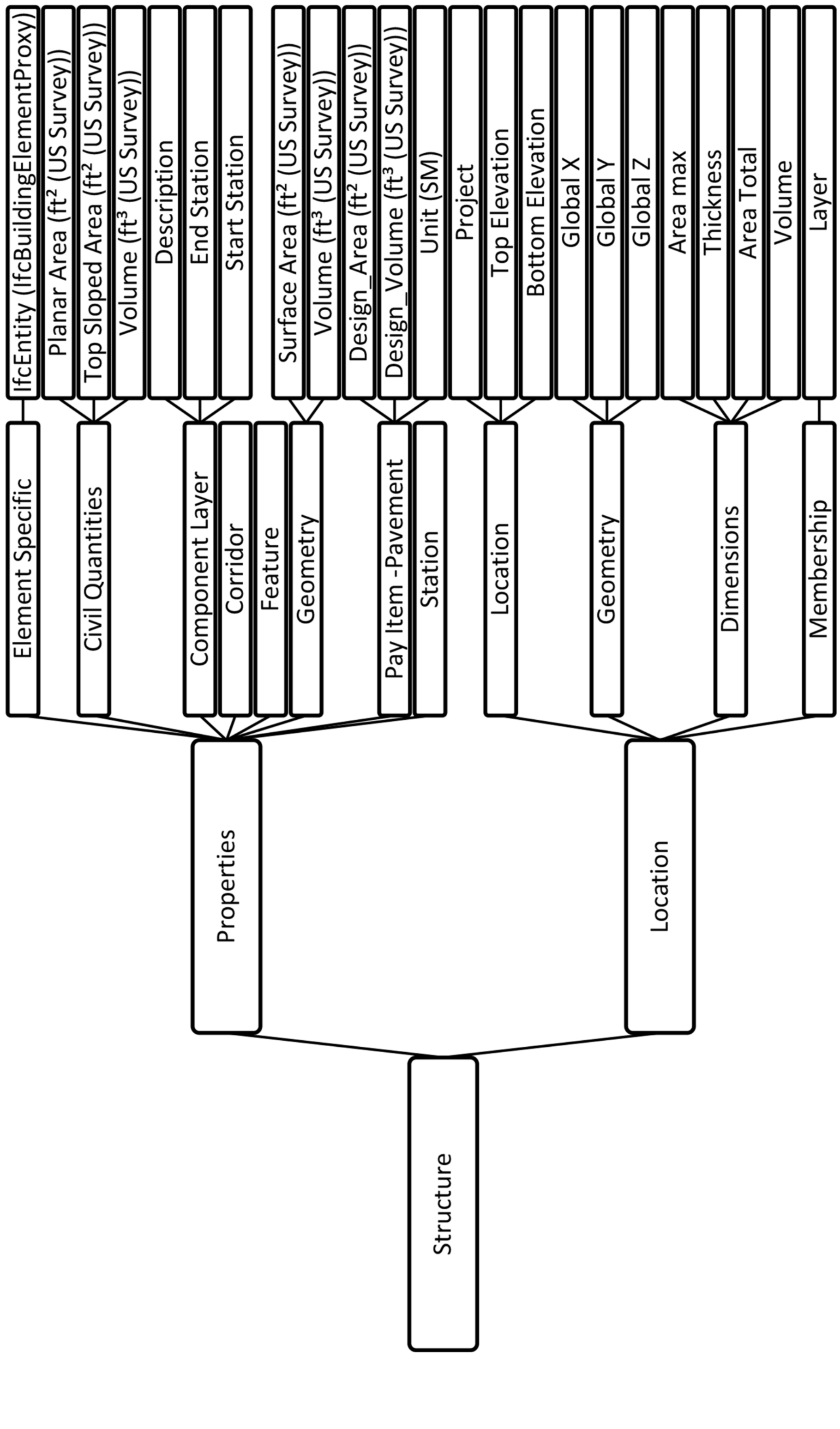


Figure 4.28 Structure of the IFC4 version.

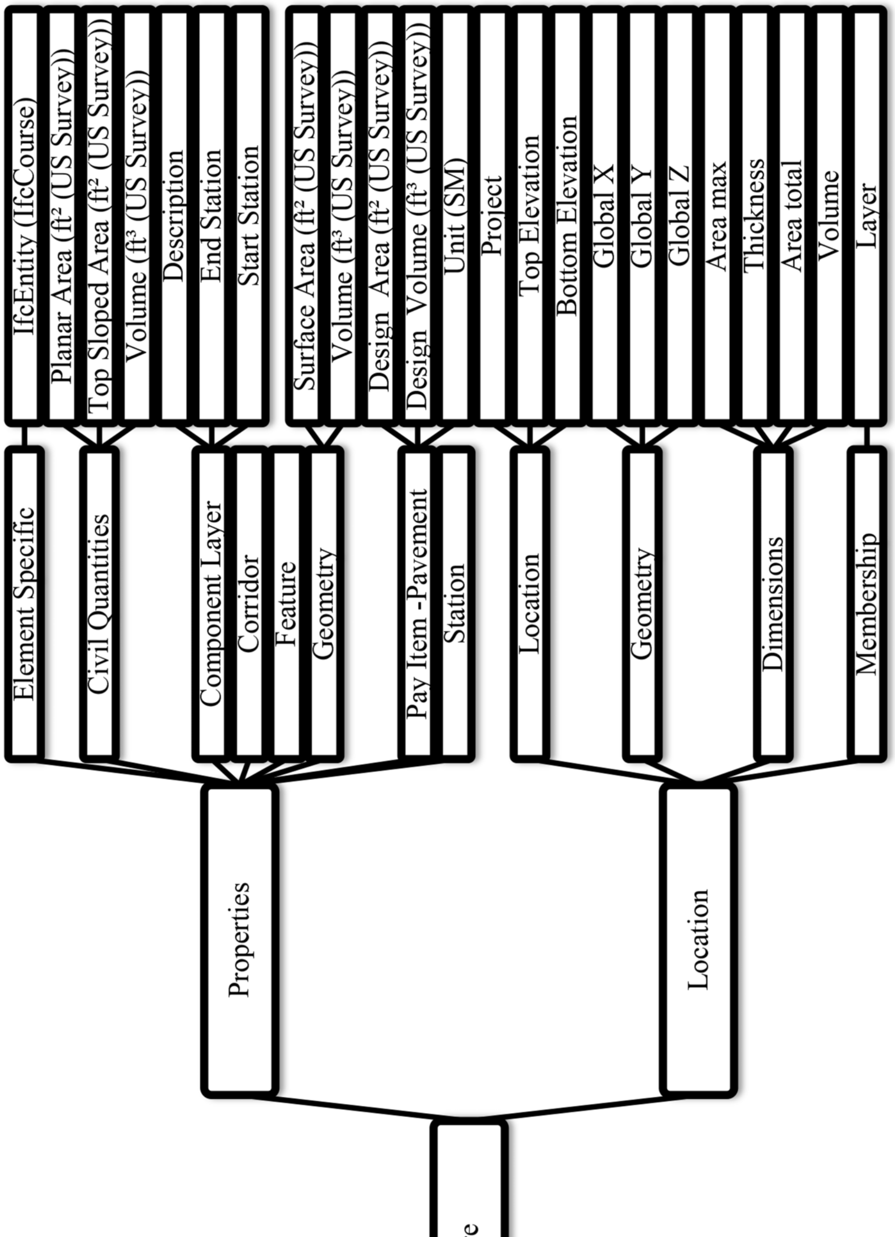


Figure 4.29 Structure of the IFC4 × 3 version.

TABLE 4.3
Example practices of pavement modeling standards from different state DOTs

State/Reference	Design Criteria	Pavement Design Software
UDOT (UDOT, n.d.; UDOT, 2022)		Bentley View CONNECT: 10.16.02.22 MicroStation CONNECT: 10.16.02.34 OpenRoads Designer: 10.10.21.04
Virginia DOT (VDOT, 2018b)	Effective Structural Number (SNeff) Layer Moduli Resilient Modulus of the Subgrade Pavement Material Types ThicknessVisual Condition Elastic Modulus of the PCC Composite Modulus of Subgrade Reaction Load Transfer at Cracks and Joints and Potential for the Presence of Voids	AASHTOWare Pavement ME
California DOT (Caltrans, 2019, 2023)		MicroStation Connect Civil 3D
Delaware DOT (MediaWiki, 2021; DelDOT, 2021; DelDOT, 2019)	Design Speed (mph) Travel Lane–Width (ft) Travel Lane–Cross Slope (%) Inside Shoulder–Width (ft) Inside Shoulder–Cross Slope (%) Outside Shoulder–Width (ft) Outside Shoulder–Cross Slope (%) Auxiliary Lanes–Width (ft) Auxiliary Lanes–Cross Slope (%) Median–Width (ft) Minimum Horizontal Curve Radius (ft) Superelevation Rate (%) Stopping Sight Distance (ft) Maximum Percent Grade (%) Minimum K (Crest) Minimum K (Sag) Maximum Front Slope (Unprotected) Maximum Back Slope Clear Zone Width (ft) Lateral Offset (ft) Barrier Offset (ft) Structural Capacity Bridge Width (ft) Vertical Clearance (ft)	MicroStation Connect OpenRoads Designer OpenBridge Modeler ProStructures
Iowa DOT (Iowa DOT, 2017, 2021)	Design Speed Lane Width Design Loading Structural Capacity Shoulder Width Horizontal Curve Radius Superelevation Rate Maximum Grade Stopping Sight Distance Cross Slope Vertical Clearance	OpenRoads Designer Geopak MicroStation Connect
Oregon DOT (ODOT, n.d.)		InRoads Design OpenRoads Designer
South Dakota DOT (SDDOT, 2023)		InRoads Design MicroStation

Continued

TABLE 4.3
(Continued)

State/Reference	Design Criteria	Pavement Design Software
Connecticut DOT (CTDOT, n.d.)	Number of Lanes Lane Width Shoulder Width Median Width Climbing Lanes Superelevation Traffic Barriers and Guide Railing Cross Slope Pavement Depth Pavement Composition Curbing Side Slopes Sidewalks (Location and Width)	OpenRoads Designer InRoads 8.5 MicroStation
New York State DOT (NYSDOT, 2020; NYSDOT, 2022b)	Design Speed Lane Width Shoulder Width Horizontal Curve Radius Super Elevation Stopping Sight Distance (Horizontal and Vertical) Maximum Grade Cross Slope Vertical Clearance Design Loading Structural Capacity ADA Compliance	MicroStation Connect OpenRoads Designer OpenBridge Modeler OpenBridge Designer ProStructures

TABLE 4.4
Geometric signatures of drainage components (node elements)

Feature	Inlet	Outfall	Grate	Junction
Invert Elevation (ft)	24.5–28	25.75	25.16–28	27.12–27.13
Ground Elevation (ft)	30.2–33.95	29	32–33.8	32.7
Structure Depth (ft)	5–7.85	3.25	7.83–7.84	5.57–5.58
Width	N/A	N/A	3	N/A
Length	N/A	N/A	4.5	N/A
Grate Width	N/A	N/A	3.33	N/A
Grate Length	N/A	N/A	4.33	N/A
Diameter (m)	1.2192	N/A	N/A	0.9144–0.9145
Longitude Slope	+0.12%–0.81%	N/A	N/A	N/A
Match Slope of Conduit	No	No	No	No
Curb Opening Length	13–20	N/A	N/A	N/A

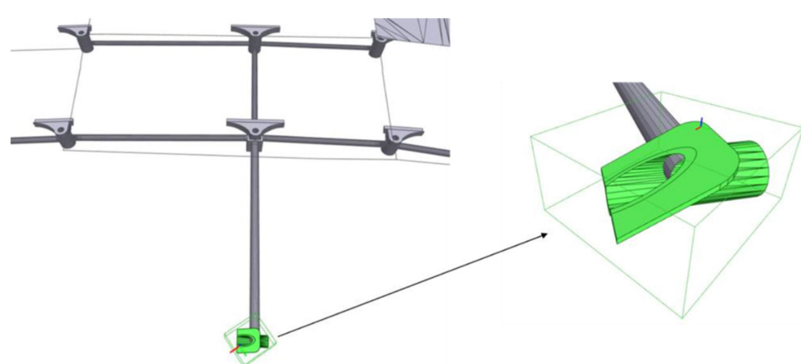


Figure 4.30 Outfall IFC model.

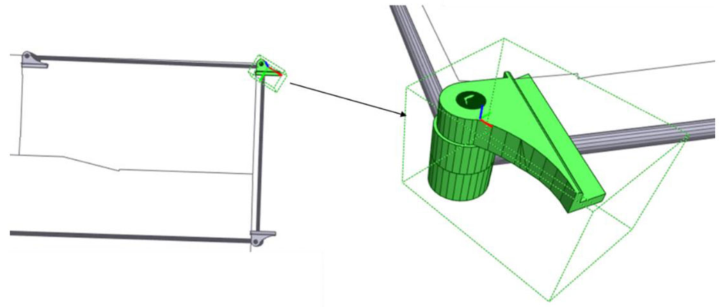


Figure 4.31 Curb inlet IFC model.

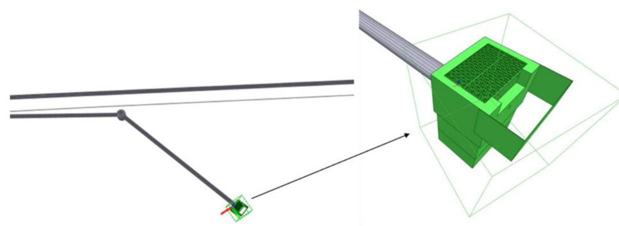


Figure 4.32 Grate IFC model.

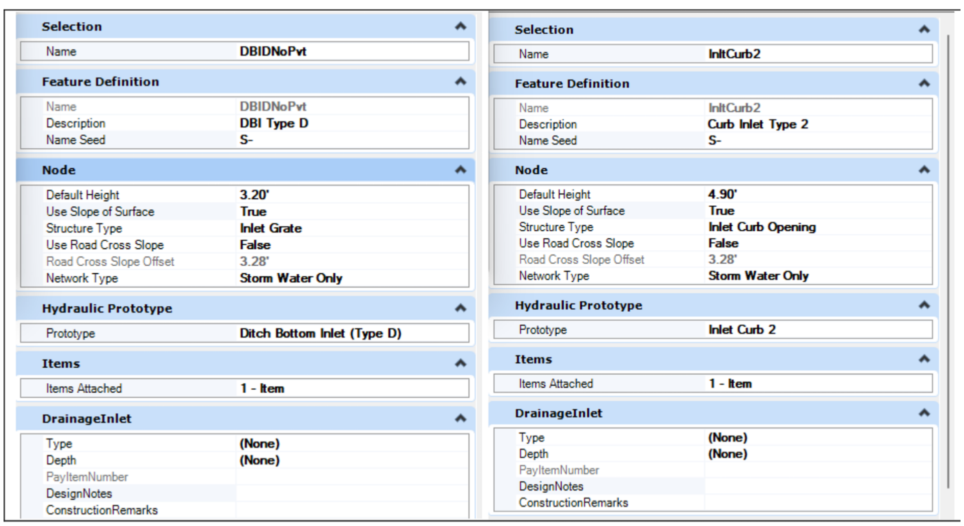


Figure 4.33 Feature definition (left: grate; right: inlet) in Bentley OpenRoads.

Typical geometric signatures of example conduits are shown in Table 4.5. An example conduit in IFC is shown in Figure 4.34.

4.3.1.1 Data collection. The drainage IFC models were collected from HNTB, an American infrastructure design firm. Two IFC models exported from Auto Desk Civil 3D were leveraged to start developing the QA tool. The IFC models were then loaded by IfcOpenShell, an open-source IFC toolkit in Python (IfcOpenShell, 2023). Invariant signatures including frame type, diameter or width, floor thickness, height, inner diameter or width, and inner length were extracted through IfcOpenShell and organized into a table as shown in Figure 4.35. There are 161 drainage elements in total including inlets and manholes with 14 frame types. Figure 4.36 shows the detailed inlet and manhole types extracted from the IFC models.

4.3.1.2 Experiments and results. In the experiment, Machine Learning (ML) models were used to train classifiers to classify the frame type of inlets and manholes as shown in Figure 4.36. The 14 inlet types and manhole types were encoded into numerical labels as shown in Table 4.6.

The 161 drainage elements were randomly divided following the ratio of 80% / 20% for training and testing, respectively. After that, three machine learning algorithms were leveraged to train the classifier, which were logistic regression, decision tree, and random forest, respectively. The trained classifiers were then tested with the testing data. The performance is shown in Table 4.7.

Then, additional invariant signatures were added in the training to improve the classifier performance,

TABLE 4.5
Geometric signatures of example conduits

	Conduit	
Feature	**Pipe**	**Gutter**
Start Node	S-104	S-211
Stop Node	S-105	S-212
Start Invert (ft)	29	27.1
Stop Invert (ft)	28.6	26.9
Shape	Circle	Circle
Slope (calculated/construction)	+0.37% / +0.4%	+0.39% / +0.43%
Length (unified/construction) (ft)	107.73/101.01	51/47
Single Gradient	True	True
Number of Barrels	1	1

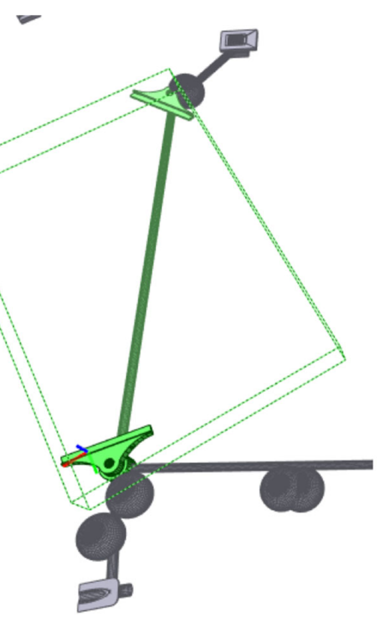


Figure 4.34 Node S-104, S105, and the conduit connecting them.

including pipe lowest bottom depth, pipe upper top depth, rim elevation, and rim to sump height. The improved accuracy is shown in Table 4.8. It can be seen that the classifier trained by the random forest algorithm achieved a promising 91% accuracy.

4.3.1.3 Error analysis. Error analysis on the improved random forest model was performed in this section. Because the training and testing data were randomly divided and the original data were not uniformly distributed, the testing data only contained 7 frame types, which were {3, 4, 5, 6, 9, 10, 13}, as shown in the output of "ground_truth" in Figure 4.37. The predicted results of the trained model were shown in the output of "predicted_results" in Figure 4.37.

A confusion matrix was plotted and utilized to carry out error analysis as shown in Figure 4.38. The resulting confusion matrix is a 7×7 array, where each row "represents the instances in a predicted class, and each column represents the instances in an actual (true) class," (Giommi, 2023) in the order of {3, 4, 5, 6, 9, 10, 13}. The matrix is populated with instance counts, so the value in each cell represents the number of instances that were predicted to belong to the corresponding row class and actually belonging to the corresponding

```
set(Frame)

{'Curb Inlet',
 'Inlet',
 'Inlet Type E-7',
 'Inlet Type E-7, Modified',
 'Inlet Type P-12',
 'Inlet, Type B-15',
 'Inlet, Type C-15',
 'Inlet, Type E-7',
 'Inlet, Type F-7',
 'Manhole Type F-4  Mod.',
 'Manhole, Type C-15',
 'Manhole, Type C-4',
 'Manhole, Type C-7',
 'Manhole, Type J-4',
 'Rectangular Junction Structure NF'}
```

Figure 4.36 Inlet and manhole types.

	Description	ObjectType	Description Detail	Diameter Or Width	FloorThickness	Frame	Height	InnerDiameterOrWidth	InnerLength
0	Manhole	StructJunction	Manhole	4.666667	0.833333	Manhole, Type C-4	0.916667	4.0	0.0
1	Inlet	StructJunction	Inlet	3.500000	0.500000	Inlet, Type B-15	6.590000	2.5	3.5
2	Inlet	StructJunction	Inlet	3.500000	0.500000	Inlet, Type B-15	4.000000	2.5	3.5
3	Inlet	StructJunction	Inlet	3.500000	0.500000	Inlet, Type B-15	4.000000	2.5	3.5
4	Inlet	StructJunction	Inlet	3.500000	0.500000	Inlet, Type B-15	4.000000	2.5	3.5
...	...	...	...	...	...	...	...	...	...
156	Inlet Type P-12	StructJunction	Inlet Type P-12	2.666667	0.500000	Inlet Type P-12	3.500000	2.0	4.0
157	Inlet Type P-12	StructJunction	Inlet Type P-12	2.666667	0.500000	Inlet Type P-12	3.740000	2.0	4.0
158	Inlet Type E-7	StructJunction	Inlet Type E-7	3.666667	0.500000	Inlet Type P-12	3.500000	3.0	3.0
159	Inlet Type P-12	StructJunction	Inlet Type P-12	2.666667	0.500000	Inlet Type E-7	2.166667	2.0	4.0
160	Inlet Type P-12	StructJunction	Inlet Type P-12	2.666667	0.500000	Inlet Type P-12	3.430000	2.0	4.0

161 rows × 9 columns

Figure 4.35 Data collected from drainage IFC models (partial).

column class. The diagonal elements of the confusion matrix represent the number of true positives for each class. Off-diagonal elements represent the number of misclassifications. For example, the confusion matrix shows that for frame type 3 (Inlet Type P-12), there are 14 correctly classified instances (true positives). There are 3 elements wrongly classified in total. The “1” in the 2nd row and 3rd column (as shown in the green box in Figure 4.38) indicates that there is one instance that is frame type 5 (Inlet, Type C-15) but wrongly classified as type 4 (Inlet, Type B-15). A potential cause of this error is that inlet Type C-15 and Type B-15 have very similar values in their invariant signatures. For example, they both have a height of around 4 to 5 inches and an inner diameter of 2.5 inch. That will cause the model more difficulty to learn and distinguish between them due to their high similarity. That issue could be solved by collecting more data. Another potential cause is the noise in the data, which can cause the model inability to learn the underlying patterns accurately because there are random errors or outliers, leading to misclassifications.

The “1” in the 3rd row and 4th column (as shown in the orange box in Figure 4.38) indicates that there is one instance that is frame type 6 (Inlet, Type E-7) but wrongly classified as type 5 (Inlet, Type C-15). In the collected data, the number of instances in type 5 is significantly more than that in type 6. That could cause model underfitting in classifying type 6 because the model is too simple and is unable to capture the underlying patterns from the limited data. This issue could also lead to misclassifications.

TABLE 4.6
Types and labels of conduits

Frame Type	Numerical Label
Curb Inlet	0
Inlet Type E-7	1
Inlet Type E-7, Modified	2
Inlet Type P-12	3
Inlet, Type B-15	4
Inlet, Type C-15	5
Inlet, Type E-7	6
Inlet, Type F-7	7
Manhole Type F-4 Mod	8
Manhole, Type C-15	9
Manhole, Type C-4	10
Manhole, Type C-7	11
Manhole, Type J-4	12
Rectangular Junction Structure NF	13

TABLE 4.7
Trained classifiers and their accuracy

ML Algorithm	Accuracy (%)
Logistic Regression	54
Decision Tree	81
Random Forest	78

TABLE 4.8
Trained classifiers and their accuracy after adding additional invariant signatures

ML Algorithm	Accuracy (%)
Logistic Regression	57
Decision Tree	82
Random Forest	91

```
In [368]: ground_truth
Out[368]: array([ 4, 10,  4,  3,  9,  4,  5,  3,  4, 10,  5,  3,  5, 13,  4,  3,  3,
                  3,  3,  3,  4,  6,  3,  3,  5,  3, 10,  4,  3, 10,  3,  4,  3])

In [369]: predicted_results
Out[369]: array([ 4, 10,  4,  3,  9,  4,  5,  3,  4, 10,  6,  3,  5,  3,  4,  3,  3,
                  3,  3,  3,  5,  6,  3,  3,  5,  3, 10,  4,  3, 10,  3,  4,  3])
```

Figure 4.37 Ground truth labels and the predicted labels.

```
In [174]: print(confusion_matrix(y_test, y_pred))
          [[14  0  0  0  0  0  0]
           [ 0  7  1  0  0  0  0]
           [ 0  0  3  1  0  0  0]
           [ 0  0  0  1  0  0  0]
           [ 0  0  0  0  1  0  0]
           [ 0  0  0  0  0  4  0]
           [ 1  0  0  0  0  0  0]]
```

Figure 4.38 Confusion matrix.

The “1” in the 7th row and 1st column (as shown in the purple box in Figure 4.38) indicates that there is one instance that is of frame type 3 (Inlet Type P-12) but wrongly classified as type 13 (Rectangular Junction Structure NF). One of the potential cause of this error is the imbalanced data. The most common inlet types are Type B-15, C-15, and P-12. There is only one instance of type 13 (Rectangular Junction Structure NF) in the collected data. If the data is imbalanced, meaning that the model will not learn enough information about the minority class, which may lead to misclassification.

To summarize, the errors were mainly due to noise and imbalance in the data. The performance can be improved with more training data that is better balanced.

4.3.2 Concrete Pavement

For concrete pavement, four invariant signature features were extracted from the two IFC pavement models, which are volume, surface area, planar area, and top slope area, respectively, as shown in Table 4.9. There are four pavement layer types as shown in Table 4.10. To distinguish the layer types, machine learning models (logistic regression and random forest) were used to train a classifier based on the 4 invariant signatures, which achieved 100% accuracy. An example IFC pavement model is shown in Figure 4.39.

TABLE 4.9
Data collected from pavement IFC models

Layers	Volume (ft^3)	Surface Area (ft^2)	Planar Area (ft^2)	Top Slope Area (ft^2)
Aggregate Type A Base Course	139	2,858	1,301	1,302
Aggregate Type B Base Course	199	2,979	1,307	1,308
Aggregate Type A Base Course	139	2,863	1,304	1,304
Aggregate Type B Base Course	665	9,096	4,365	4,366
Aggregate Type B Base Course	200	2,985	1,310	1,310
Aggregate Type B Base Course	665	9,088	4,361	4,362
Concrete Pavement	1330	17,820	8,725	8,727
Curb	137	2,200	758	913
Curb	137	2,196	757	912
Aggregate Type A Base Course	931	17,711	8,725	8,727
Aggregate Type B Base Course	665	9,088	4,361	4,362
Aggregate Type B Base Course	498	6,905	3,268	3,271
Aggregate Type B Base Course	665	9,096	4,365	4,366
Concrete Pavement	443	6,179	2,905	2,907
Aggregate Type B Base Course	499	6,922	3,276	3,279
Concrete Pavement	444	6,193	2,912	2,914
Aggregate Type A Base Course	349	6,812	3,276	3,279
Concrete Pavement	1330	17,820	8,725	8,727
Aggregate Type A Base Course	349	6,796	3,268	3,271
Aggregate Type A Base Course	931	17,711	8,725	8,727

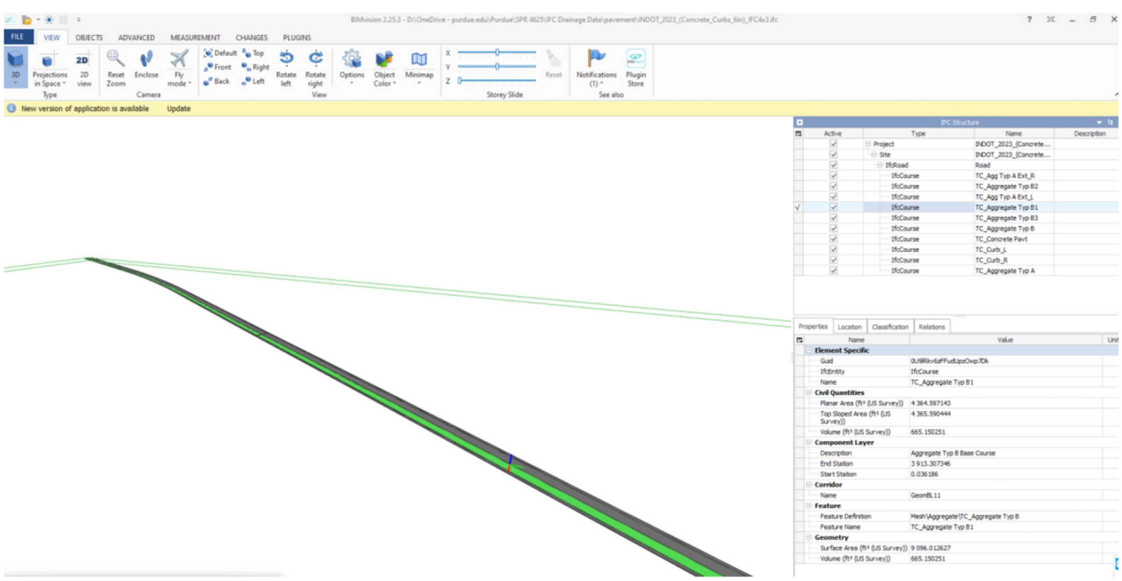


Figure 4.39 An example pavement model (partial).

TABLE 4.10
Pavement component types

Component Type	Numerical Label
Aggregate Type A Base Course	0
Aggregate Type B Base Course	1
Concrete Pavement	2
Curb	3

5. SUMMARY AND RECOMMENDATIONS

5.1 Summary and Findings

In this study, drainage and concrete pavement modeling standards from different state DOTs were reviewed and compared. It was found the most frequently referenced software for drainage and concrete pavement modeling is InRoads and GEOPAK. However, Bentley OpenRoads Designer was selected for investigation in this study because they incorporate the capabilities of InRoads and GEOPAK. Investigation on interoperability of OpenRoads Designer and Civil 3D, respectively, with IFC was conducted. It was found both tools could transform drainage and concrete pavement models to IFC following certain paths. All the drainage and concrete pavement components and their properties could be converted without error.

Even though OpenRoads Designer and Civil 3D could transform drainage models to IFC successfully with different approaches, the transformed IFC heavily used *IfcBuildingElementProxy*, at the time of test. To better distinguish drainage and concrete pavement components for asset management or QA purposes, a new IFC modeling standard for drainage needs to be established. The standard should include all types of drainage and concrete pavement components. For example, curb inlet, outfall, and conduit may need to be represented by designated entities such as *IfcCurbInlet*, *IfcOutFall*, and *IfcConduit*, respectively.

To facilitate the development of the above-mentioned standard, in this project, we initially drafted a *Model Development Instruction Manual for Drainage Inlet* (Figure 5.1 and Appendix A) and a *Model Development Instruction Manual for Concrete Pavement* (Figure 5.2 and Appendix B).

Until the above-mentioned standard is well established and enforced, during the transition period, automated classification algorithms can be used to help with QA. Such algorithms can take the properties or features of the component as input and output the type of the drainage and concrete pavement component. Related foundational research can be found in (Wu & Zhang, 2019), where invariant signatures were used to develop an algorithm for AEC object classification. Their classification algorithm achieved 100% precision and recall in correctly classifying 1,891 AEC objects using the geometrical invariant signatures (Wu & Zhang, 2019). In our initial development and experiment in this SPR-4625 project, invariant signatures-based automated object classification algorithms have achieved 91% accuracy in classifying drainage components and 100% accuracy in classifying concrete pavement components. Error analysis revealed that improvement towards 100% accuracy require more training data that is balanced.

The IFC-based drainage model can facilitate INDOT's advancement/transition toward BIM-based practice and support better asset management of drainage and concrete pavement design in at least the following three dimensions. (1) Interoperability: IFC standards facilitate interoperability between different software applications used for designing drainage and concrete pavement models. Data can be easily shared between software applications, reducing errors and rework (Li & Zhang, 2023). (2) Collaboration: IFC standards promote collaboration between different stakeholders involved in the design, construction, and maintenance of drainage and concrete pavement models. This means that different stakeholders can work together more effectively to create better designs and manage assets more collaboratively (Li et al., 2022). (3) Data management: IFC standards provide a structured way of managing comprehensive data related to drainage and concrete pavement models. This means that data can be more easily stored, retrieved, and updated in a consistent and timely manner (Li et al., 2022).

5.2 Recommendations and Implementation

- In this project, model development instruction manuals for drainage and concrete pavement were initially drafted. These documents can be pilot tested with INDOT design office, contractors, and consultants to evaluate their easiness of use and level of detail incorporated. Built upon feedback from pilot testing, these manuals can be refined and expanded towards more types of infrastructure components.
- For immediate QA needs during the transition period, the invariant signature-based QA tool developed in this project can be used, because it overcame the challenge

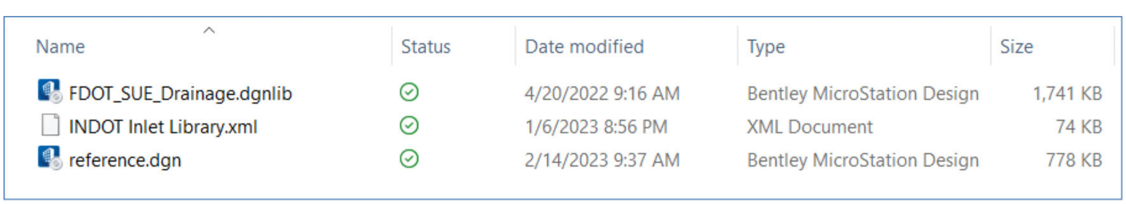
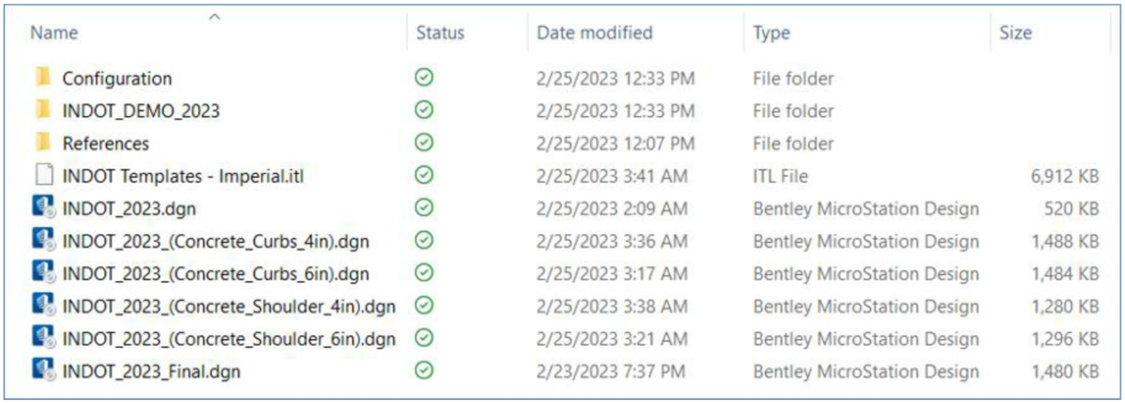


Figure 5.1 Companion documents to the *INDOT Model Development Instruction Manual for Drainage Inlet* (Draft).



Name	Status	Date modified	Type	Size
Configuration	✓	2/25/2023 12:33 PM	File folder	
INDOT_DEMO_2023	✓	2/25/2023 12:33 PM	File folder	
References	✓	2/25/2023 12:07 PM	File folder	
INDOT Templates - Imperial.itl	✓	2/25/2023 3:41 AM	ITL File	6,912 KB
INDOT_2023.dgn	✓	2/25/2023 2:09 AM	Bentley MicroStation Design	520 KB
INDOT_2023_(Concrete_Curbs_4in).dgn	✓	2/25/2023 3:36 AM	Bentley MicroStation Design	1,488 KB
INDOT_2023_(Concrete_Curbs_6in).dgn	✓	2/25/2023 3:17 AM	Bentley MicroStation Design	1,484 KB
INDOT_2023_(Concrete_Shoulder_4in).dgn	✓	2/25/2023 3:38 AM	Bentley MicroStation Design	1,280 KB
INDOT_2023_(Concrete_Shoulder_6in).dgn	✓	2/25/2023 3:21 AM	Bentley MicroStation Design	1,296 KB
INDOT_2023_Final.dgn	✓	2/23/2023 7:37 PM	Bentley MicroStation Design	1,480 KB

Figure 5.2 Companion documents to the *INDOT Model Development Instruction Manual for Concrete Pavement* (Draft).

caused by the use of non-distinguishing IFC entities (e.g., *IfcBuildingElementProxy*). This QA tool was initially tested by INDOT Management Information Systems (MIS) successfully. For the long term, the IFC-based model development standards will be able to and should include more distinguishing IFC entities as they gradually become available from exports of various BIM authoring tools.

- With maturing model development standards as described above, seamless interoperability with IFC model will become closer to reality. It is expected that the IFC-based drainage and concrete pavement models can better support the integration of BIM for infrastructure projects, helping improve asset management and QA processes at the state DOT level in terms of efficiency and accuracy.

5.3 Expected Benefits and Cost Savings

With the above research findings, the following benefits can be achieved.

The adoption of the model development instruction manuals can help INDOT design office and consultants save time and cost in the design process, as the standard prototype components can be reused through drag-and-drop.

The adoption of the QA tool can help INDOT manage the quality of model submissions in a more efficient way, reducing the need of manual checking and therefore reducing the staff labor as well as the turnaround time for such checking.

The above deliverables will facilitate the adoption of BIM technology in roads and related transportation assets at INDOT, where it saves time, cost, improve productivity, helps decision makers with easy-to-access project data and information throughout the life cycle of an infrastructure project. The researchers and practitioners interested in BIM for roads and related transportation assets could also use the outcomes of this study to inform further research and development.

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APPENDICES

Appendix A. Indiana Department of Transportation (INDOT) Model Development Instruction Manual for Drainage Inlet (Draft)

Appendix B. Indiana Department of Transportation (INDOT) Model Development Instruction Manual for Concrete Pavement (Draft)

APPENDIX A. INDIANA DEPARTMENT OF TRANSPORTATION (INDOT) MODEL DEVELOPMENT INSTRUCTION MANUAL FOR DRAINAGE INLET (DRAFT)

The deliverables for drainage information may include plan and profile drawing sheets, CAD reference files, GIS databases, 3D drainage models and associated drainage modeling reports (ASCE, 2022). In this document, drainage model (inlets) in OpenRoads is explored.

A Subsurface Utility Engineering (SUE) deliverable "contains contiguous utility segments at any utility quality level, in any combination, depending on the scope of work of the utility investigation and the achieved utility quality levels. Utility quality levels may be developed and delivered in any order, or contemporaneously, as the project progresses through project delivery" (ASCE, 2022). The dgnlib file in OpenRoads is one example of the SUE file.

A.1 Definitions in OpenRoads

WorkSpace

"A WorkSpace is a set of standards (e.g., Metric, Imperial, UK, ANZ, India Roads). These standards contain different Level naming, Road templates, superelevation calculations etc. When you select the WorkSpace, you are selecting the standards you want to use in a project or job" (Marnell, 2019). Therefore, the workspace of a specific DOT contains resources, standards, and tools necessary for designing projects in accordance with the Standards to that DOT (CODOT, 2023).

Catalog, prototype, and feature definition

"In OpenRoads, Catalogs are an efficient way to reuse common physical definitions for inlets, conduits, and gutters. Catalog items can be imported from and exported to engineering libraries. Catalogs are loaded by Prototypes, which are loaded by feature definitions" (FDOT, 2021b).

A.2 OpenRoads File Types

1. DGN Library (*dgnlib)

"The feature definitions, symbology, and hydraulic seed data for drainage design and modeling are stored in DGN libraries. The DGN Library is utilized for numerous projects, as it contains the standards for an entire organization. The DGN Library contains the storm data, hydraulic settings, standard inlet types, standard pipes configurations, spread sections, and land cover tables. These items are used by each project to accommodate standardization and information sharing among projects. The Department provides a DGN Library with the CADD deliverables" (FDOT, 2021b).

2. MicroStation Design File (*dgn)

"This file is utilized for the visualization of the drainage project and definition of certain drainage features using MicroStation graphic elements. When the designer initiates the drainage & utilities tools, the DGN Library hydraulic seed data will be referenced by the design file. Subsequently, as drainage components are placed, the DGN model automatically populates hydraulic properties from the DGN Library and drainage structure geometry from the Cell Library into the design file. All the design data is stored within the design dgn file and database attributes are attached to the

2D graphics. As the designer places components in the 2D model, drainage & utilities creates the 3D model elements in the dgn simultaneously" (FDOT, 2021b).

A.3 Set OpenRoads Library

1. Create New WorkSpace
2. Create New WorkSet
3. Create New .dng file
4. Go to File -> Settings -> Configuration -> Configuration Variables

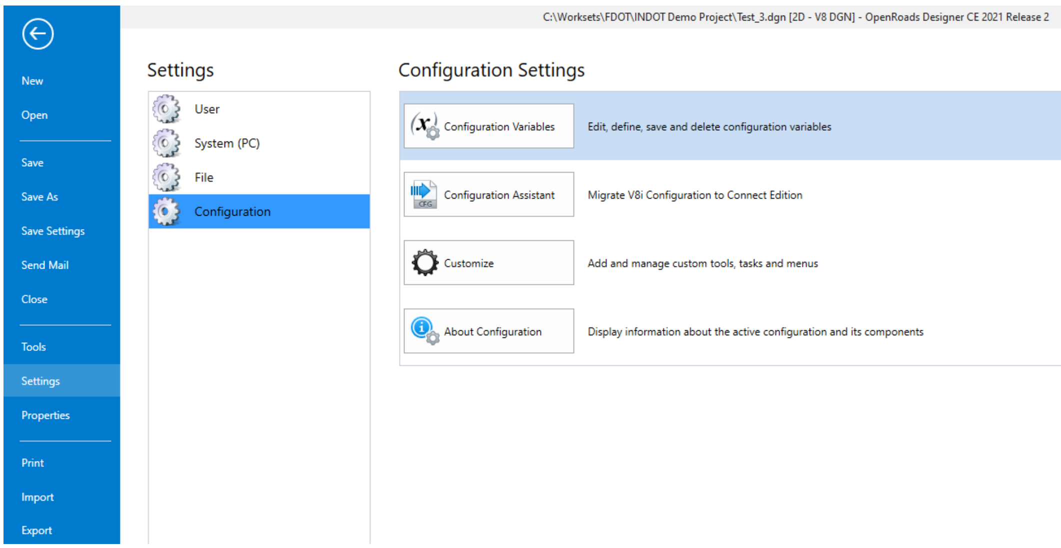


Figure A.1 Interface of setting configuration variables.

5. Create new variable named "SUDA_SEED_FILE" and set the new value (path) as the path of the "*INDOT_SUE_Drainage.dgnlib*" file.

Or

"$(CIVIL_ORGANIZATION_STANDARDS)Dgnlib\Feature Definitions\FDOT_SUE_Drainage.dgnlib."

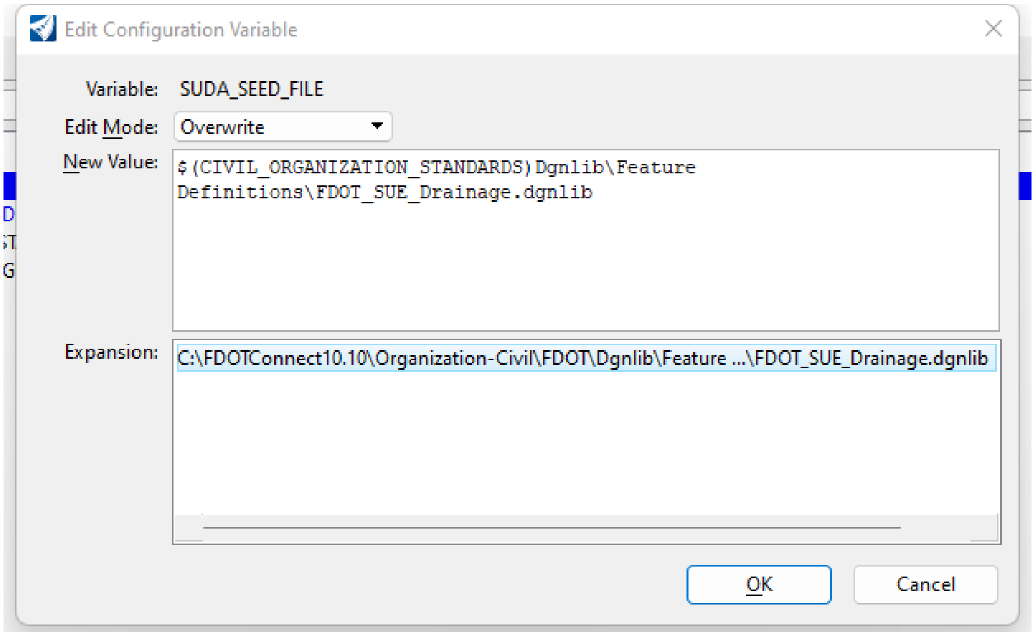


Figure A.2 Set SUDA_SEED_FILE.

6. Create new variable named "SUDA_SEED_MODEL" and set the new value (path) as "Default."

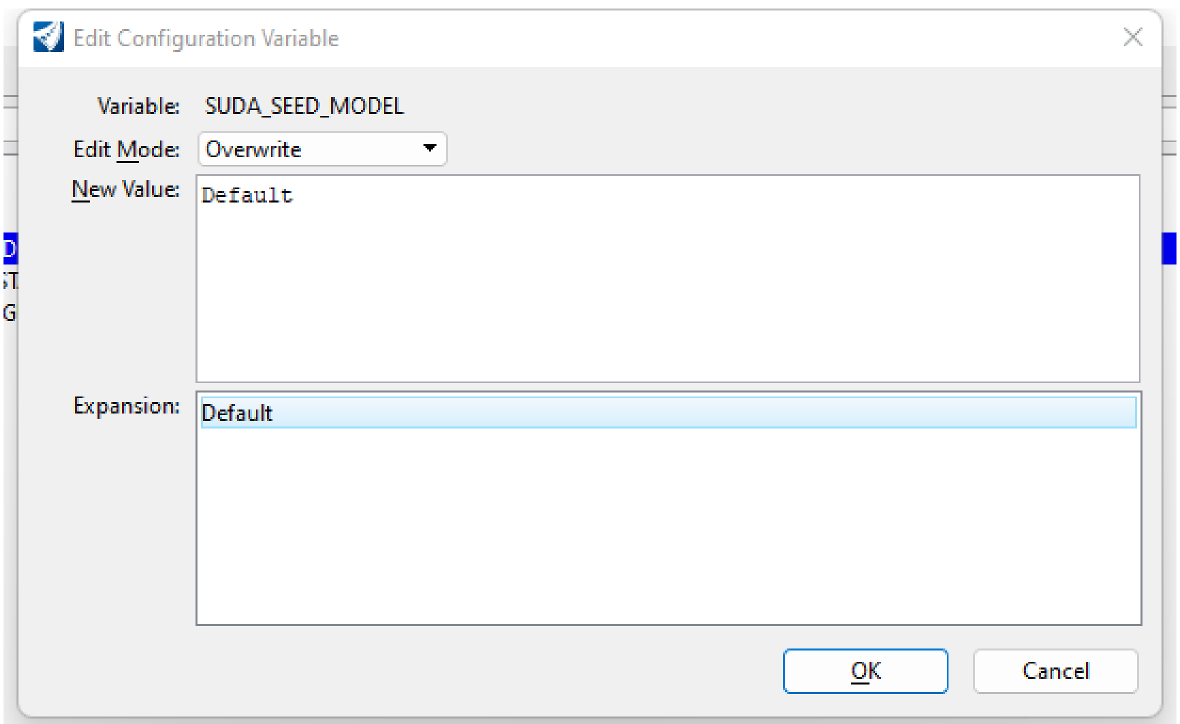


Figure A.3 Set SUDA_SEED_MODEL.

7. Click "OK."

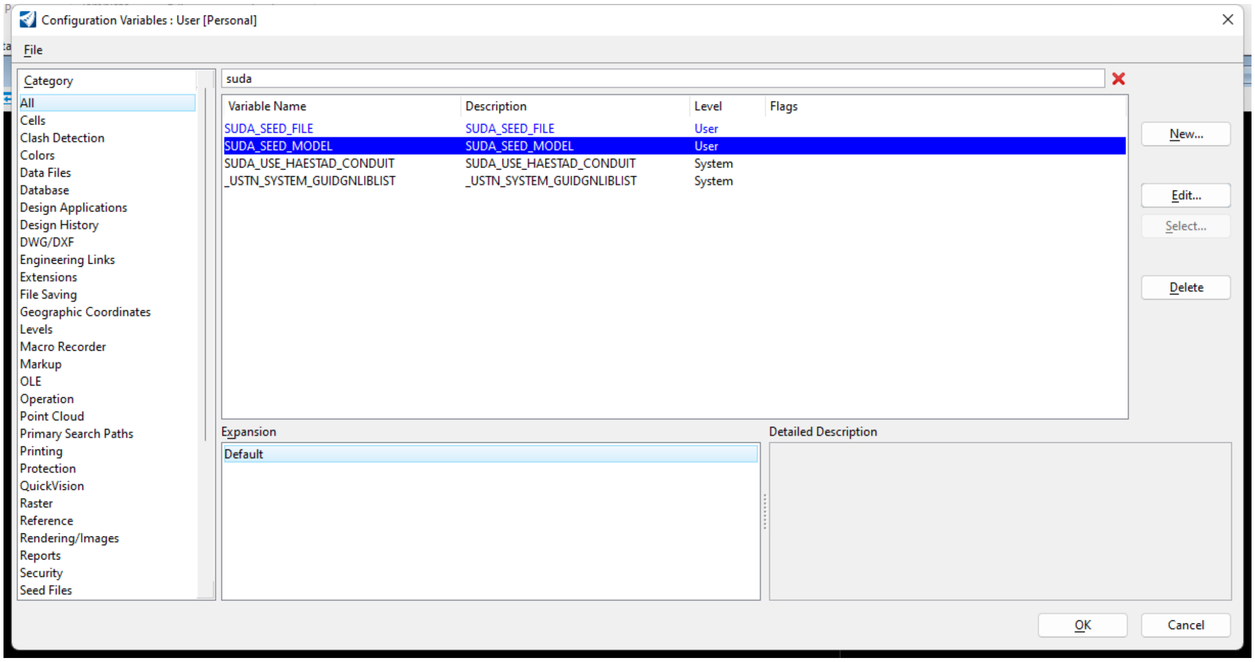


Figure A.4 Interface of configuration variables.

8. Go to Drainage and Utility -> Components -> Catalog. Now you should be able to access all the drainage catalog in the library.

A.4 Import XML Library

1. Go to Inlet Catalog -> Synchronization Option -> Import from Library.

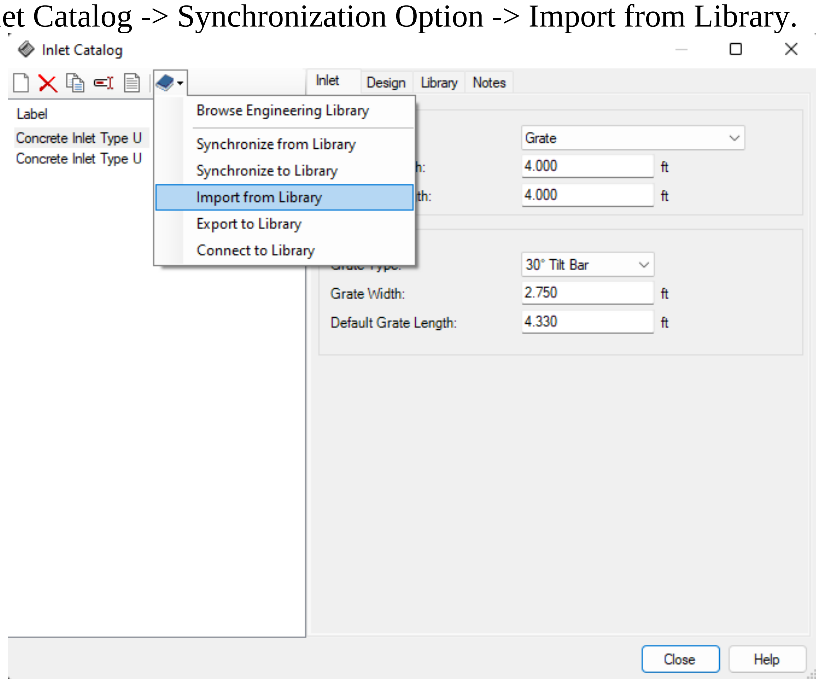


Figure A.5 Interface of importing xml library.

2. Add existing Library, select the “INDOT Inlet Library.xml” file.

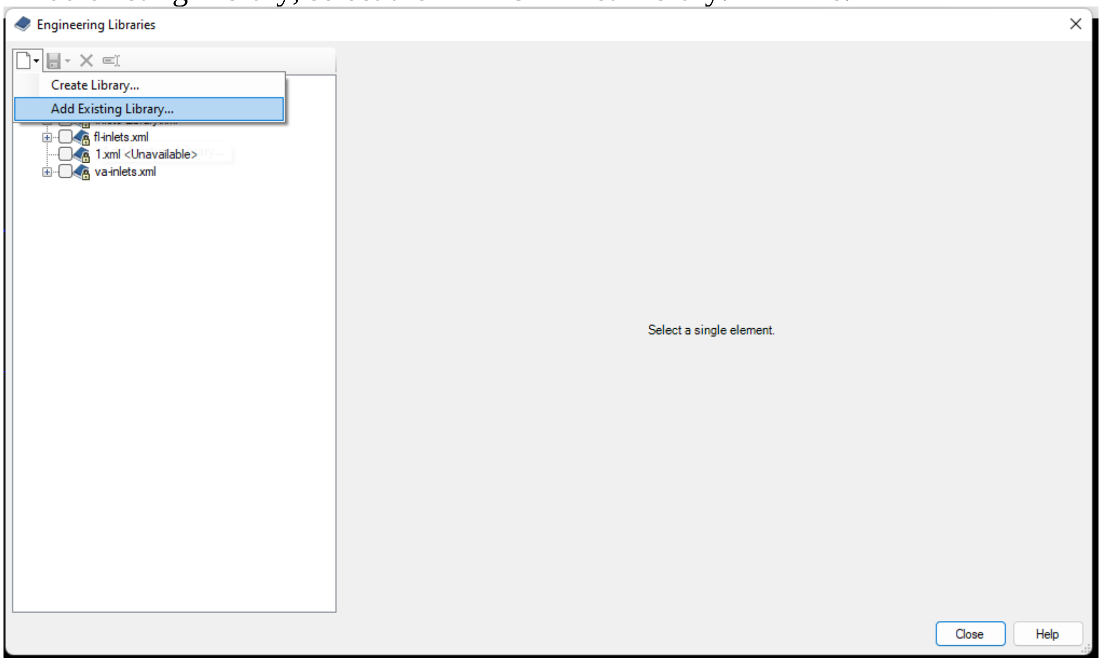


Figure A.6 Interface of engineering library.

3. Import the inlet catalog (concrete inlet type U and W) from the library.

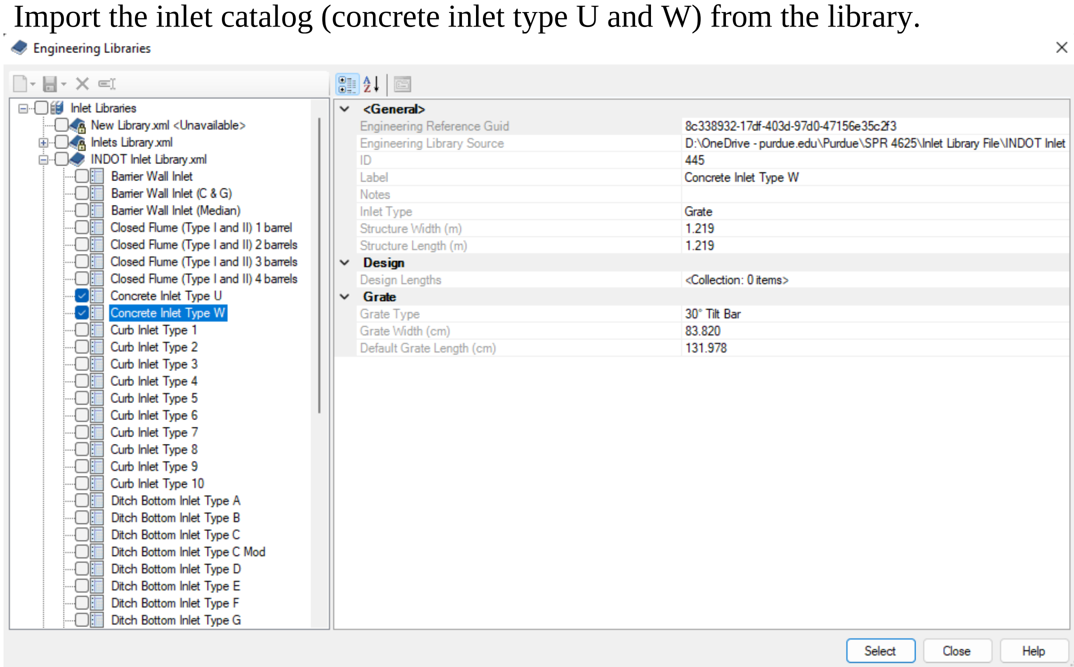


Figure A.7 Interface of importing INDOT standard drainage inlet models.

A.5 Three Steps of Creating/Importing a New Inlet

1. Create inlet catalog.
2. Create inlet prototype, link to the inlet catalog.
3. Create feature definition, link to the inlet prototype.
4. Create a new inlet model using the newly created feature definition.

Step 1. Create inlet catalog.

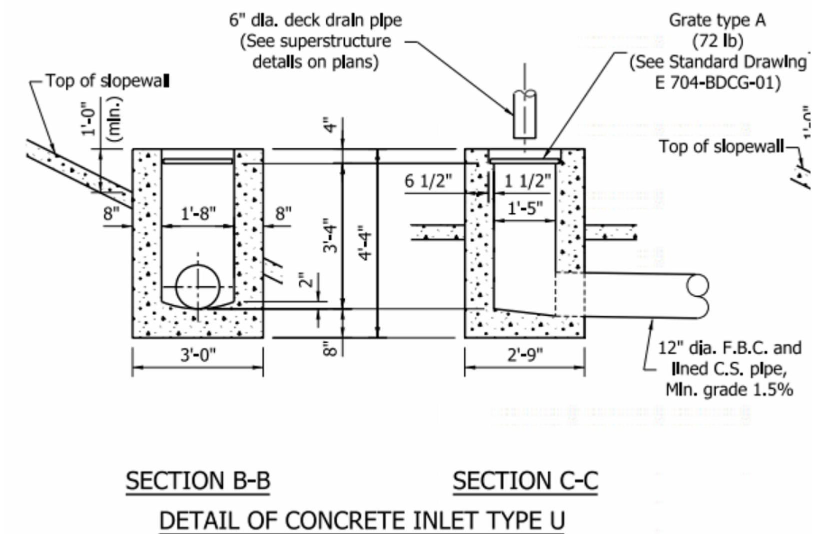


Figure A.8 Detailed drawing of concrete inlet type U from INDOT standard (INDOT, 2022b).

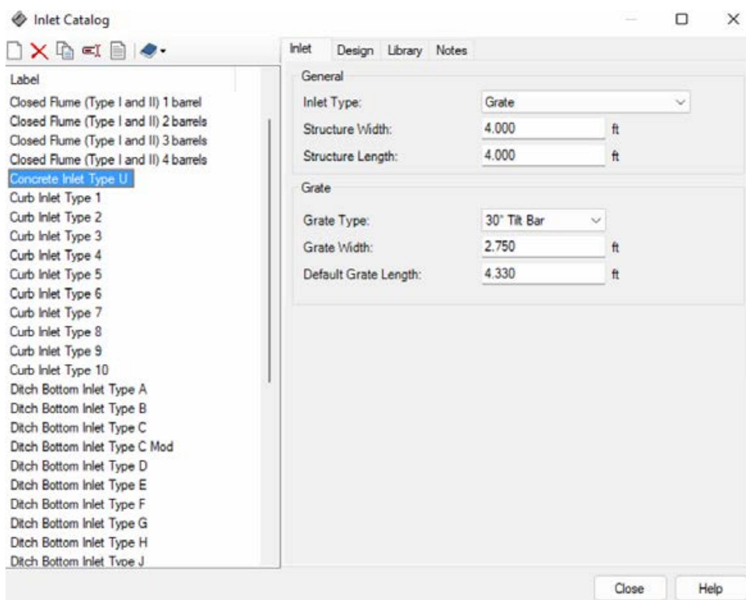


Figure A.9 Created inlet catalog of concrete inlet type U.

Step 2. Create inlet prototype.

1. Go to Component -> Catalog -> Prototypes.

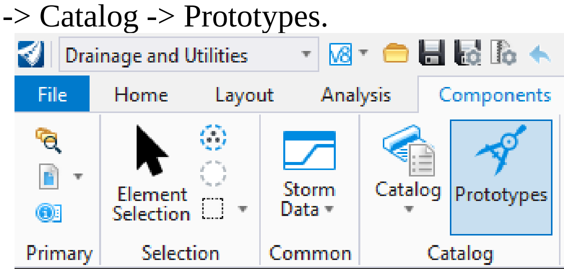


Figure A.10 Interface of creating prototypes.

2. Under "Catch Basin", click "new" to create a new prototype.

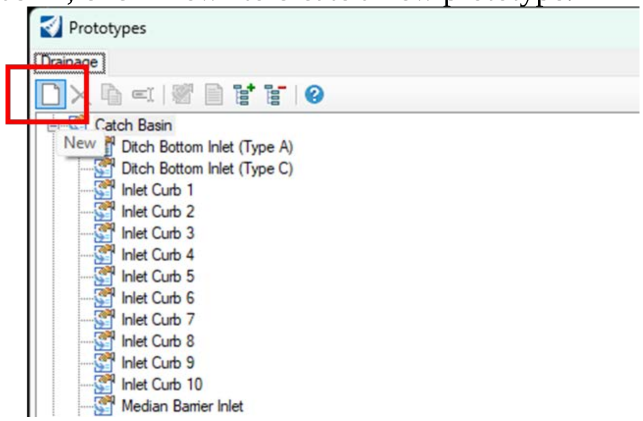


Figure A.11 Create a new inlet prototype under the catch basin category.

3. Rename the newly created prototype to the desired name ("Concrete Inlet Type U" as shown in Figure A.12 as an example). Then double-click it to modify it. Under "Inlet", select "Inlet Type" as "Catalog Inlet" and "Inlet" as "Concrete Inlet Type U" (the one imported from dgnlib). Then, the prototype is created.

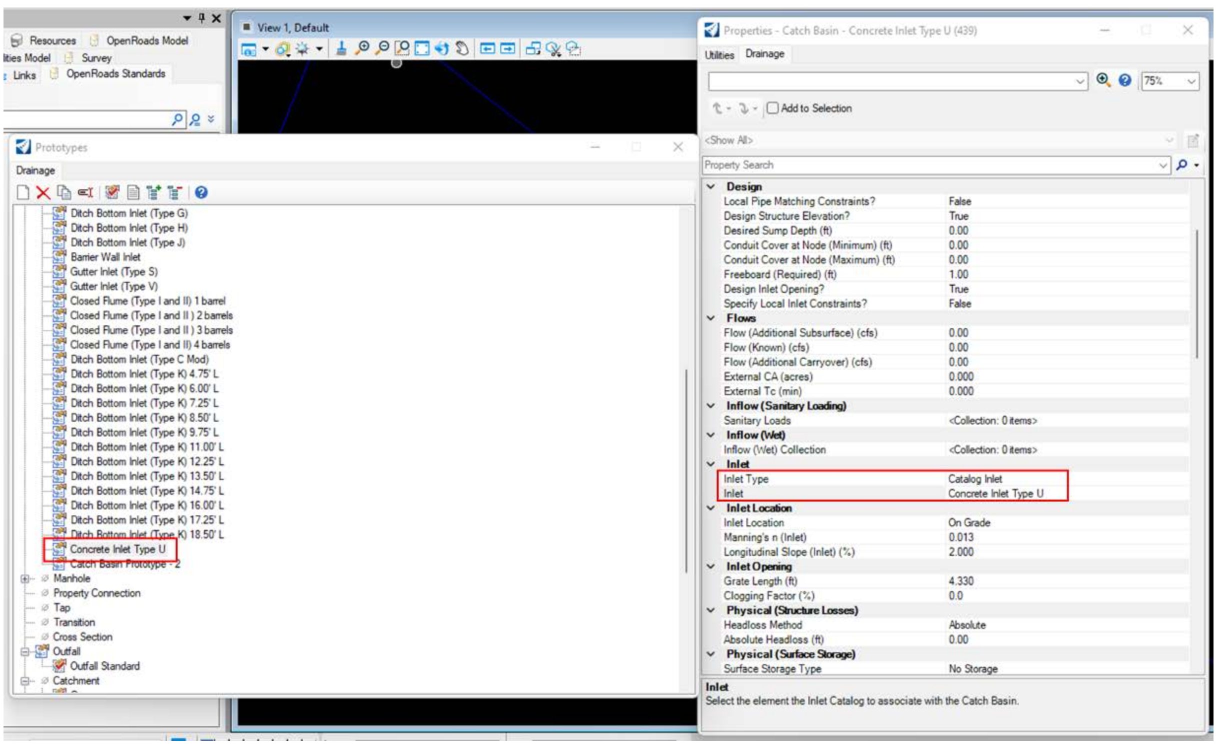


Figure A.12 Interface of creating the prototype of concrete inlet type U.

Step 3. Create feature definition.

1. Click Home -> Explorer -> OpenRoads Standards -> Feature Definitions -> Node -> StormWaterNode. Right-click it and select "New Feature Definition" to create a new feature definition under the subfolder. The detailed steps are illustrated in Figure A.13.

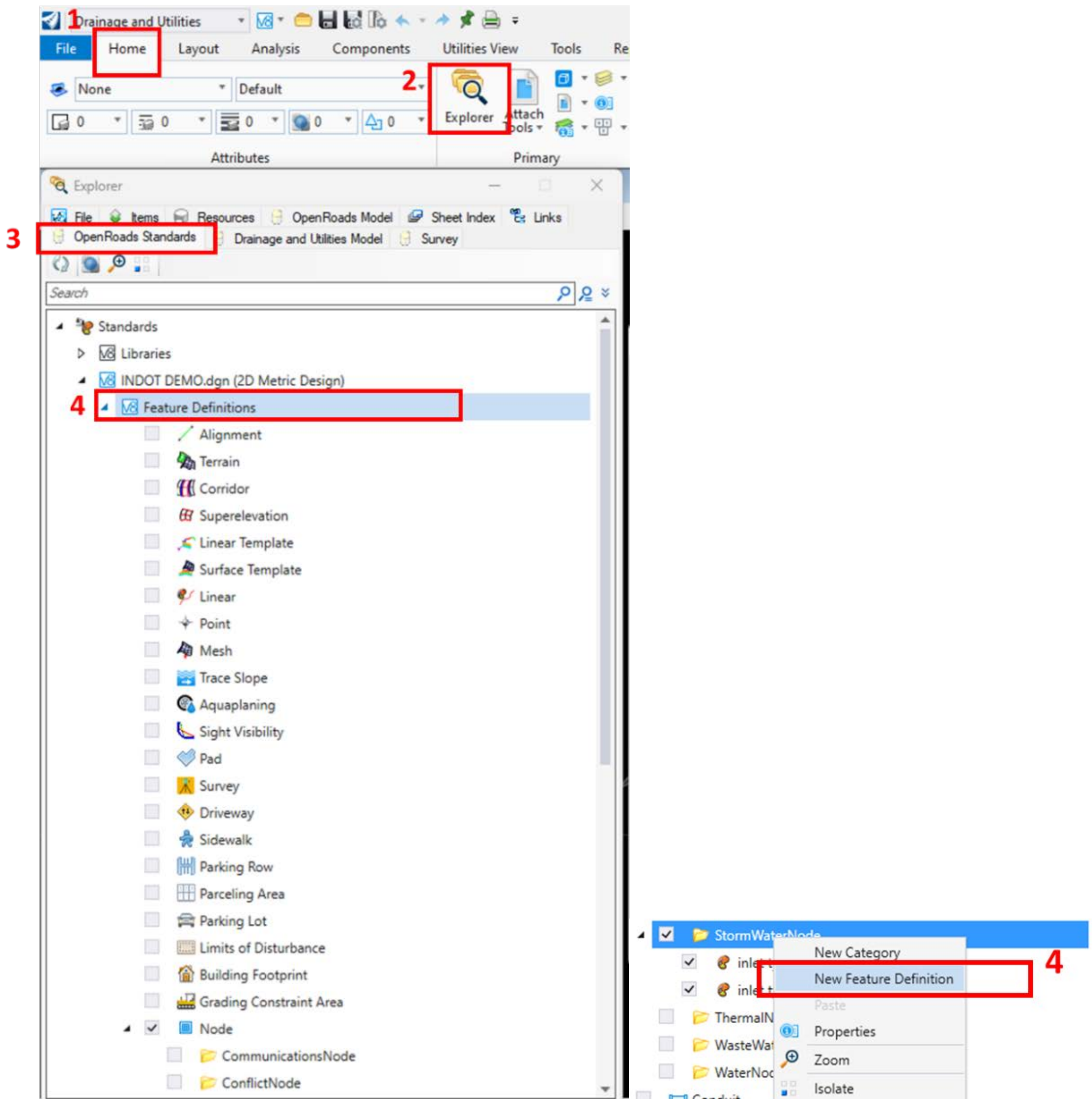


Figure A.13 Detailed step for creating a new feature definition for the stormwater node (inlet).

2. Right-click the newly created feature definition, select “edit feature definition”, then select “Concrete Inlet Type U” as its prototype as shown in Figure A.14. The new feature definition is then completed.

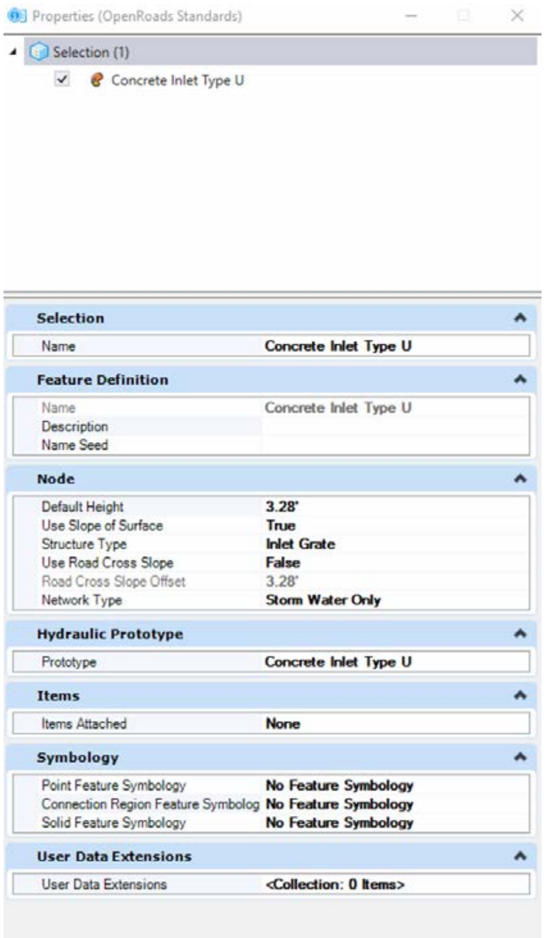


Figure A.14 Interface of creating the new feature definition for concrete inlet type U.

Step 4. Create a new inlet model using the newly created feature definition.
Firstly, we need to import reference terrain data. Go to Home -> Attach Tools -> References -> Tools -> Attach and select “reference.dgn”. Then click “OK”.

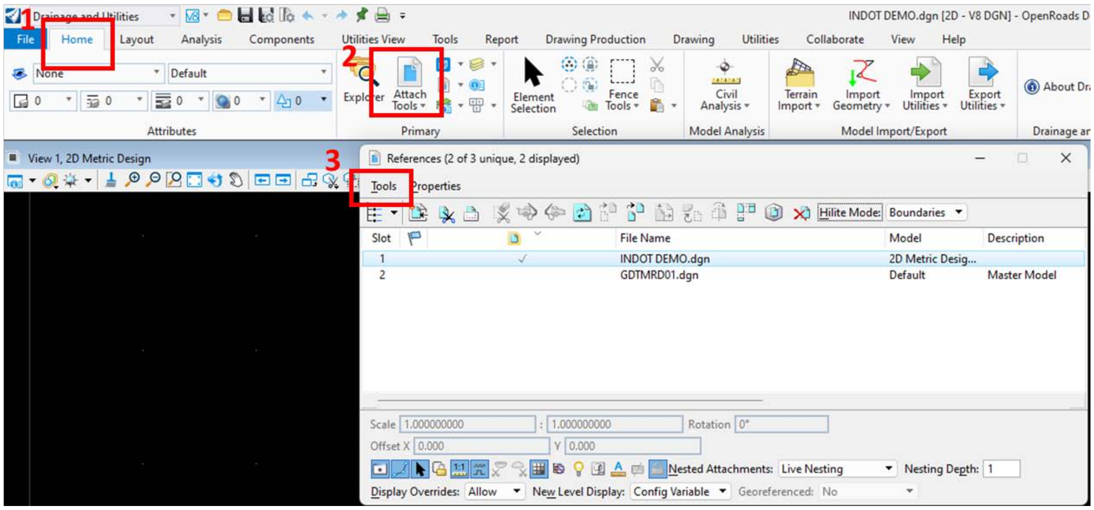


Figure A.15 Steps to import reference data.

Then, if you click on the “Fit View” button as shown in Figure A.16. You can see the reference terrain data as shown in Figure A.17.

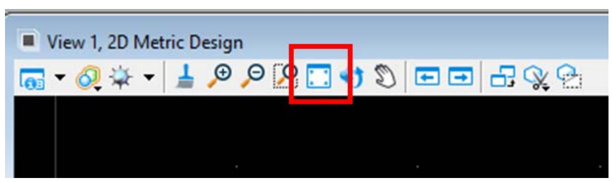


Figure A.16 Fit view button.

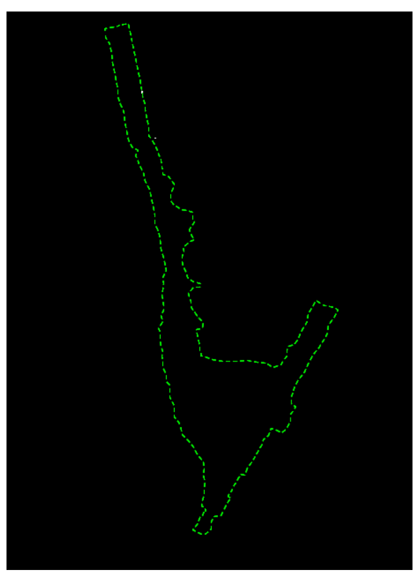


Figure A.17 Overview of reference background data.

Then, we can place the inlet model. Go to Layout -> Place Node, click on it. In the popped-out window, select “inlet type U” as the feature definition, as shown in Figure A.18. Then you can place a new inlet model on the terrain.

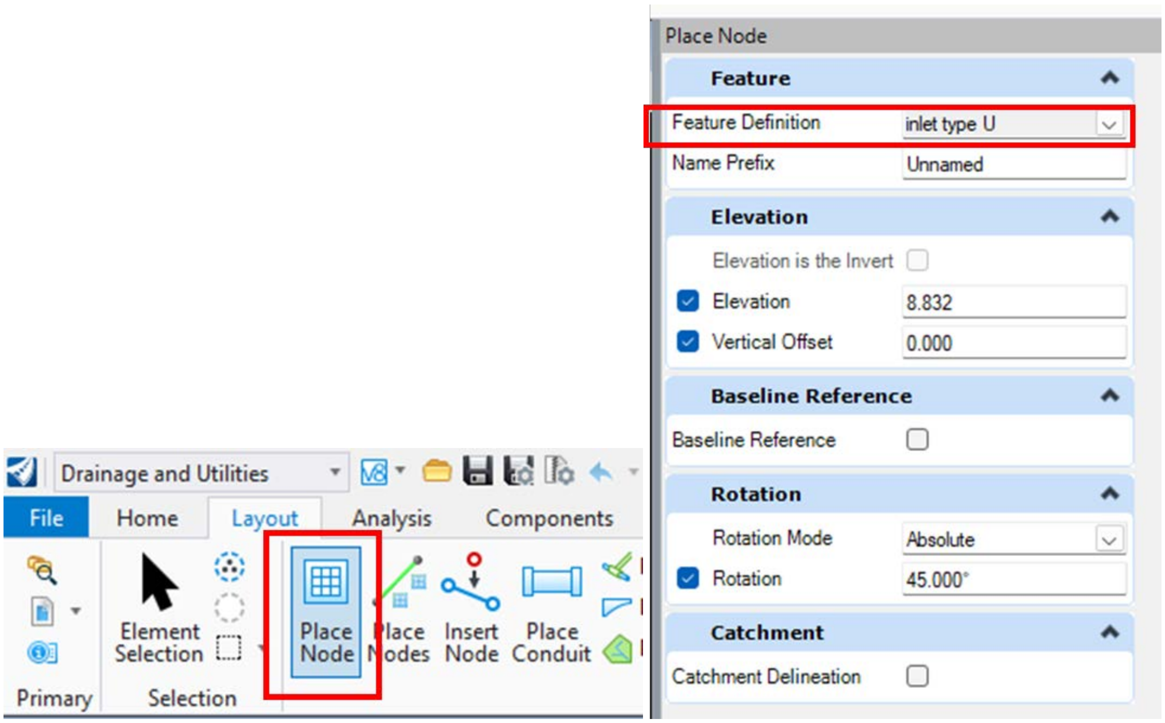


Figure A.18 Interface of creating a new inlet model.

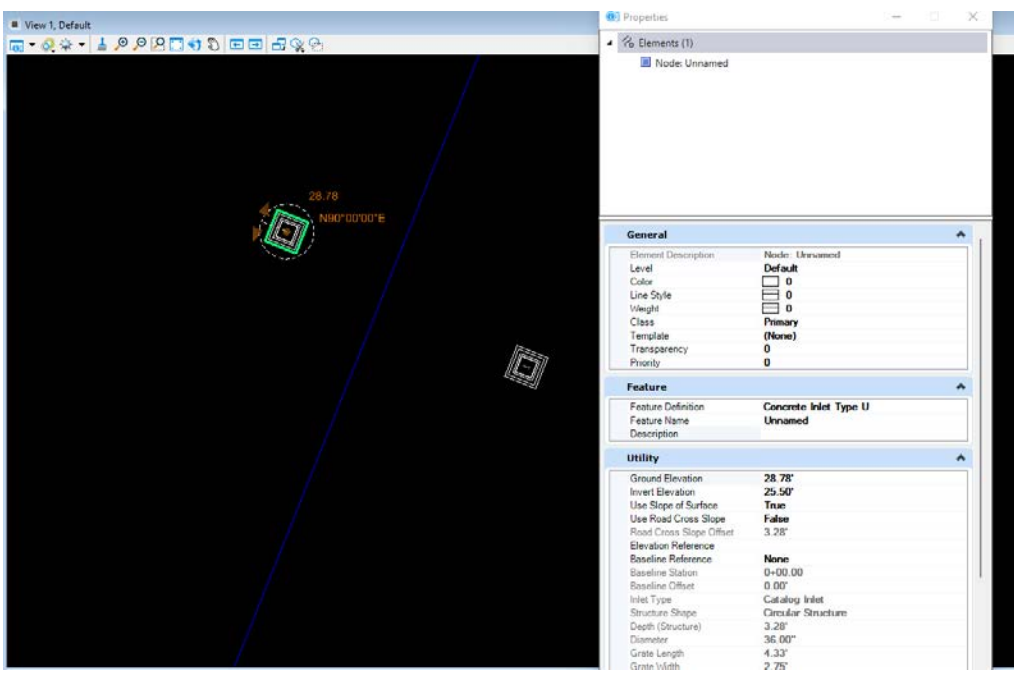


Figure A.19 Created inlet model of concrete inlet type U and W.

To create a 3D view of the model, click on the "2D Metric Design" at the bottom of the interface and select "2D Metric Design-3D Views" (as shown in Figure A.20 Steps 1 and 2). Then, select the "Rotation View" at the top of the interface (as illustrated in Step 3) and drag your mouse to change the angle of view in 3D perspective. Figure A.21 shows the 3D view of the created concrete inlets type U and W.

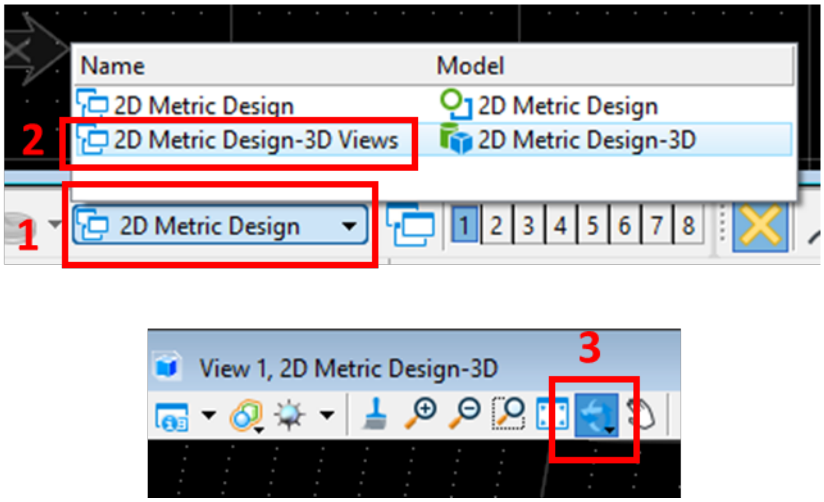


Figure A.20 Steps for creating 3D view of the model.

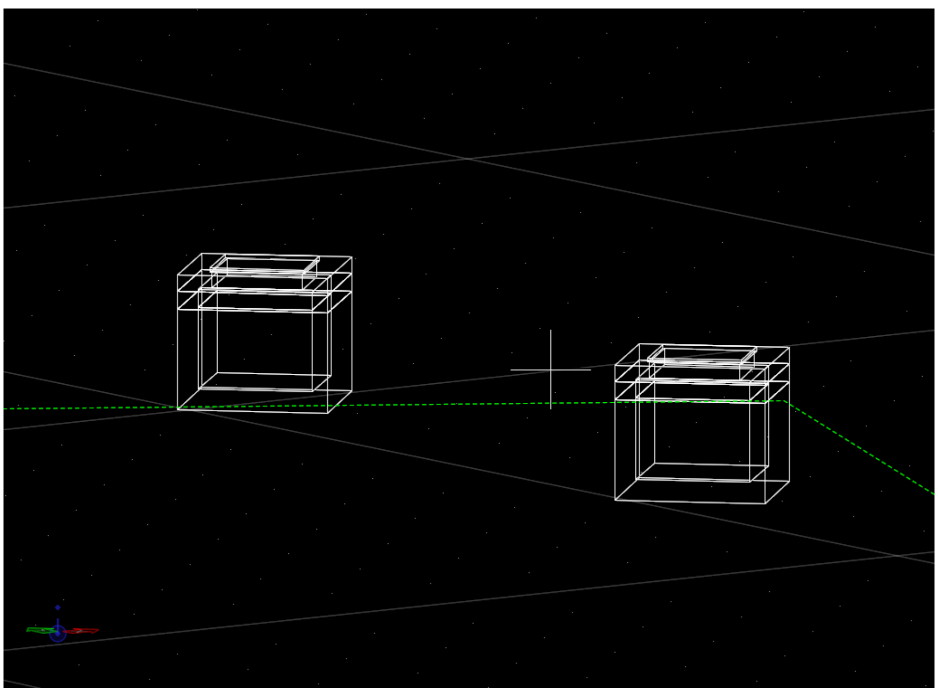


Figure A.21 3D view of concrete inlets type U and W.

APPENDIX B. INDIANA DEPARTMENT OF TRANSPORTATION (INDOT) MODEL DEVELOPMENT INSTRUCTION MANUAL FOR CONCRETE PAVEMENT (DRAFT)

B.1 Design and Analysis

Pavement design is "the process of selecting a practical and economical combination of materials of known strength and adequate thicknesses to support anticipated traffic under the prevailing environmental conditions. Pavement will be designed following the appropriate procedures noted in this document" (VDOT, 2018a).

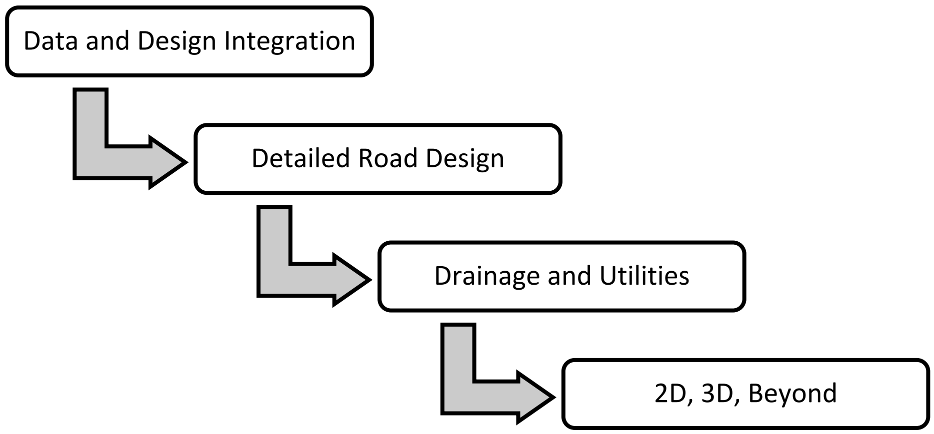


Figure B.1 Pavement design workflow.

FHWA Pavements and Materials Program Areas according to the Federal Highway Administration (FHWA, 2023):

- Pavement Design
- Materials
- Quality Assurance
- Pavement Construction
- Pavement Management
- Pavement Rehabilitation & Preservation
- Sustainable Pavements

Select material, subbase, and base material (aggregate-type material).
For rigid pavements, the Pavement designer will determine (VDOT, 2018a):

- Elastic Modulus of the PCC.
- Composite Modulus of Subgrade Reaction.
- Load Transfer at Cracks and Joints.
- Potential for the Presence of Voids.

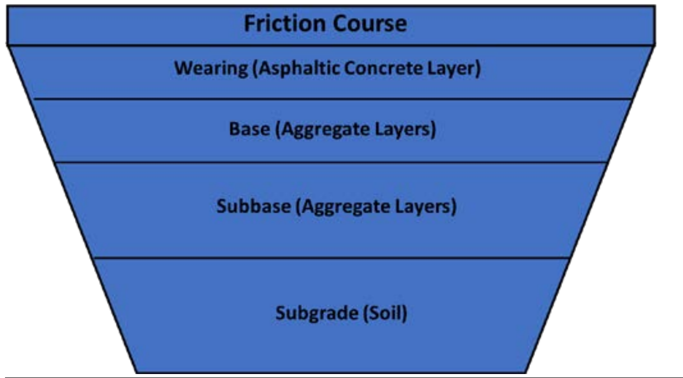


Figure B.2 Layers of concrete pavement (adapted from Kar et al., 2020).

Proposed Full Depth Roadway Typical Section (VDOT, 2018a).

- Length (ft)
- Number of Lanes
- Paved Lane Width (ft)
- Right Total Shoulder Width (ft)
- Left Total Shoulder Width (ft)
- Right Paved Shoulder Width (ft)
- Left Paved Shoulder Width (ft)
- Paved Shoulder Type
- Curb and Gutter Required
- Length of c & G (ft)
- % of New Horizontal Alignment

Pavement Design Considerations according to Federal Highway Administration (FHWA, 2020).

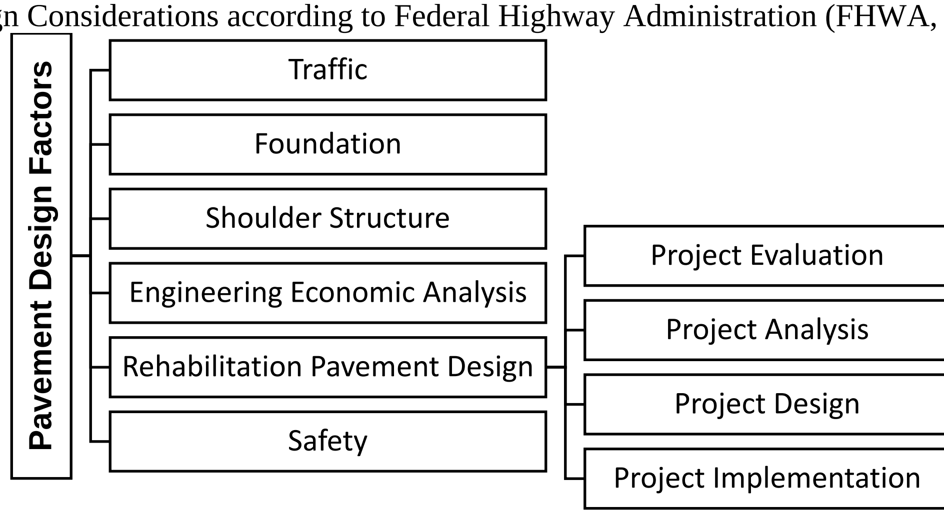


Figure B.3 Factors that affect pavement design (Johnson & Carrion, 2021).

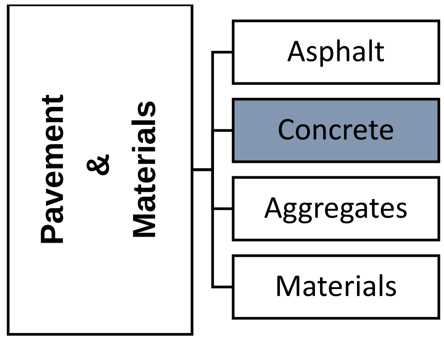


Figure B.4 Materials of pavement.

According to (FHWA, 2018a): "Evaluate the following design controls to understand the factors influencing the design and to determine the applicable criteria for establishing the standards for the project:

- contextual factors and environmental constraints,
- functional classification,
- topography within the corridor,
- location (i.e., rural or urban),
- existing and expected traffic volumes and composition (e.g., ADT),
- level of service and mobility,
- level of access and management,
- cross-section type and level of multi-modal accommodation,
- existing and expected users and their characteristics,
- superelevation rate,
- existing and expected speed characteristics,
- appropriate design speed,
- existing and expected safety performance, and
- other technical factors (geotechnical, hydraulic, pavement, structural, etc.)."

According to FHWA (2018b), "for all projects, document the selection of applicable design criteria from approved standards, and when approved standards are not attained, document all exceptions." All 13 principal design elements are considered controlling criteria, and the 4 supplemental standards require formal approval and documentation each time they are not attained. The 13 principle controlling criteria are the following:

- design speed,
- lane width,
- shoulder width,
- bridge clear roadway width,
- horizontal curvature,
- vertical curvature,
- gradient,
- stopping sight distance,
- normal travel lane cross slopes (crown),
- superelevation,
- structural capacity,
- horizontal clearance to structures (tunnels and bridge underpasses), and
- vertical clearance.

The four supplemental standards are the following:

- clear zone,
- barrier crashworthiness,
- design flood, and
- pavement design service life."

According to NYSDOT (NYSDOT, 2022), design criteria are influenced by the following:

- The highway functional classification;
- Traffic volumes (from all surface, highway, and transit modes);
- Operating speed;
- Terrain (level, rolling, mountainous);
- Development density and land use; and
- Project type (e.g., new construction, reconstruction, 3R, 2R - simple 3R projects)

The design criteria (DelDOT, 2022) are shown in Table B.1.

Table B.1 List of design criteria (DelDOT, 2022)

Design Criteria	
Design Speed	(mph)
Travel Lane - Width	(ft)
Travel Lane - Cross Slope	(%)
Inside Shoulder - Width	(ft)
Inside Shoulder - Cross Slope	(%)
Outside Shoulder - Width	(ft)
Outside Shoulder - Cross Slope	(%)
Auxiliary Lanes - Width	(ft)
Auxiliary Lanes - Cross Slope	(%)
Median - Width	(ft)
Minimum Horizontal Curve Radius	(ft)
Superelevation Rate	(%)
Stopping Sight Distance	(ft)
Maximum Percent Grade	(%)
Minimum K (Crest)	
Minimum K (Sag)	
Maximum Front Slope (Unprotected)	
Maximum Back Slope	
Clear Zone Width	(ft)
Lateral Offset	(ft)
Barrier Offset	(ft)
Structural Capacity	
Bridge Width	(ft)
Vertical Clearance	(ft)

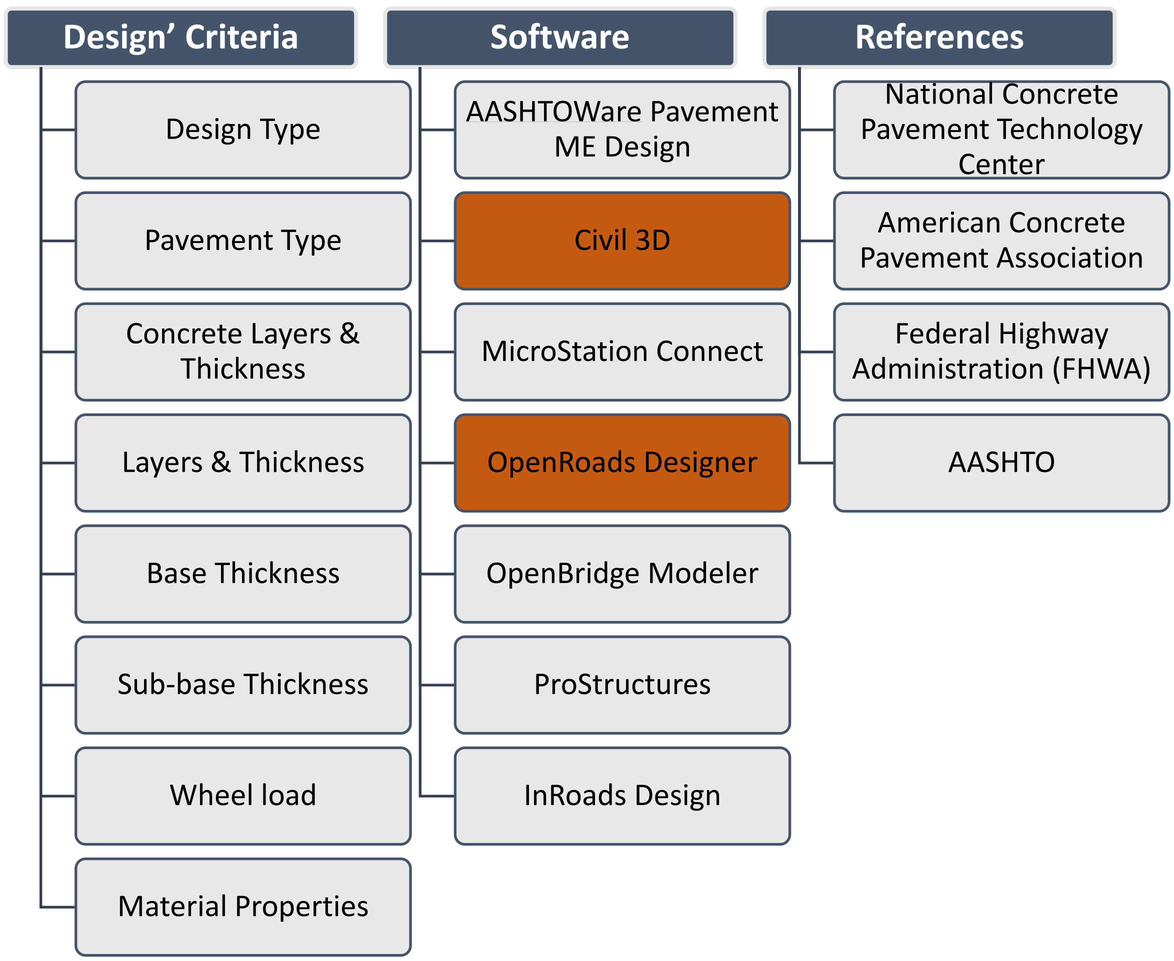


Figure B.5 Summary for design criteria with software and references.

According to (VDOT, 2018a), the preliminary pavement evaluation, as shown in Figure B.6, includes the following tasks:

- Task 1: Data Gathering.
- Task 2: Field Data Collection.
- Task 3: Preliminary Recommendation.
- Task 4: Determine the Need for Detailed Pavement Evaluation.

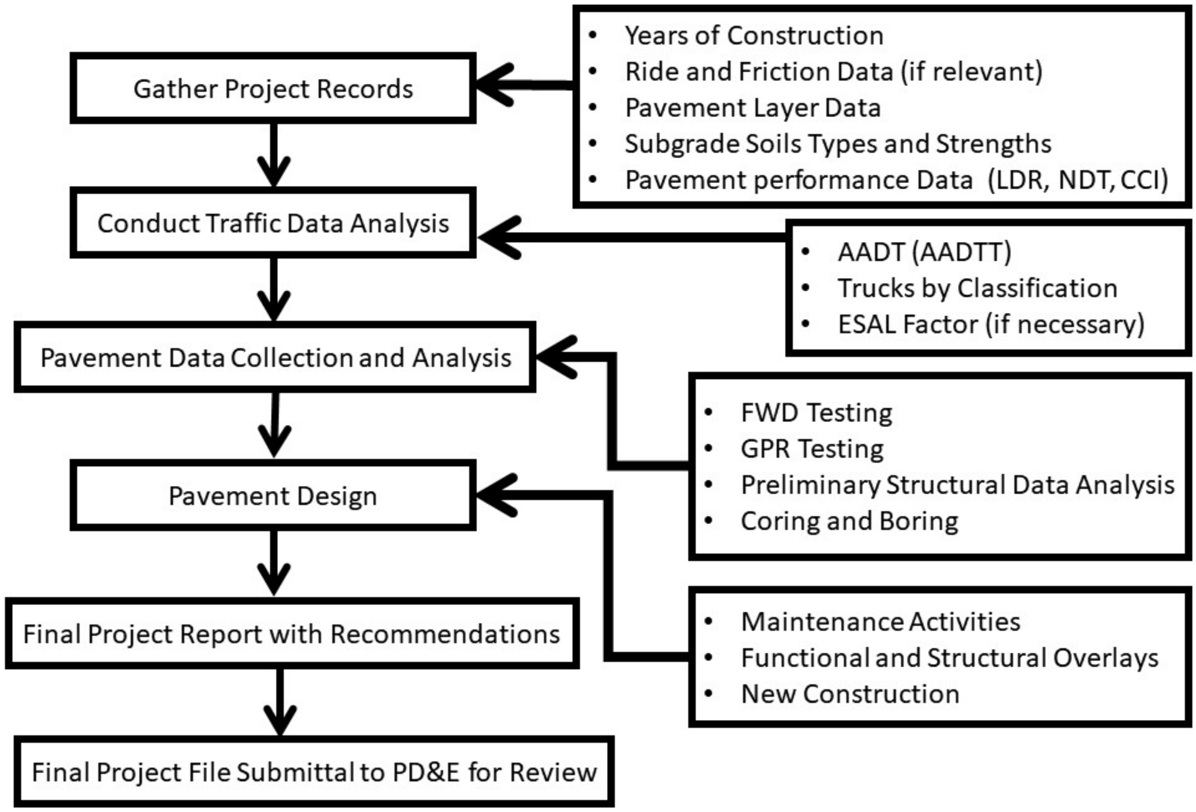


Figure B.6 Detailed pavement evaluation process flow (VDOT, 2018a).

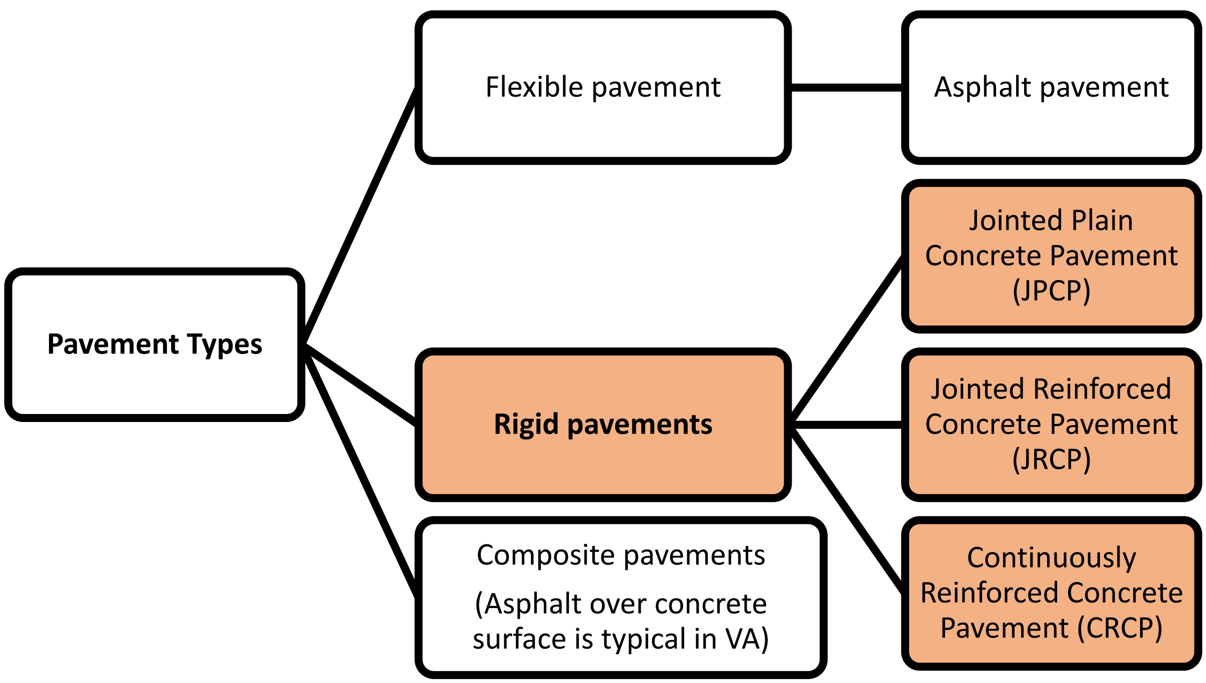


Figure B.7 Pavement types (VDOT, 2018a).

Design Procedures: Two design approaches can be used as follows (VDOT, 2018b):

Conventional Pavement Design Method

Alternate Pavement Design Method

The evaluation of design variables

- The traffic in terms of projected Annual Average Daily Traffic (AADT)
- The soil support value of the subgrade

Design considerations

- Determination of the required Thickness Index of the pavement
- The selection of paving materials based on the sum of the products of their thickness and thickness equivalencies equaling or exceeding the required Thickness Index value.

Figure B.8 Design methods for rigid pavement (VDOT, 2018b).

Conventional Pavement Design Method

Alternate Pavement Design Method

- The **thickness** shall be rounded up to the nearest 0.5 inches
- **Concrete** shall be Class A-3 paving concrete according to the current Road and Bridge Specifications and appropriate supplemental specifications
- The **pavement** shall be Plain Jointed Portland Cement Concrete with a designed transverse joint spacing not to exceed 15 feet (the joint spacing in feet shall not exceed 2 times the pavement thickness in inches).
- **Non dowelled pavement 6" or less in thickness**, shall have at least 3 longitudinal joints (no joint along the wheel path), shall have maximum aspect ratio of 1:1 (length to width) and shall have maximum panel size of 8 feet by 8 feet. Continuously Reinforced Concrete Pavement may be considered an acceptable option.
- In the case of very weak or very low resiliency soils having CBR values less than 2, the soil should be stabilized for a depth of six (6) inches with cement, 10% - 12% by volume, or in accordance with a detailed geotechnical design which the developer shall submit with the design documents for each new subdivision street.

Figure B.9 Details for the conventional pavement design method (VDOT, 2018b).

Alternate Pavement Design Method

Slab: A Minimum thickness of 5 inches non doweled, jointed plain concrete pavement shall be used.

Materials: Class A-3 concrete shall be used.

Base: A minimum of 6 inches aggregate base (21B) shall be used.

Joints: The subdivision street shall use minimum three (3) longitudinal joints within the road width. Longitudinal joints shall not be located in the wheel path. Joints will be sealed using hot pour asphalt or other approved joint sealant materials.

Paneling: Panels will be created using an aspect ratio of 1:1. The maximum panel size shall be 8 feet by 8 feet.

Figure B.10 Details for the alternative pavement design method (VDOT, 2018b).

Table B.2 Layers' details according to the alternative pavement design method (VDOT, 2018b)

Design AADT	Minimum Slab Thickness	Minimum Aggregate Thickness	Maximum Transverse Joint Spacing
0-400	5 inches	6 inches	8 feet

B.2 OpenRoads Designer

Figure B.11 shows a map for supporting DOTs using Bentley GEOPAK/InRoads V8i and Autodesk Civil 3D (EnvisionCAD, 2021).

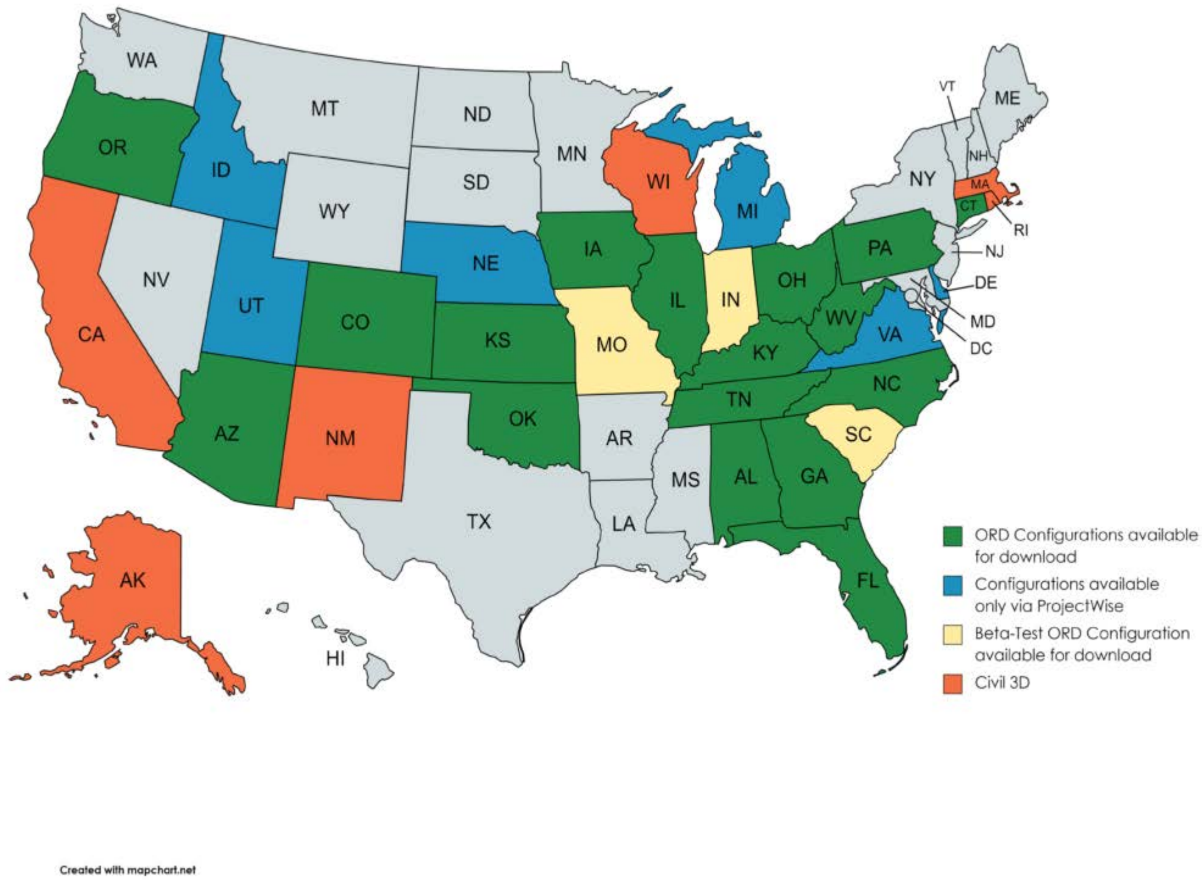


Figure B.11 A map for supporting DOTs' BIM for infrastructure (EnvisionCAD, 2021).

Building Information Modeling (BIM) for Infrastructure (FHWA, 2021):
"Many State Departments of Transportation (DOTs) recognize the benefits associated with the bigger picture of BIM as a data-centric approach for project delivery and asset management practices." (FHWA, 2021).
"The objectives of the FHWA BIM for Infrastructure program are to do the following.

1. Describe BIM for Infrastructure and educate stakeholders.
2. Share the implementation of BIM-related technologies and practices of the State DOTs.
3. Help State DOTs identify steps to move from one maturity level to the next for a specific area." (FHWA, 2021).

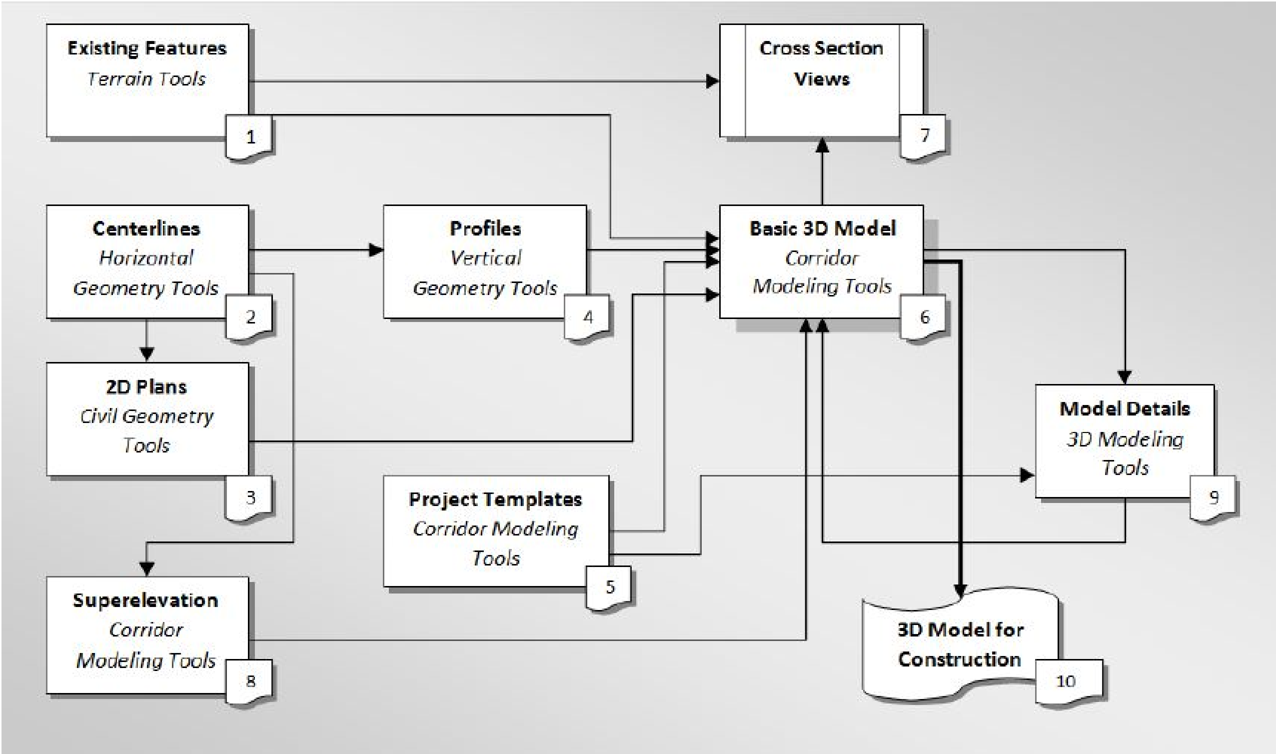


Figure B.12 FDOTCONNECT design and 3D modeling overview (FDOT, 2021).

➢ Feature Definitions

As defined in the Bentley Civil Tools help files (Bentley, 2021) (FDOT, 2021):

"Feature Definitions are used to control symbology, annotation, and various other properties that are applied to the geometric elements. The feature definitions are used to:

- Define what the geometric elements actually are. For example, what is being modeled, such as curb, centerline, pavement edge, etcetera.
- Control symbology in various views, including the capability to define differing symbology in a plan, profile, and 3D spaces.
- Define terrain modeling attributes (spot, break line, void, etcetera).
- Define surface display characteristics."

➢ Civil Geometry - Design Intent

As defined in the Bentley Civil Tools help file (FDOT, 2021):

"Design intent builds associations and relationships between civil elements. Object information (how, where, and by what method it was created) is stored with the object to ensure the original intent is retained and honored in the design. Any related elements will recreate themselves based on these stored relationships if an element is modified."

➢ Design Standards

Also known as Design Geometrics and Criteria and as defined in the Bentley Civil Tools help files (FDOT, 2021):

"Design standards can be used to maintain required curvature and other alignment checks when performing geometric layouts. They work at two levels:

- *Provide values for the element creation tools (for example, minimum radius and transition lengths)*
- *Check the suitability of complex elements (for example, check for kinks in the alignment)*

Design standards are very alignment oriented. You may find limited value in using design standards for non-alignment computations.
When a design standard is violated, feedback is provided in two ways:

- *An icon in the graphics on the element that has the problem. Hover over the icon to reveal a tooltip report of the error.*
- *In the Civil Message Center"*
- Inputs
    - Design Type (New Pavement, Overlay, Restoration, or Rehabilitation)
    - Pavement Type (JPCP or CRCP)
    - Concrete Layers & Thickness
    - Layers & Thickness
    - Base Thickness
    - Sub-base Thickness
    - Material Properties

According to *2013 Indiana Design Manual*, *INDOT 2022 Standard Specifications*, and Bentley Education (2023), concrete pavement model was developed following the process in Figure B.13.

WorkSpace and WorkSets

Terrain

Geometry

Templates

Corridors

Cross Sections and Earthwork Quantities

Figure B.13 Process for "openroads designer."

B.3 Setup and Installation of the "OpenRoads Designer" Software

The software created this model: OpenRoads Designer CE - 2022 Release 1.
The link for downloading the software:
https://softwaredownloads.bentley.com/en/ProductDetails/2515?data=onRI2lTeYEZmEca3ZgxpPqjBBQaDUqVyu3ksyqyqDoTXhdaKslC8HjtKqOTu0A35rW6y5HLN7BQ%3D

After downloading "OpenRoads Designer CONNECT Edition," as shown in Figure B.14. Then click on Setup_OpenRoadsDesignerx64_10.11.00.115 to start the installation of the software.

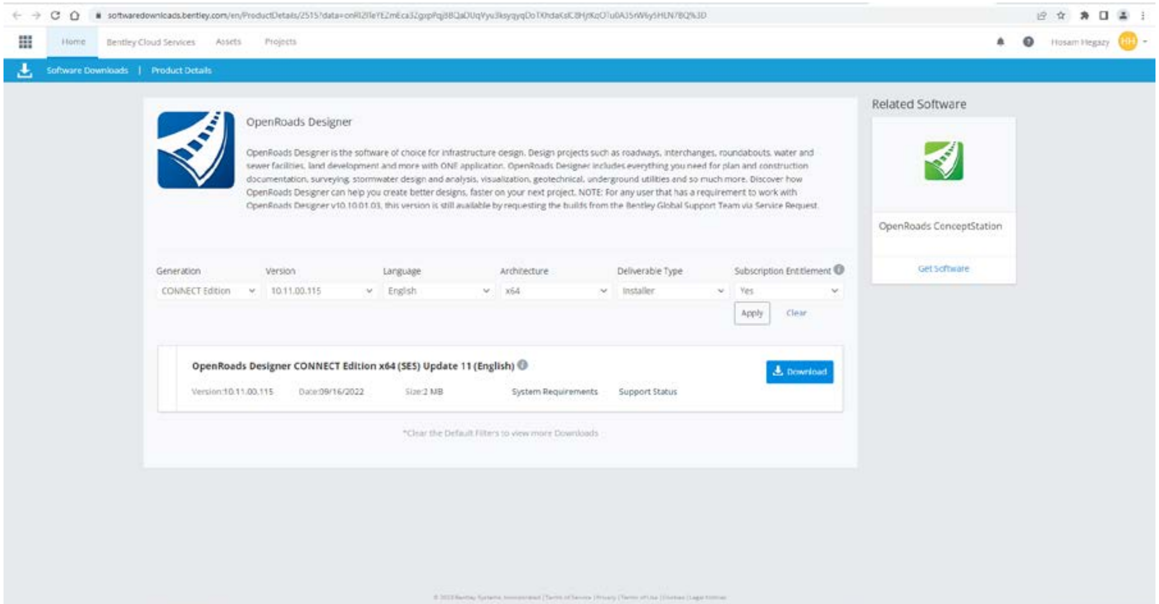


Figure B.14 Download the software.

We should configure the software to change the installation options, select "Configure," as shown in Figure B.15.

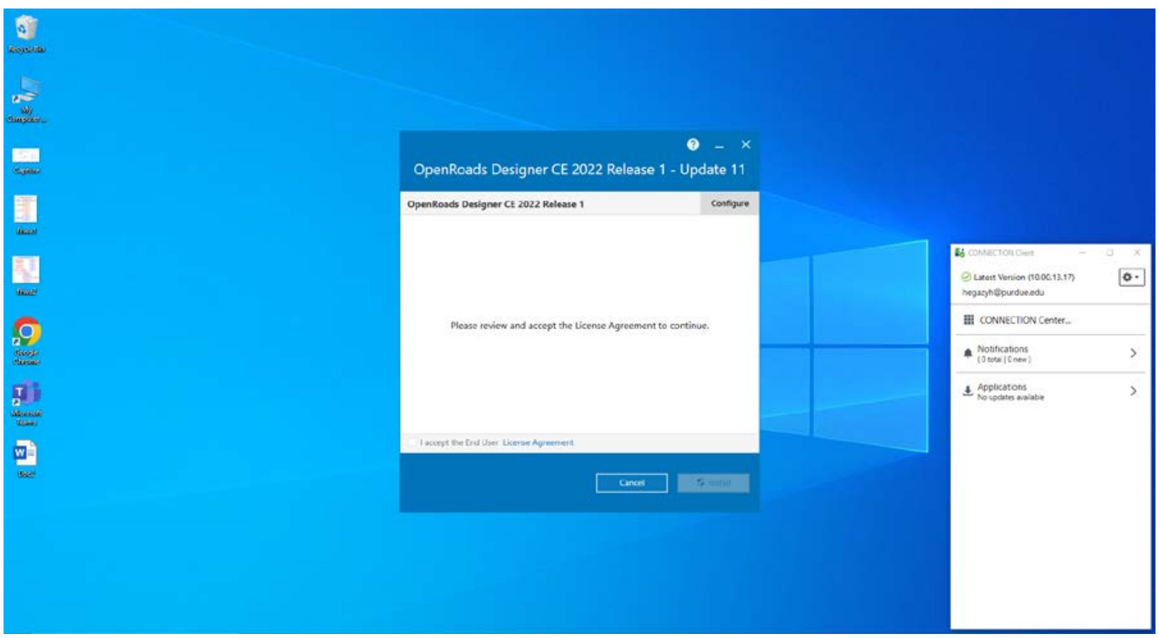


Figure B.15 Interface in the start: installation of the software.

We can select “GenerativeComponents,” then click next.

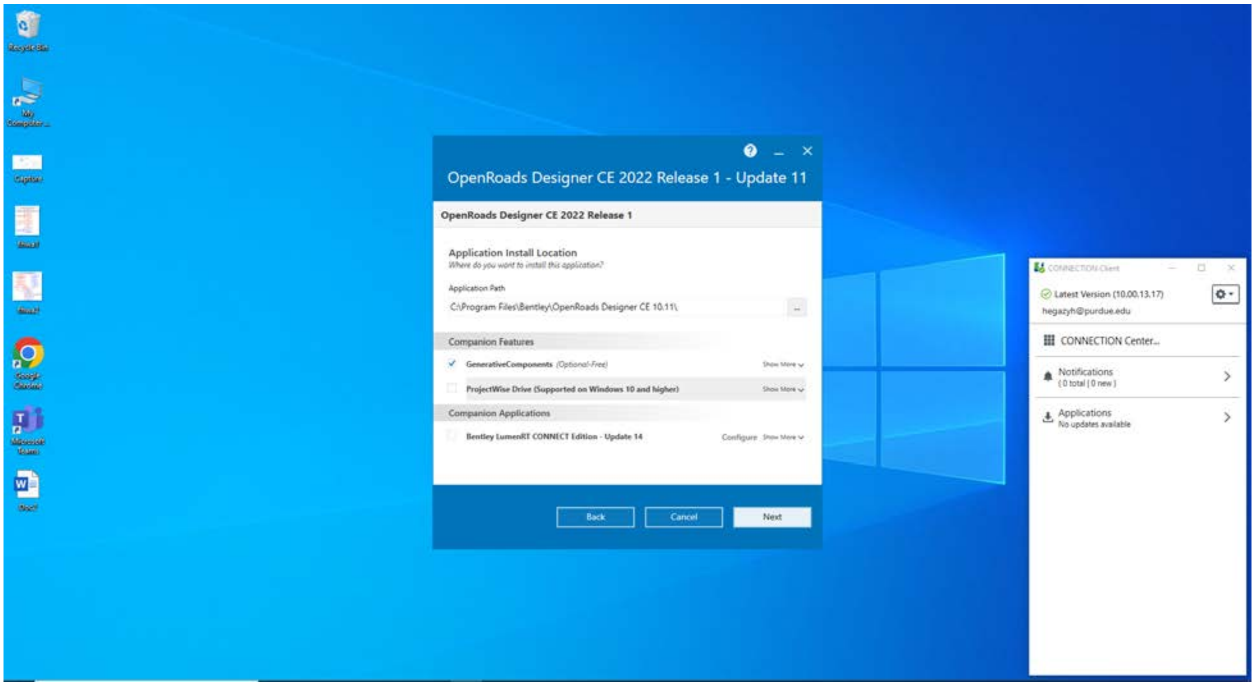


Figure B.16 Interface for the “application install location” and “companion features.”

Select the option “custom configuration (plus delivered configuration),” as shown in Figure B.17. Browse to select the folder where the “custom configuration” will be located, then click next.

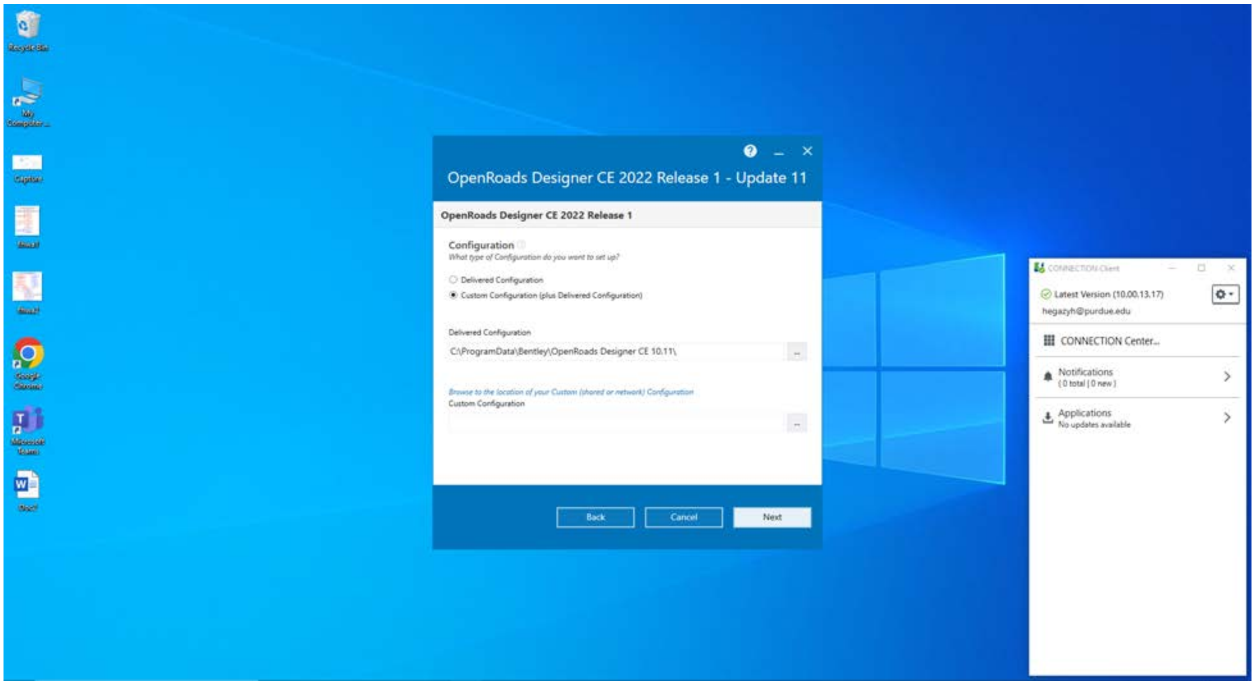


Figure B.17 Interface for the type of configuration.

Click Done to finalize the choices, as shown in Figure B.18.

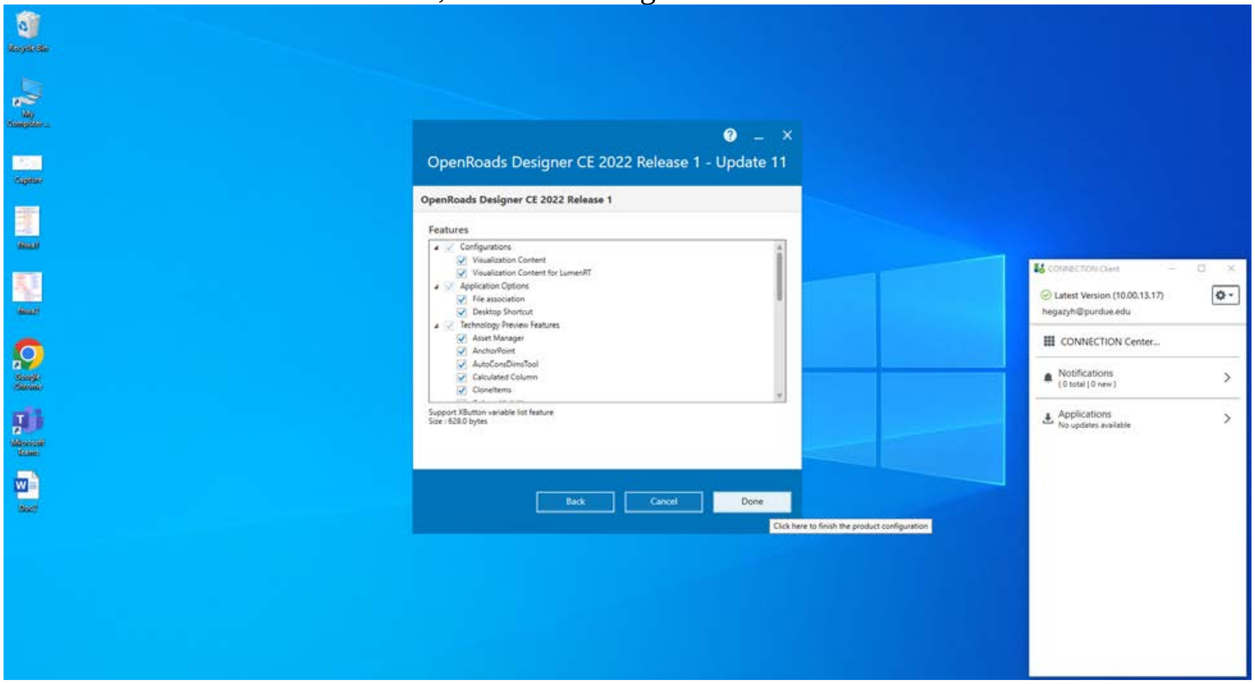


Figure B.18 Interface for the “features.”

Choose “I accept the End User License Agreement” and then click “Install,” as shown in Figure B.19, to start installation processes.

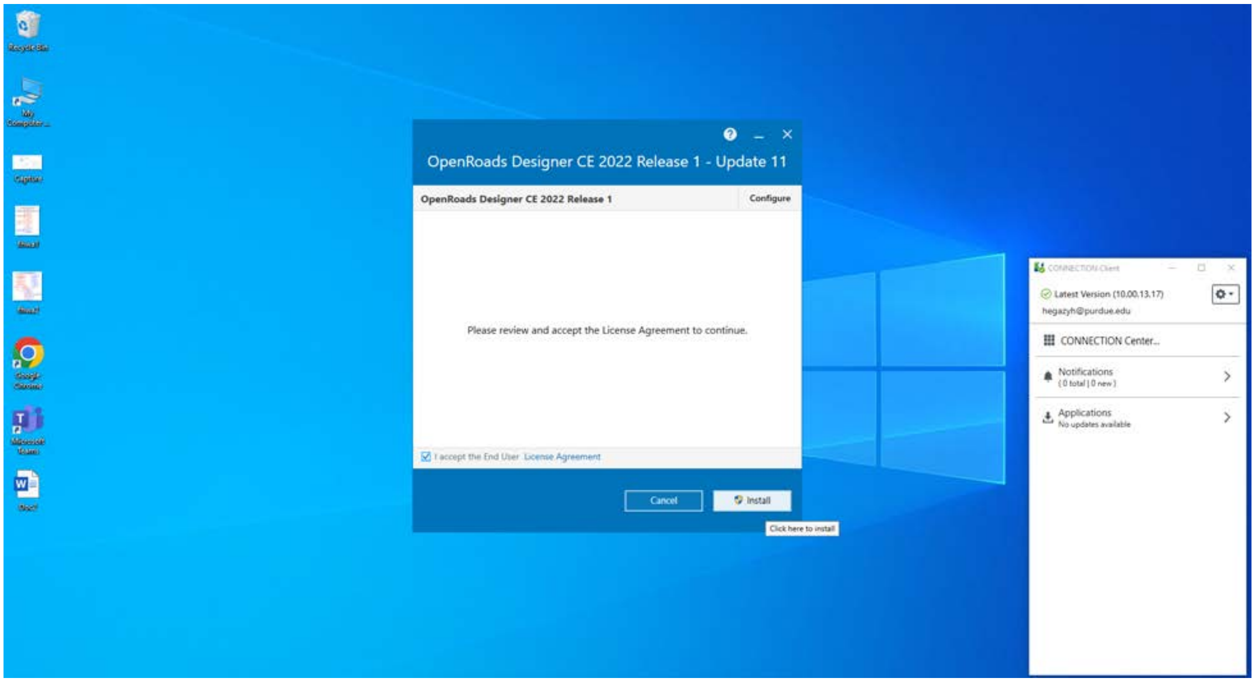


Figure B.19 Install the software.

B.4 Create OpenRoads Model (Step by Step)

First Step: Launch INDOT Connect for OpenRoads Designer, create a workspace, worksets, and create files.

Set OpenRoads Model

1. Create New WorkSpace.
2. Create New WorkSet.
3. Create New (*dgn) file.

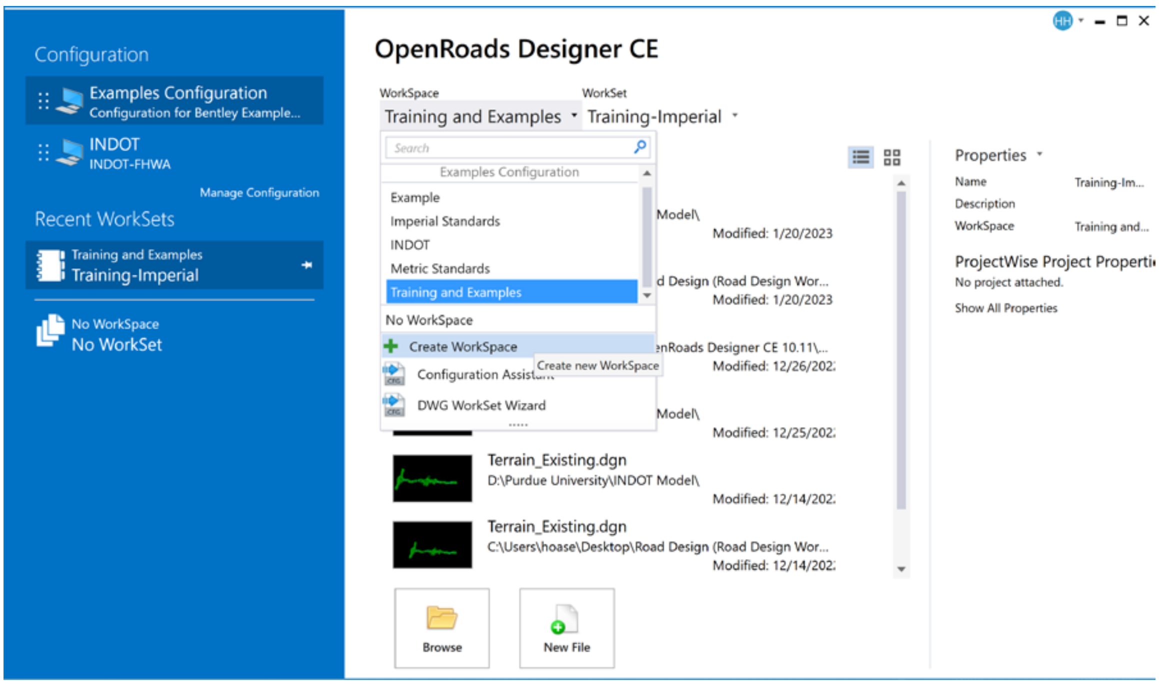
- Select the WorkSpace & WorkSet, as shown in Figures B.20 to B.31, in OpenRoads Designer using a file (*dgn).
- 

Figure B.20 Create new "workspace."

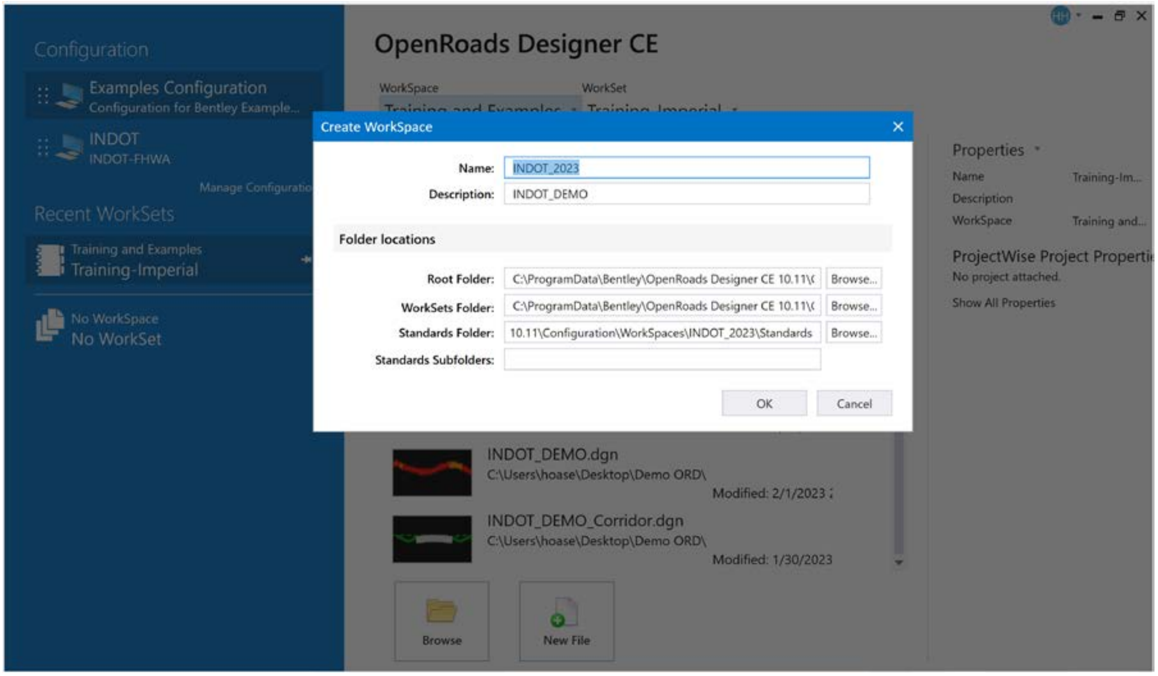


Figure B.21 Define the name and description for new "workspace" as "INDOT_2023."

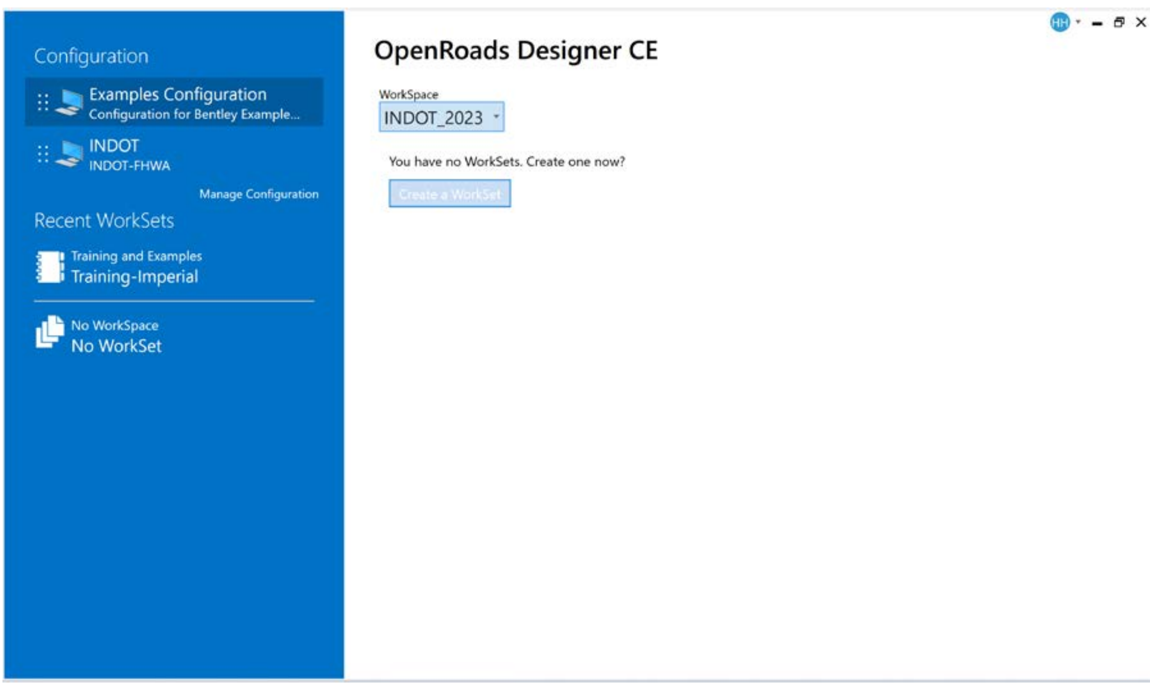


Figure B.22 Create new "workset."

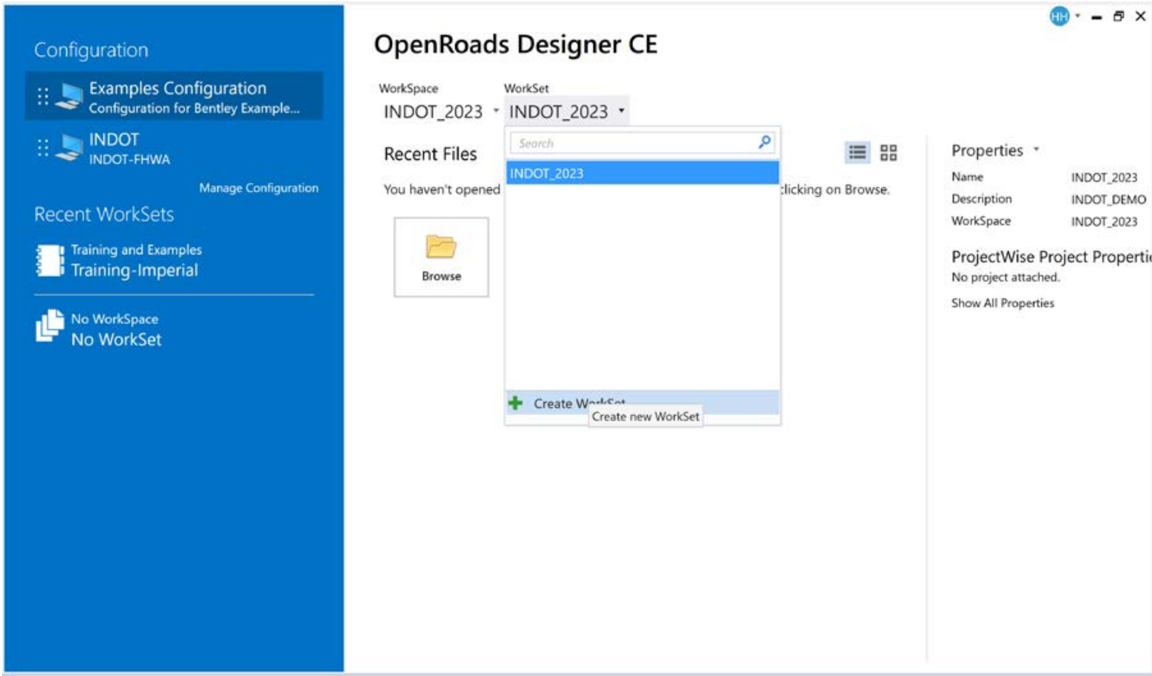


Figure B.23 Select “create workset.”

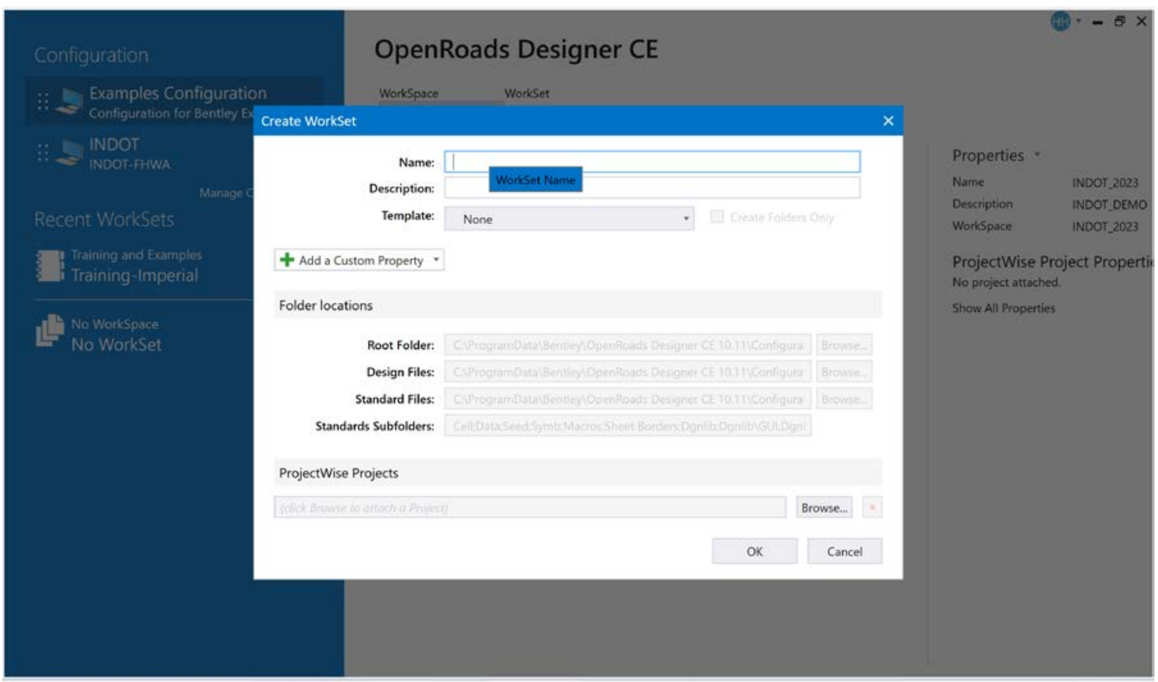


Figure B.24 Interface for “create workset” dialog.

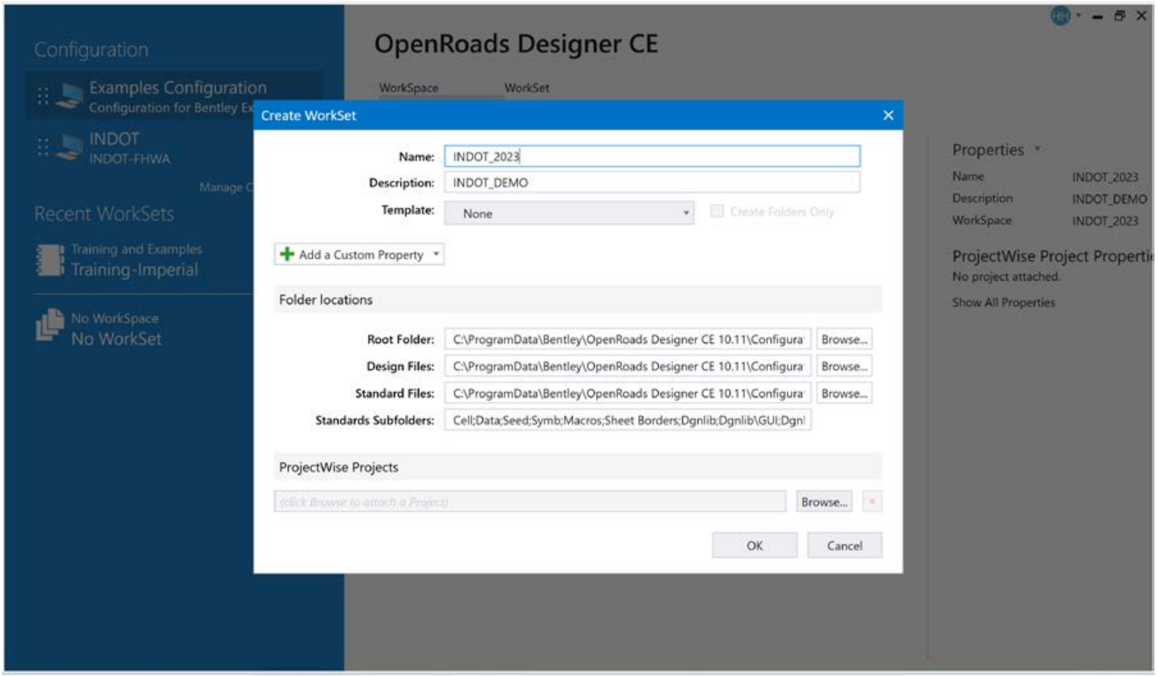


Figure B.25 Define the name and description for new “workset” as “INDOT_2023.”

- Create New File: New File>File Name>Browse>Seed2D - Imperial Design

Notes:

  - *When we create a new file, we should choose “Seed”: Click “Browse” and check that the Seed is: “Seed2D - Imperial Design.dgn”*

(Configuration\Organization-Civil_Civil Default Standards - Imperial\Seed\Seed2D - Imperial Design.dgn)

  - *Save the file as “DGN Files (*.dgn)” type*

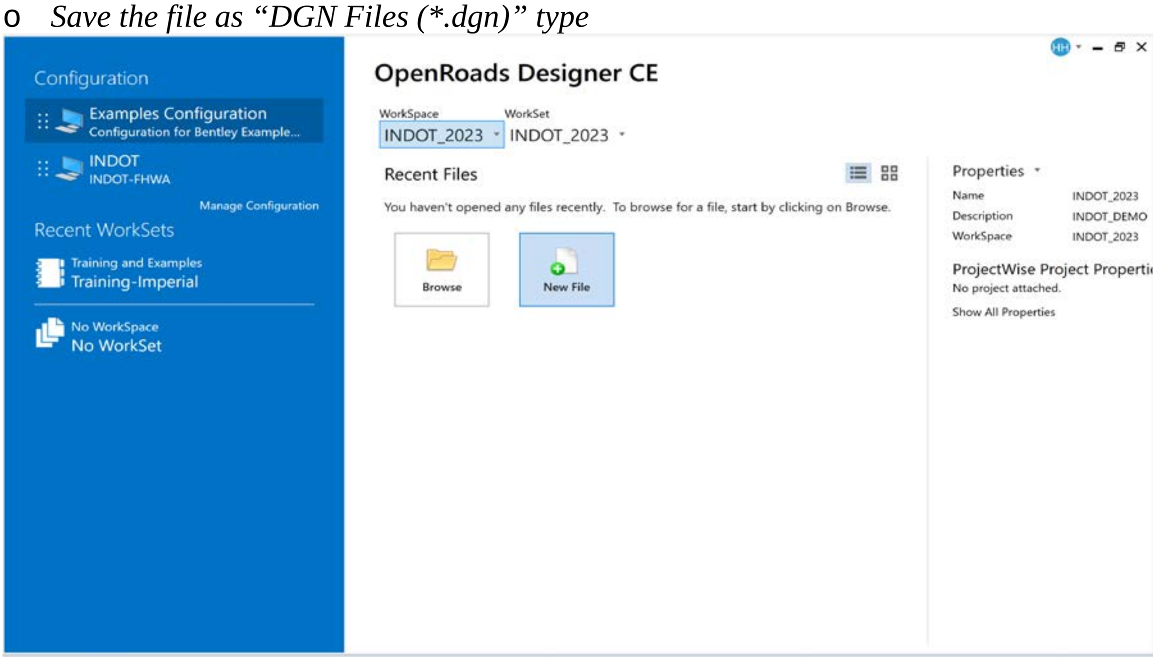


Figure B.26 Create a “New file.”

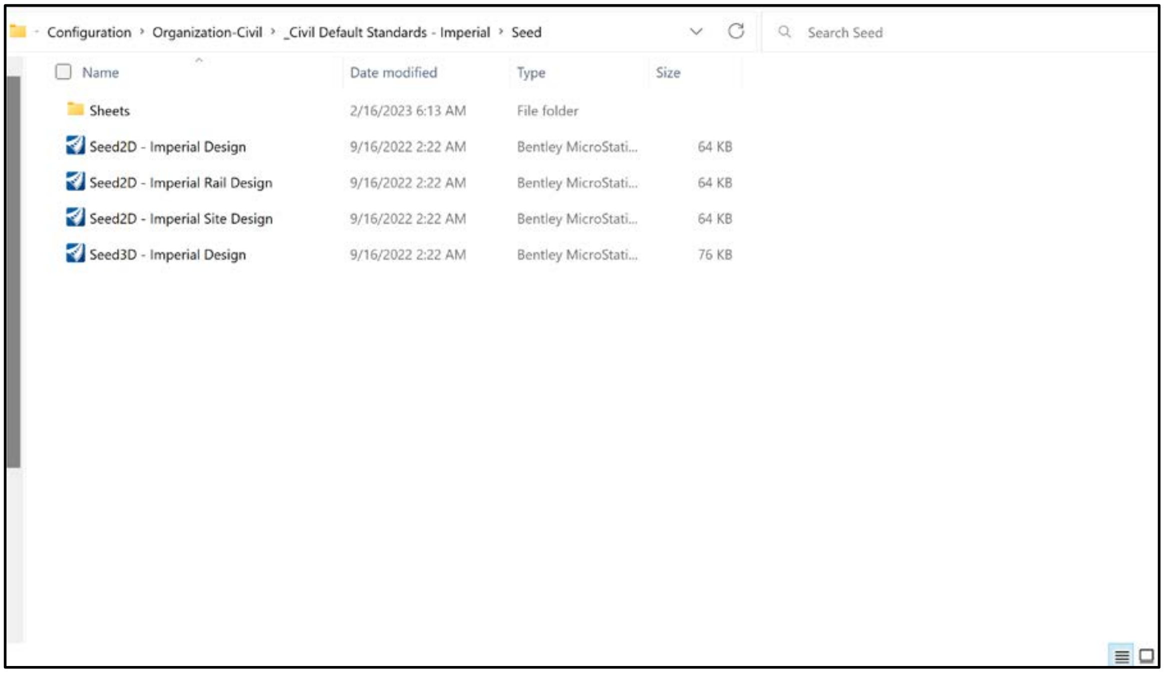


Figure B.27 Files for “standards-imperials” “seed.”

Imperial System Units

- Length/Distance
  - Inches (in)
  - Feet (ft)
  - Yard (yd)
  - Mile (mi)
- Imperial System Conversion
  - 1 ft = 12 in
  - 1 yd = 3 ft
  - 1 yd = 36 in
  - 1 mile = 1760 yards
- Imperial System to Metric
  - 1 in = 2.54 cms
  - 1 ft = 30.48 cms
  - 1 yd = 91.44 cms
  - 1 yd = 0.9144 m
  - 1 mile = 1609.34 m
  - 1 mile = 1.6 kms

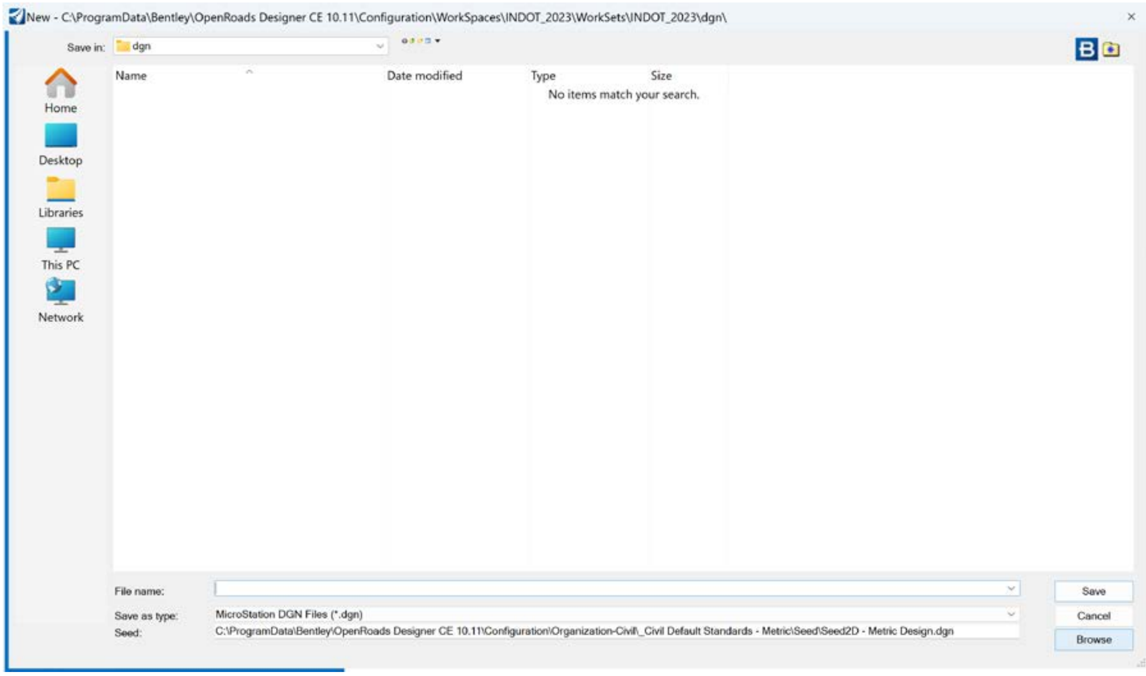


Figure B.28 Interface for the “file save,” click on “browse” to select the seed file.

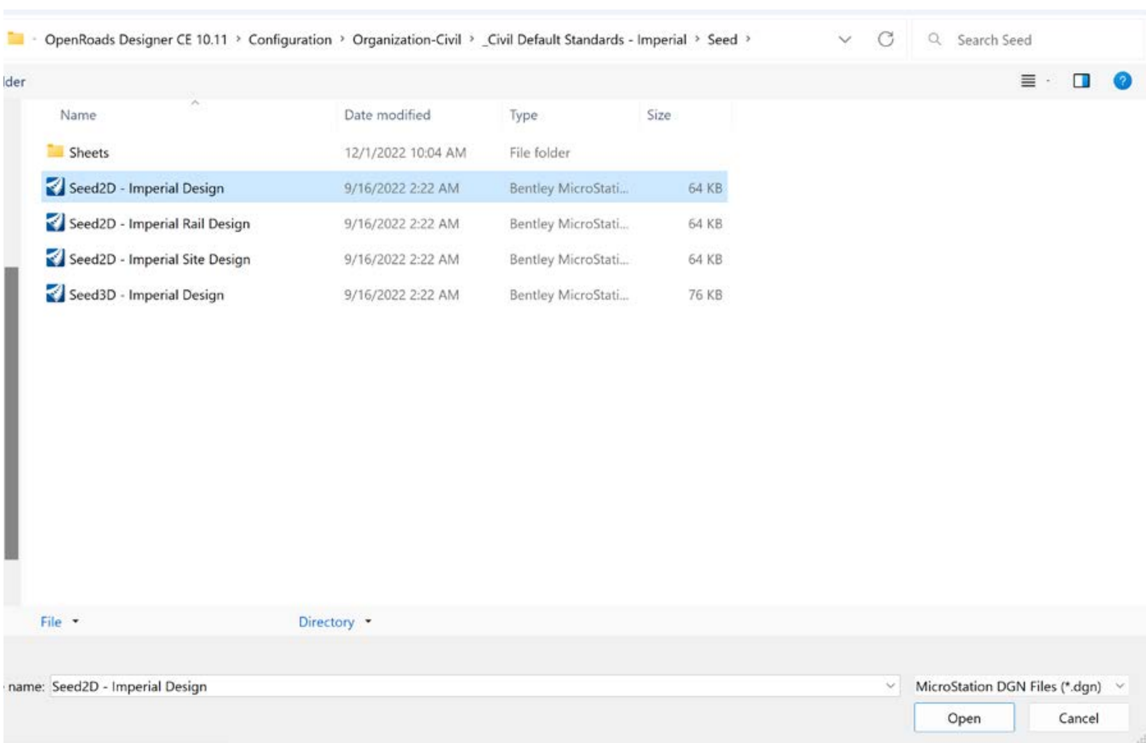


Figure B.29 Seed files.

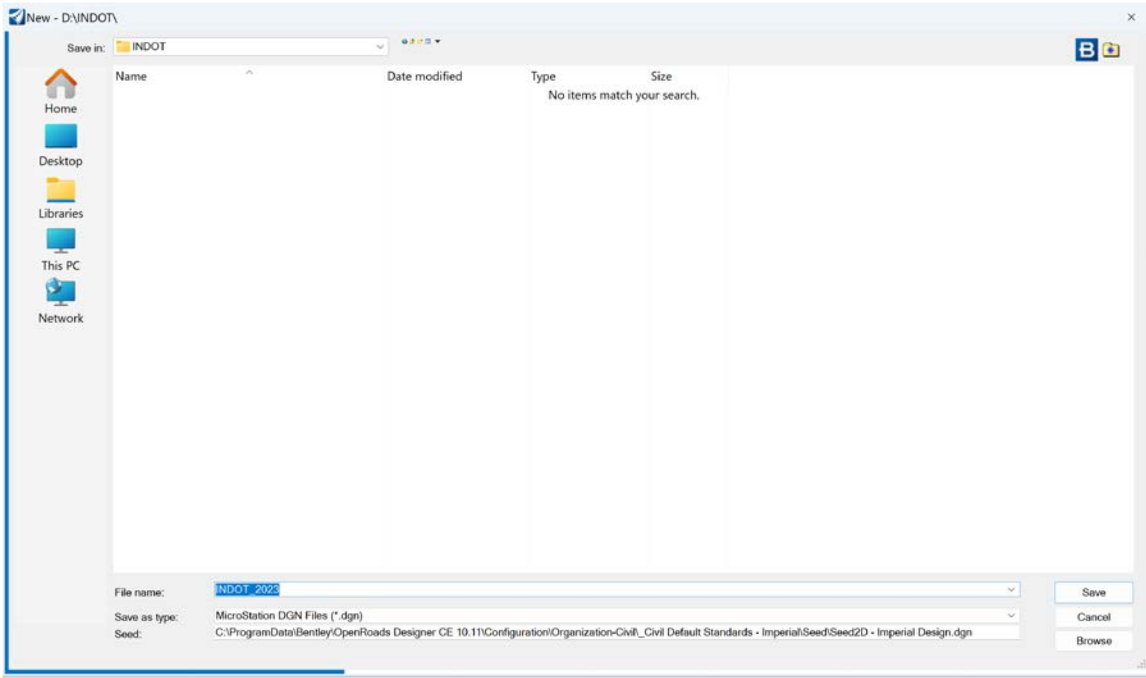


Figure B.30 Define the "file name."

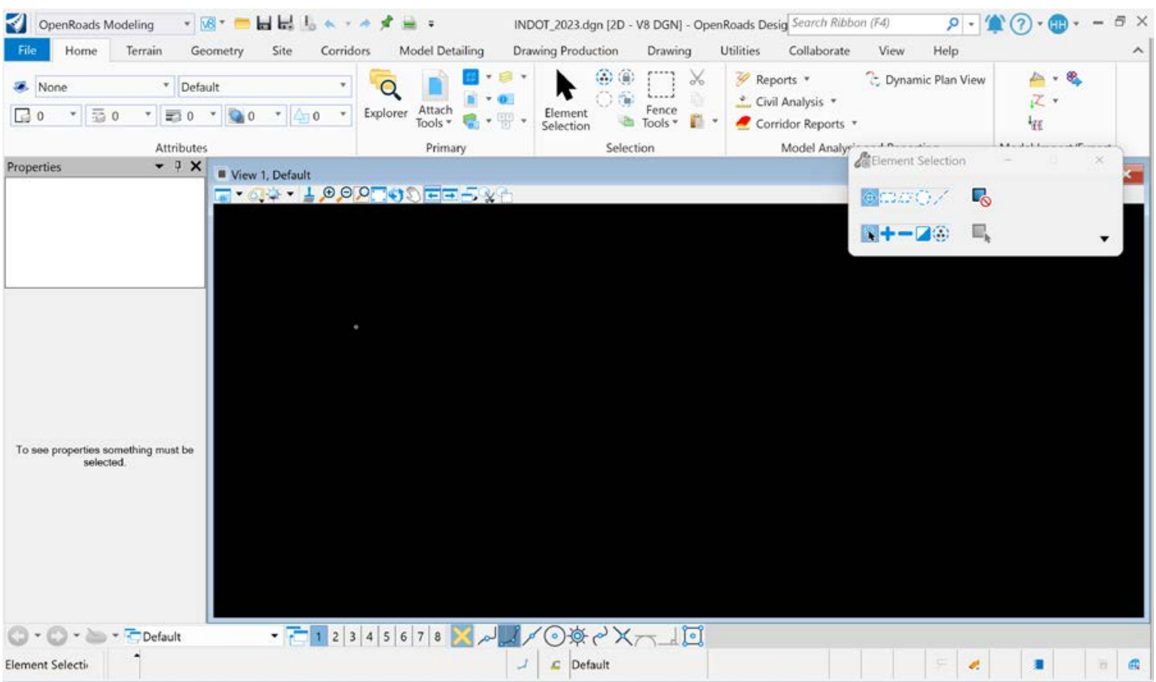


Figure B.31 Interface for the "new file."

Notes: To start working on the pavement roads, please check that "OpenRoads Modeling" is selected, as shown in Figure B.32.

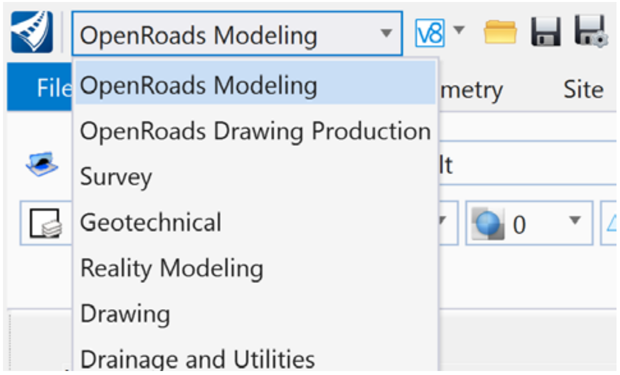


Figure B.32 Interface for selecting "OpenRoads Modeling."

Second Step: 2D Design Geometrics Alignments - According to (INDOT, 2022a).

Create feature definition: from geometry tab choose "Standards," as shown in Figure B.33 to Figure B.38.

- Standards: *(Geometry Tab>Standards>Feature Definition Toolbar>Alignment>Road>Geom_Baseline)*

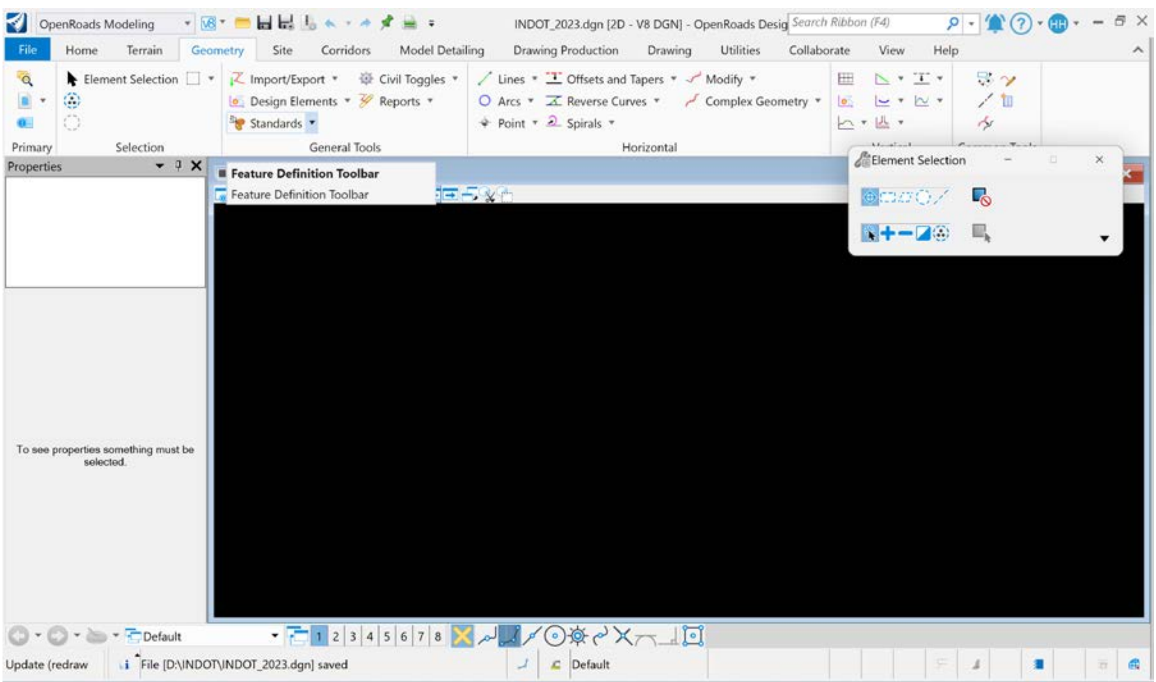


Figure B.33 Select "standards."

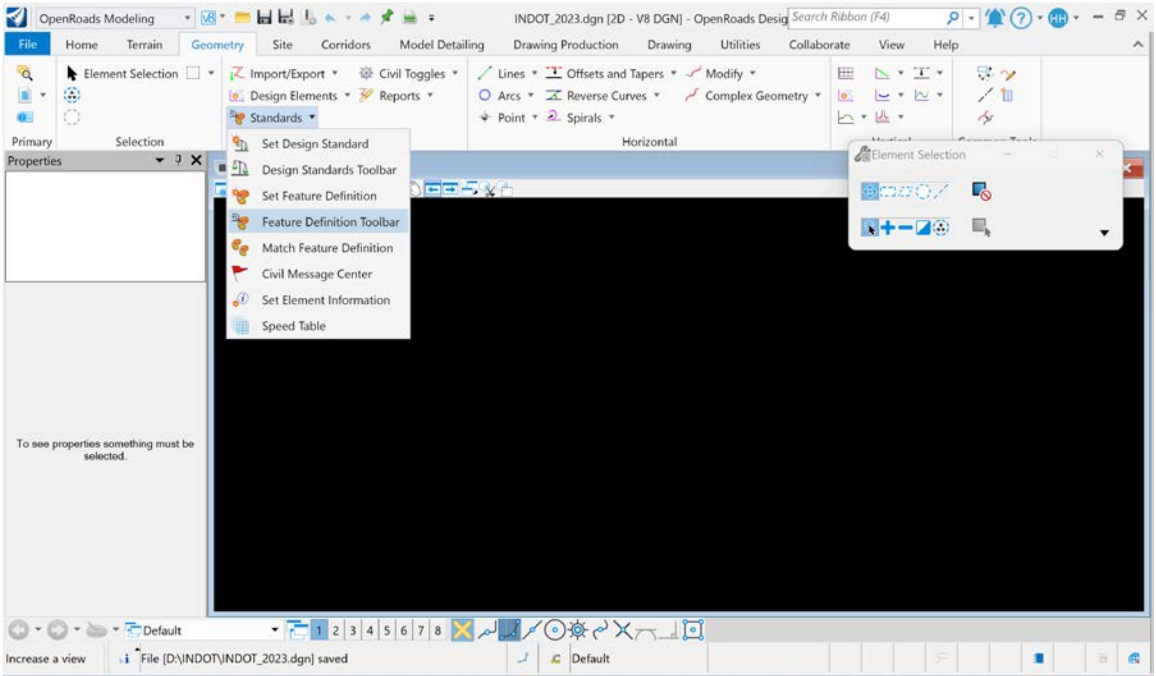


Figure B.34 Select “feature definition toolbar.”

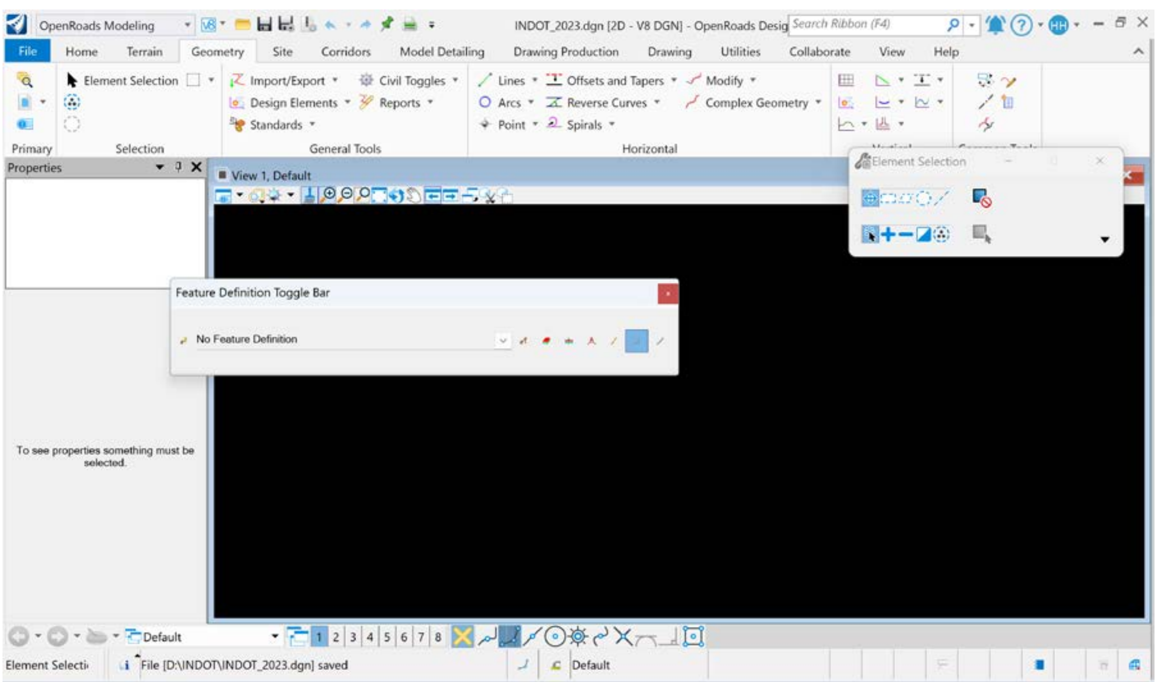


Figure B.35 Interface for the “feature definition toggle toolbar.”

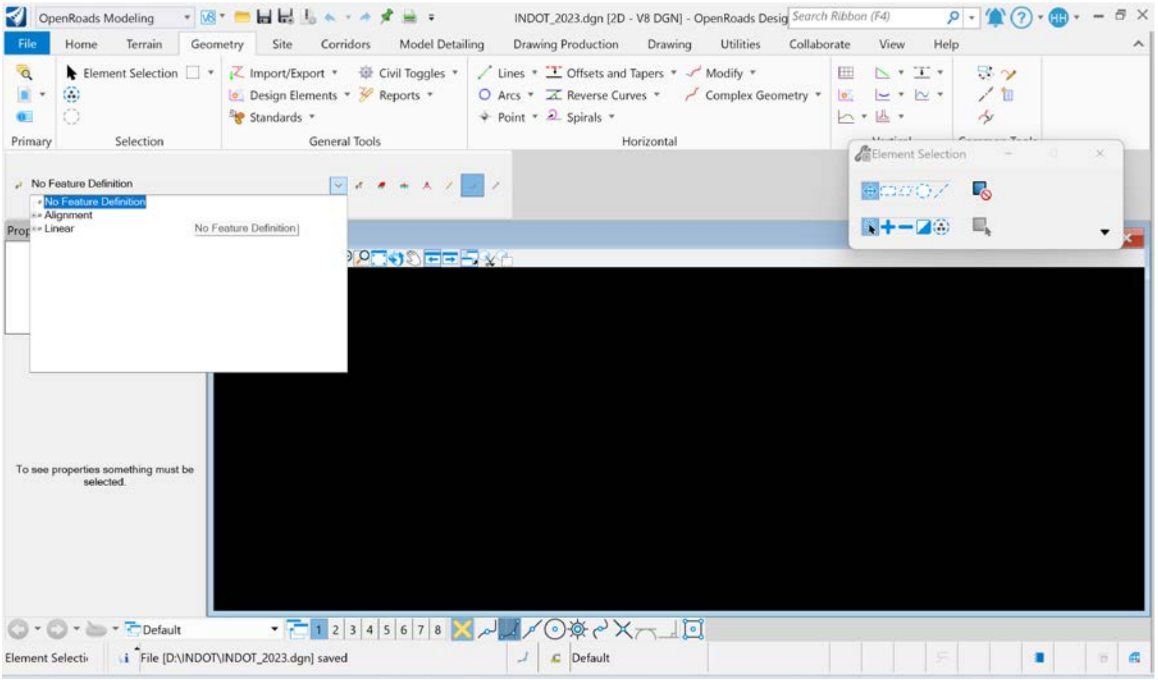


Figure B.36 Select the feature definition.

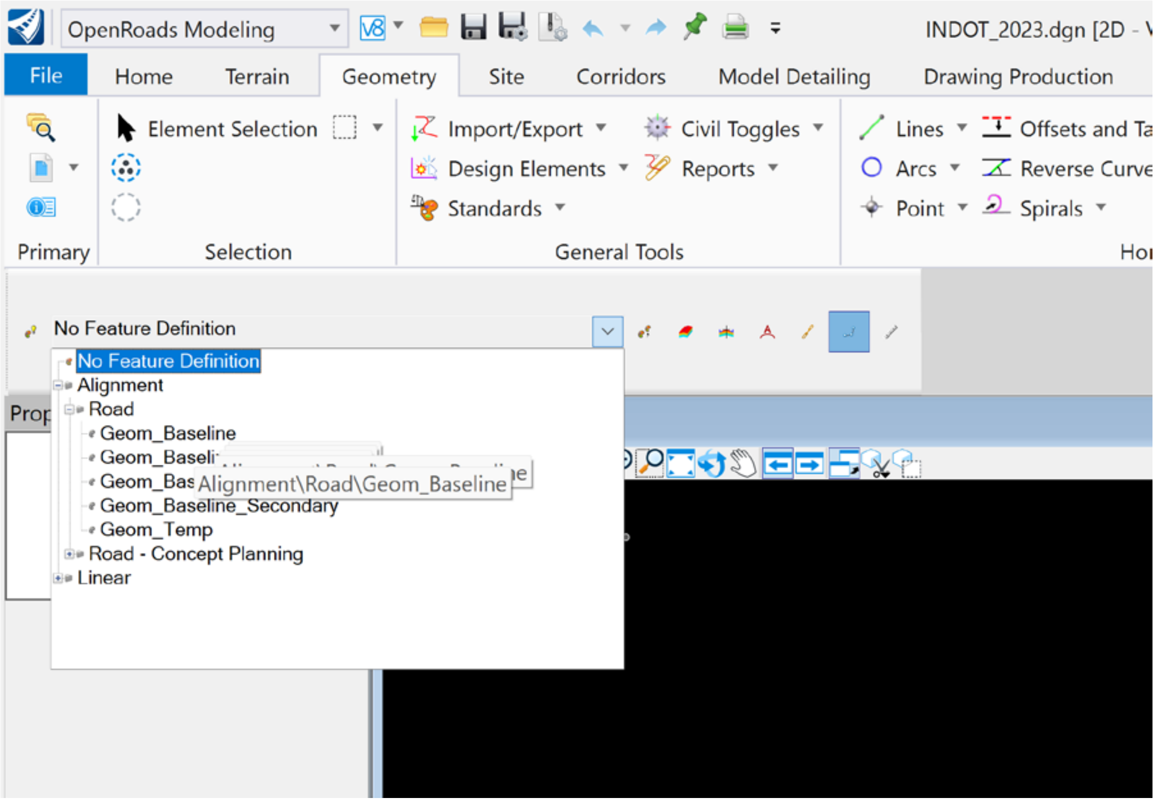


Figure B.37 Select the “geom_baseline” as a feature definition.

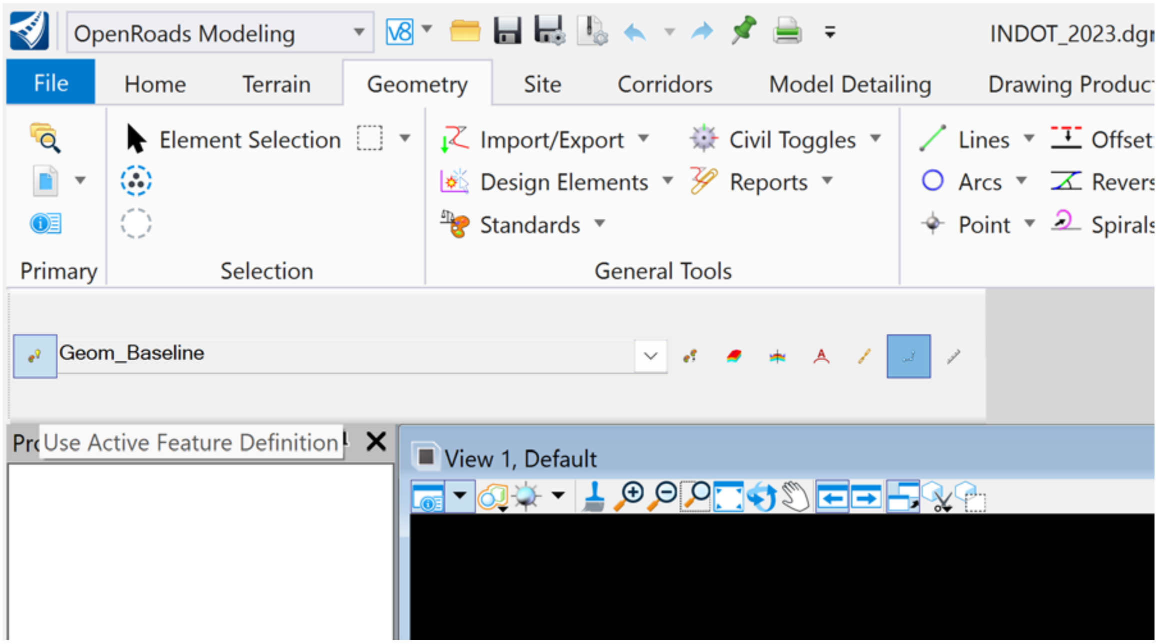


Figure B.38 Make active the "geom_baseline" as a feature definition.

Third Step: 2D Design Geometrics Alignments—according to (INDOT, 2022c).

- Create horizontal tangent elements: Attach tools (geometry and terrain) as references, as shown in the following steps.

Create horizontal tangent elements and terrain (Go to Home Tab>Attach Tools> References> References Interface>Tools>Attach).

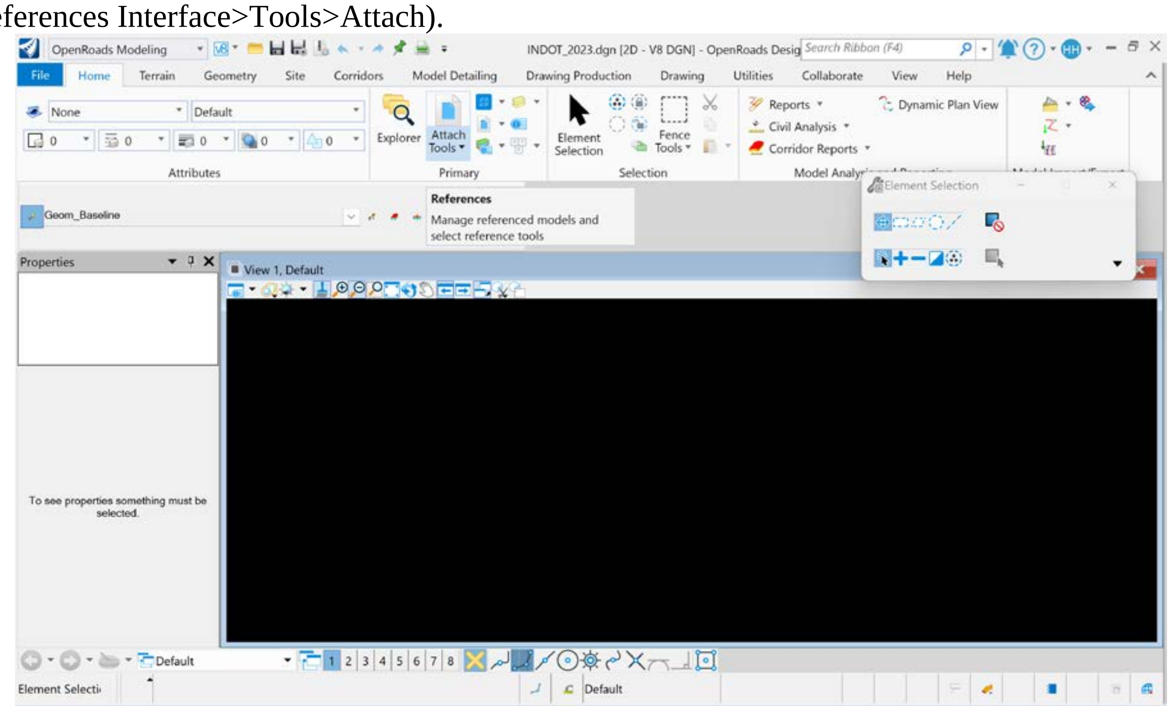


Figure B.39 Interface for selecting the "references."

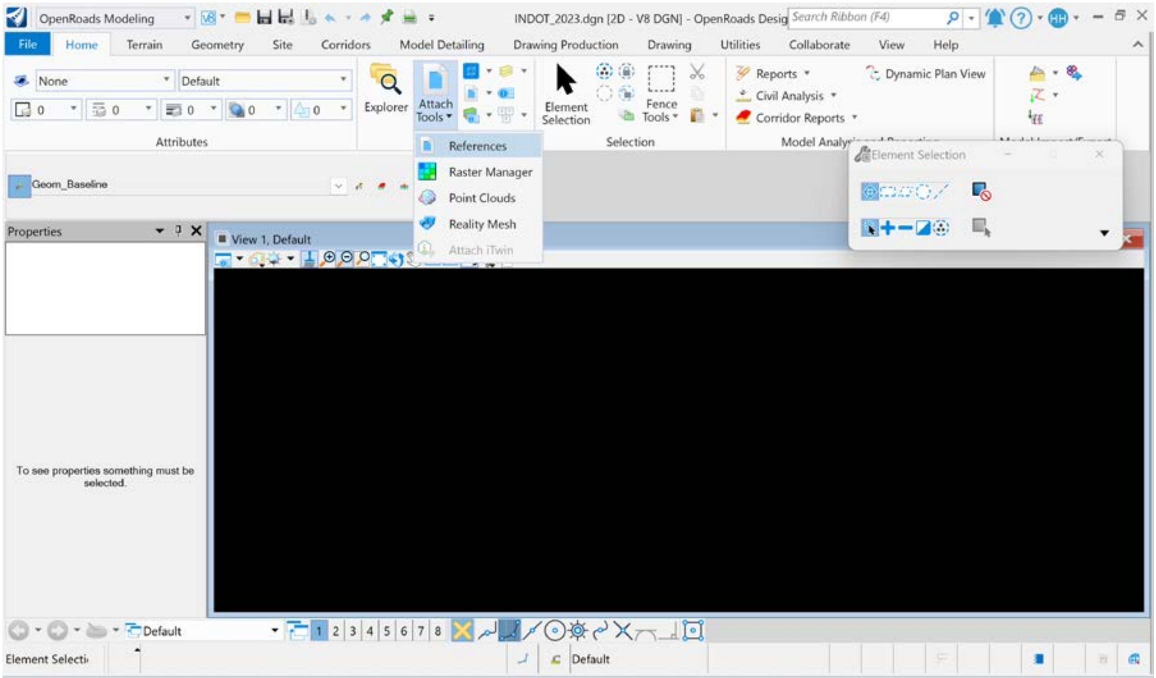


Figure B.40 Interface for selecting the “references” by using “attach tools.”

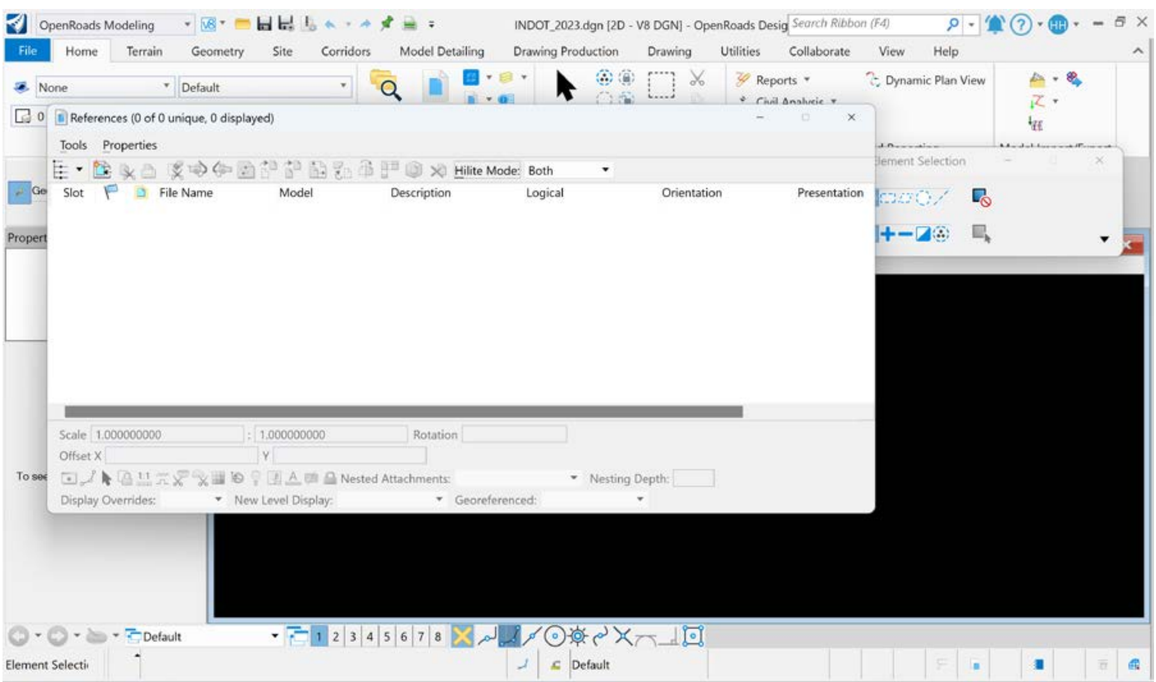


Figure B.41 References dialog.

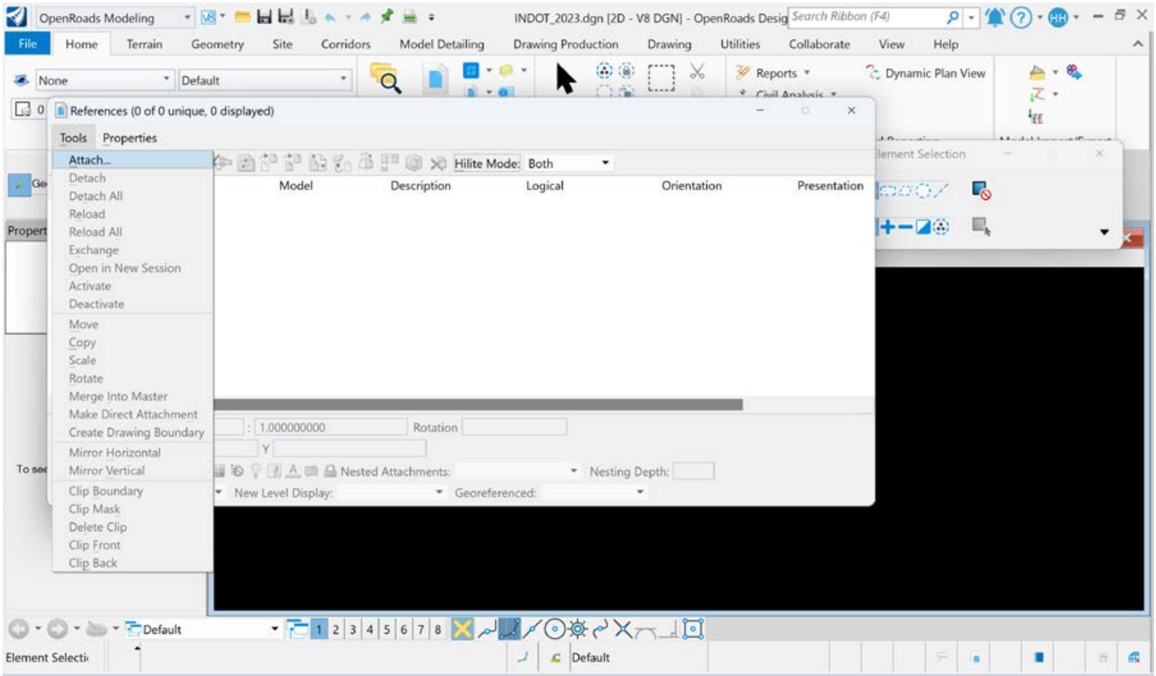


Figure B.42 From tools tab choose “attach.”

Notes: We can attach the file adapted from the (\ORD Documents - 2023\QuickStart for Geometry – Road) (located in the \References folder in the companion digital package).

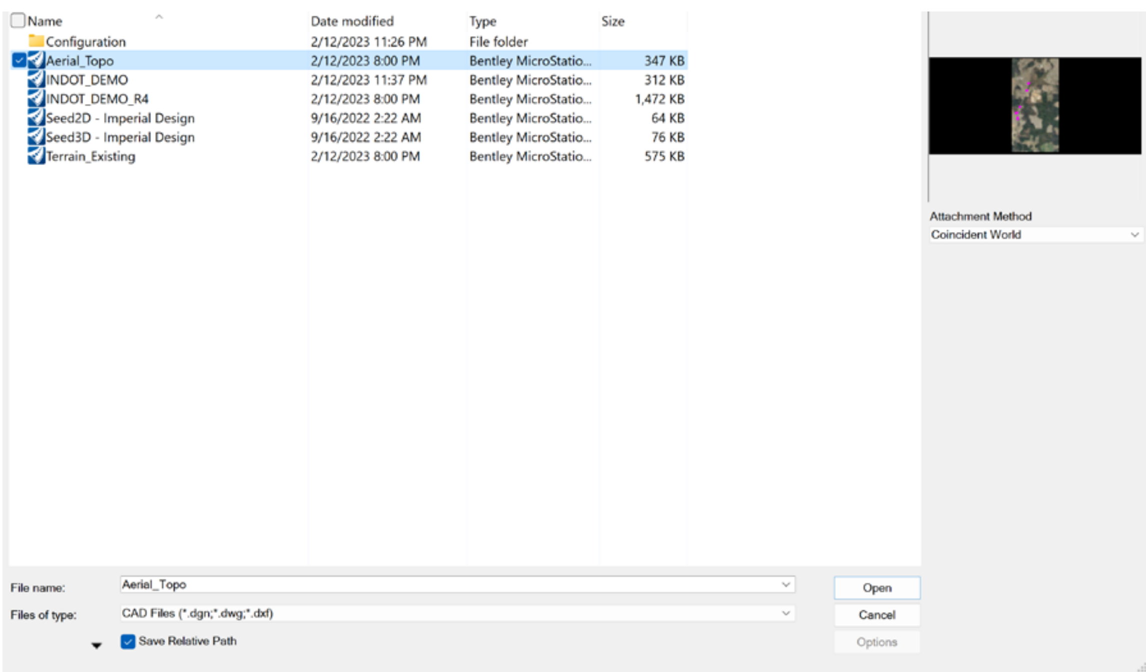


Figure B.43 Select “aerial_topo” as a reference for geometry.

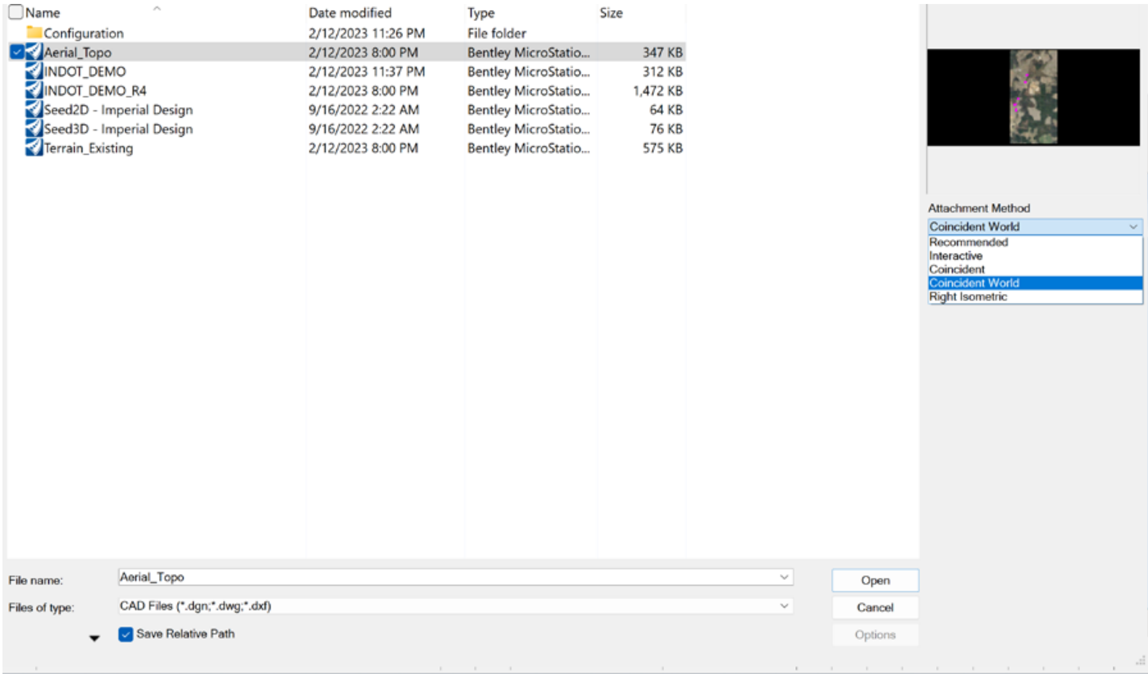


Figure B.44 Check the “attachment method” is “coincident world.”

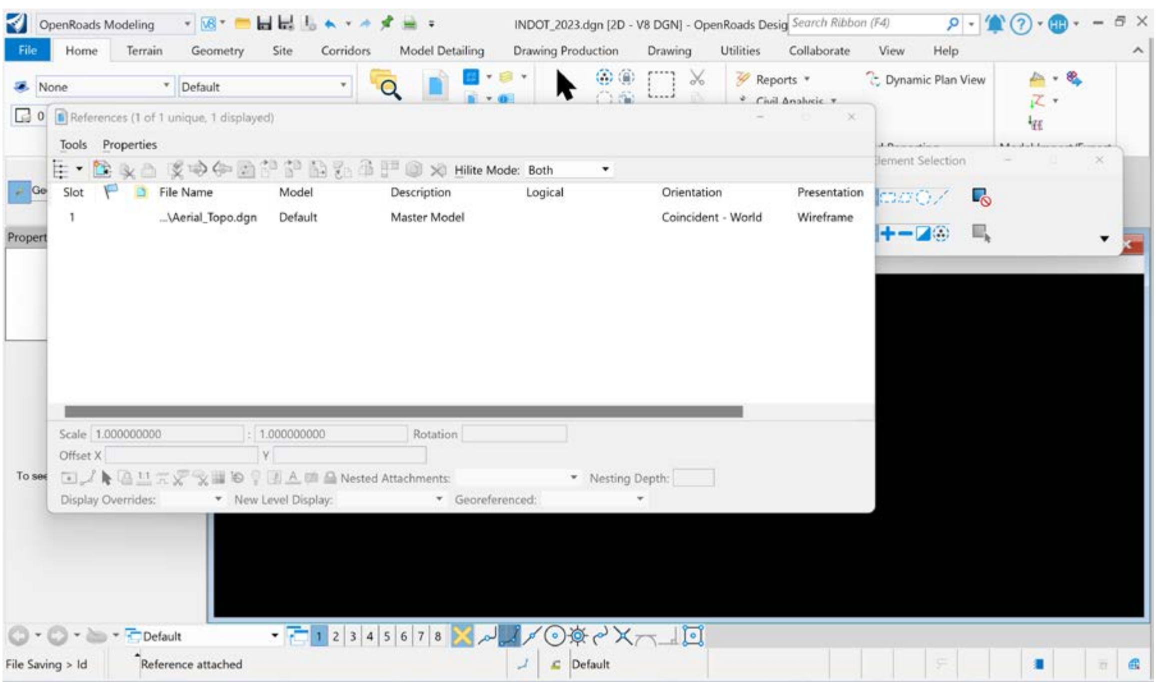


Figure B.45 Approve the import of an “aerial_topo” as a reference.

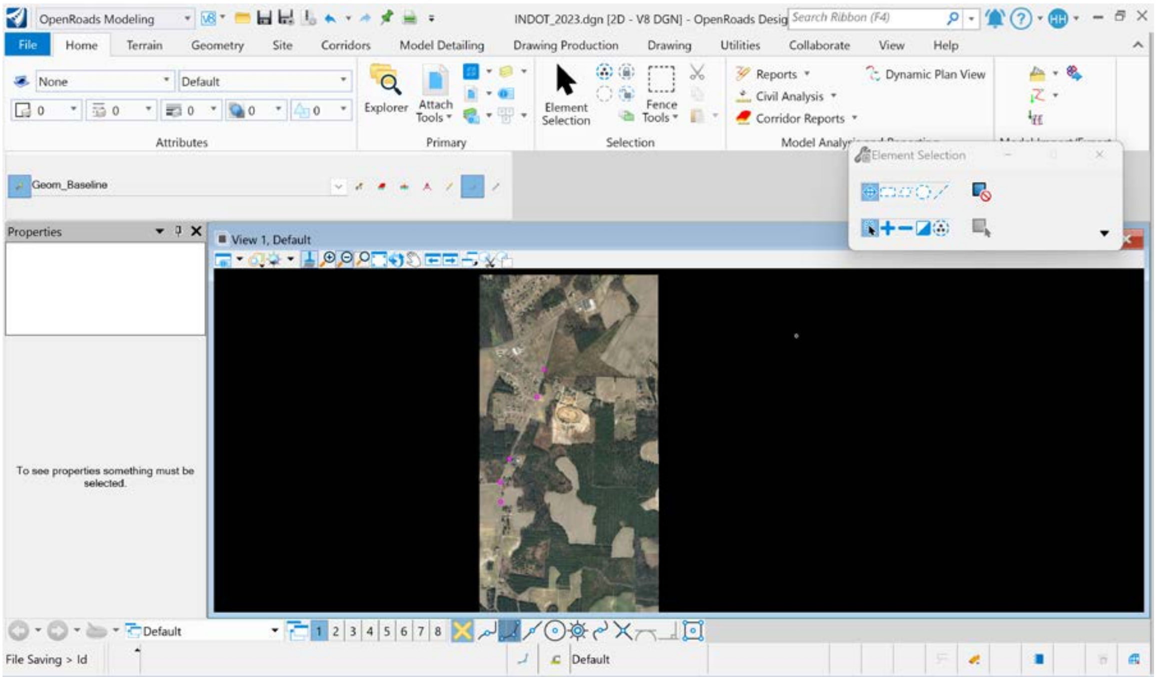


Figure B.46 Interface for the geometry shape.

- Create horizontal tangent and curves and alignment.

Steps to draw the profile line: *Geometry Tab>Lines> Line Between Points*

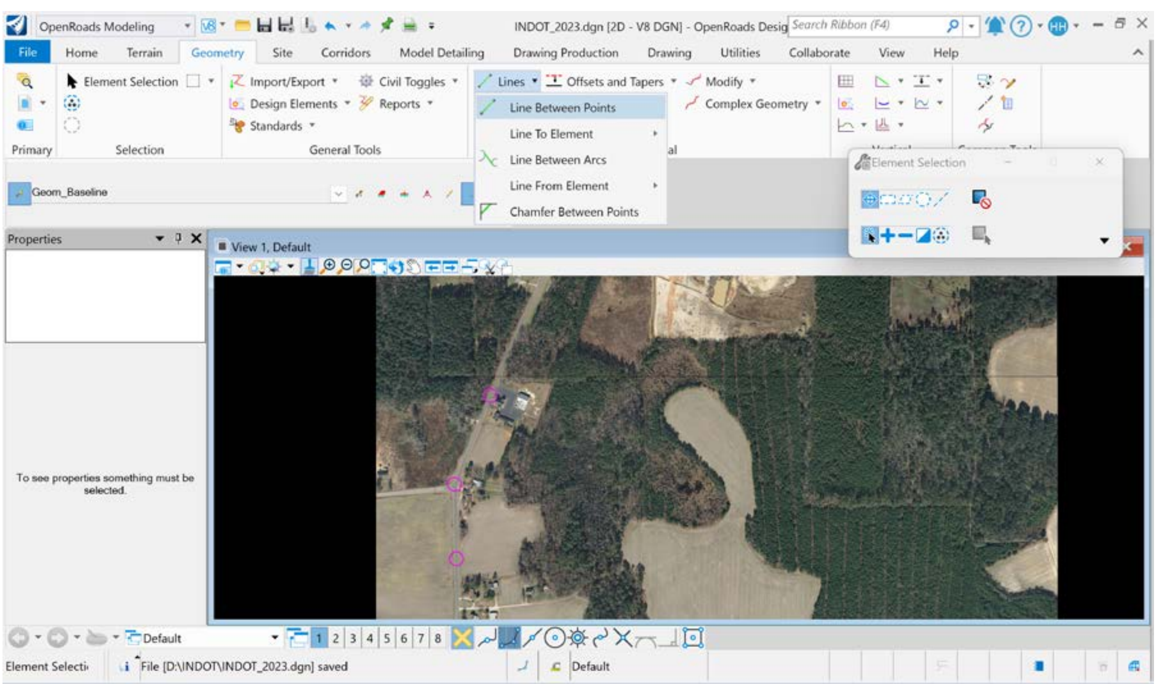


Figure 1.47 Identify the “line between points” to start drawing the profile.

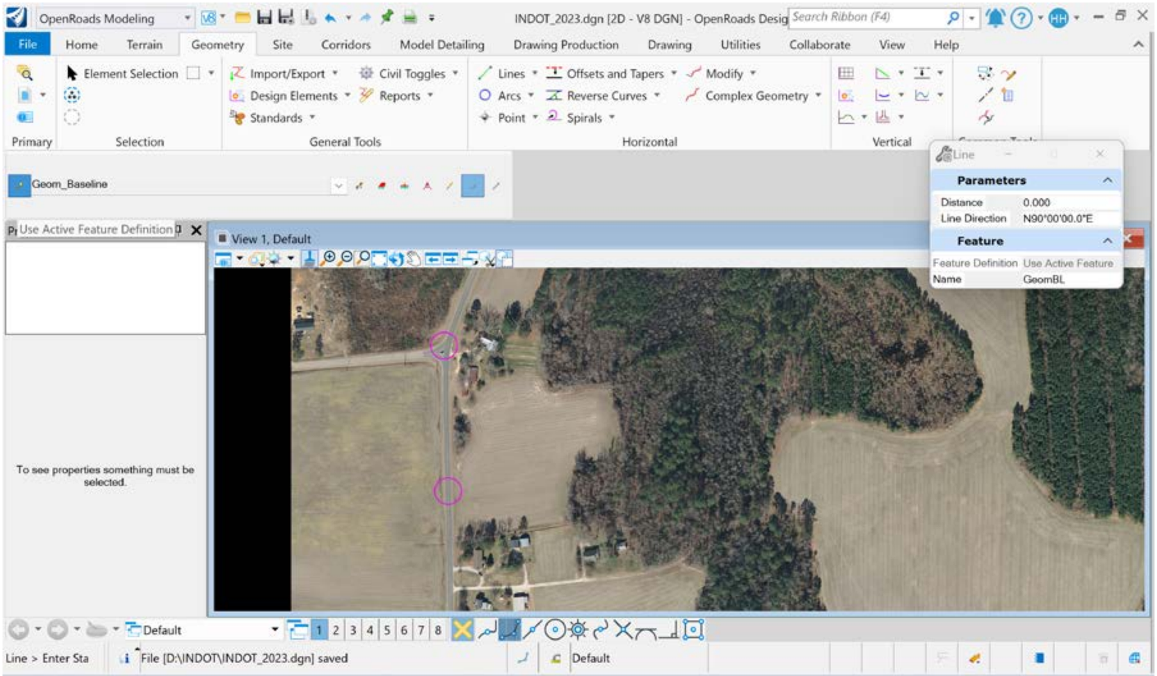


Figure B.48 Check the details of the line from “line” dialog.

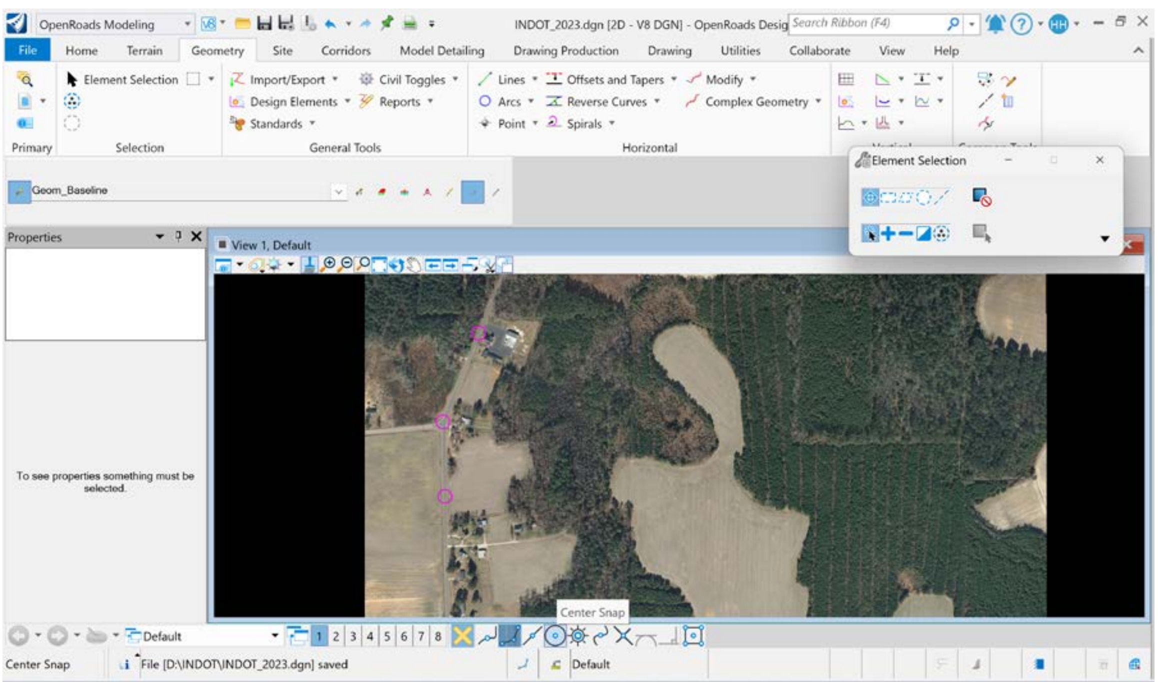


Figure B.49 To start from the center of the circle, select “center snap.”

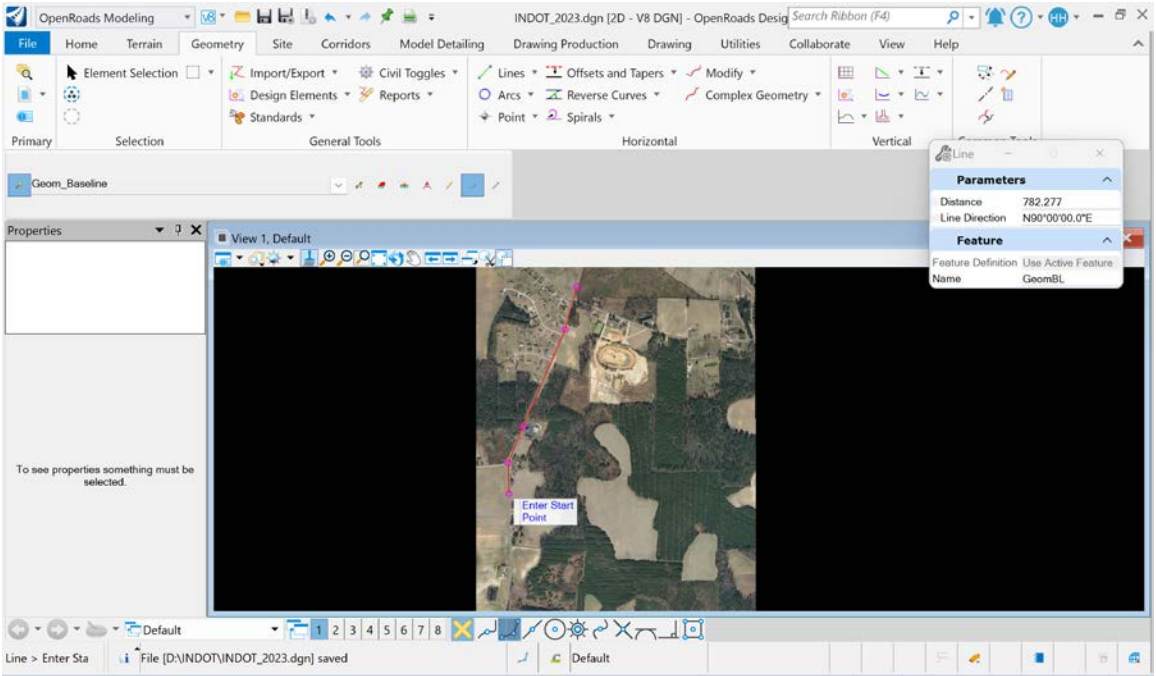


Figure B.50 Start to draw the line.

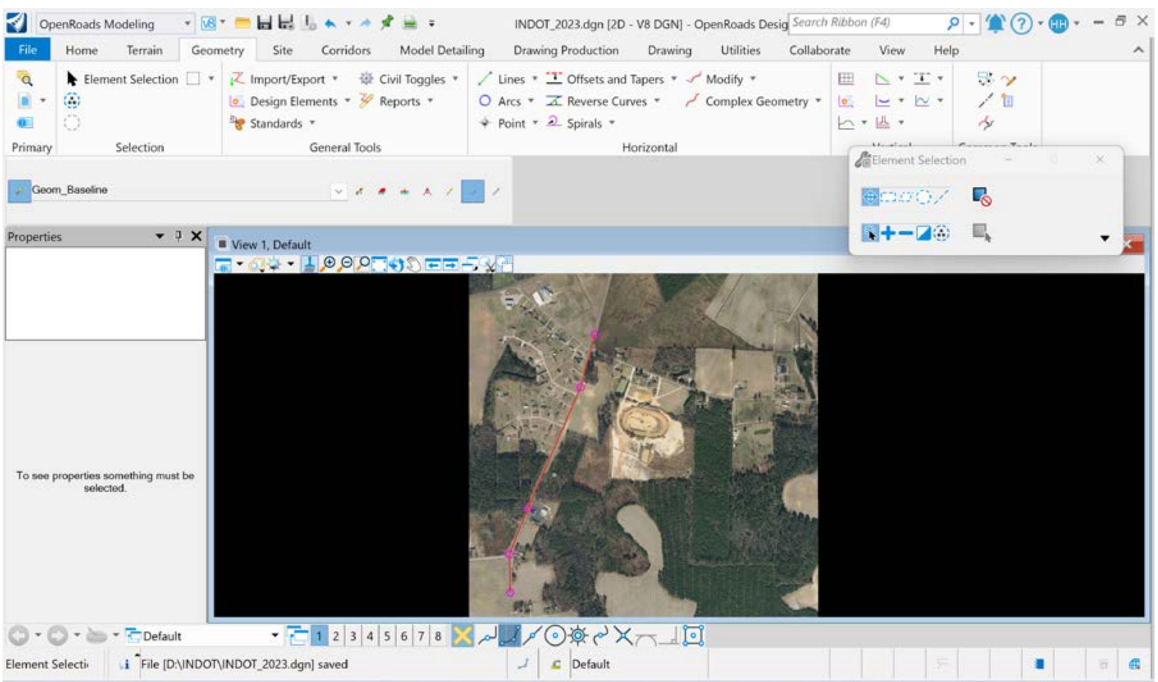


Figure B.51 Complete the line for all points.

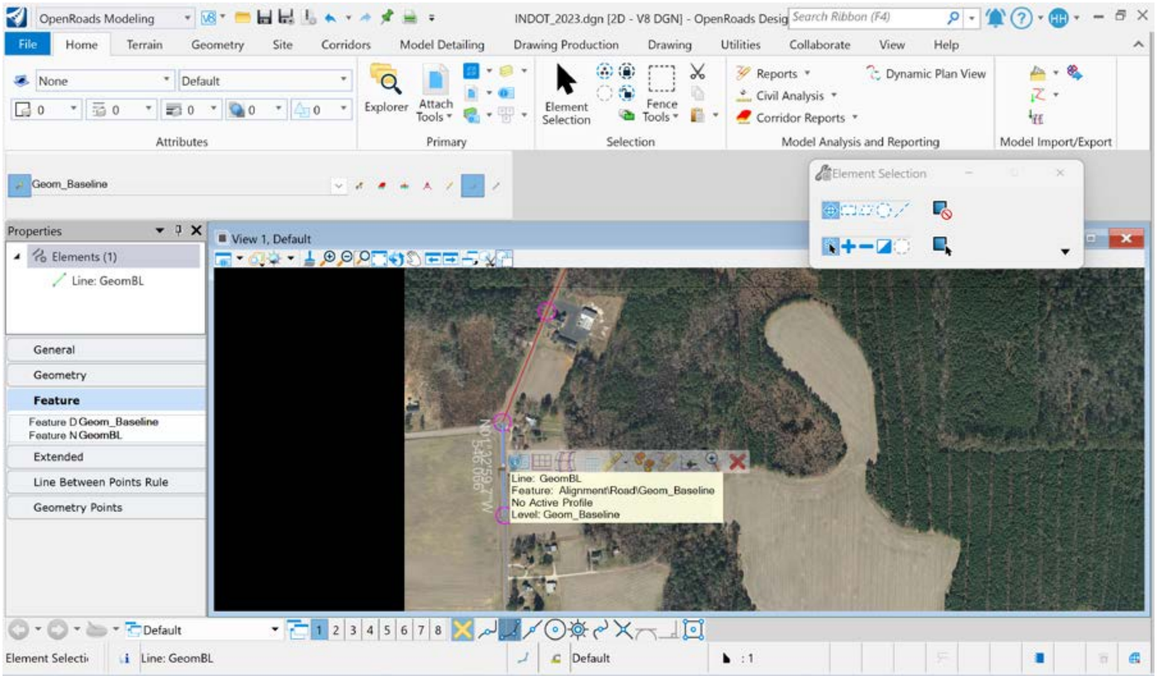


Figure B.52 Select the line to check the details.

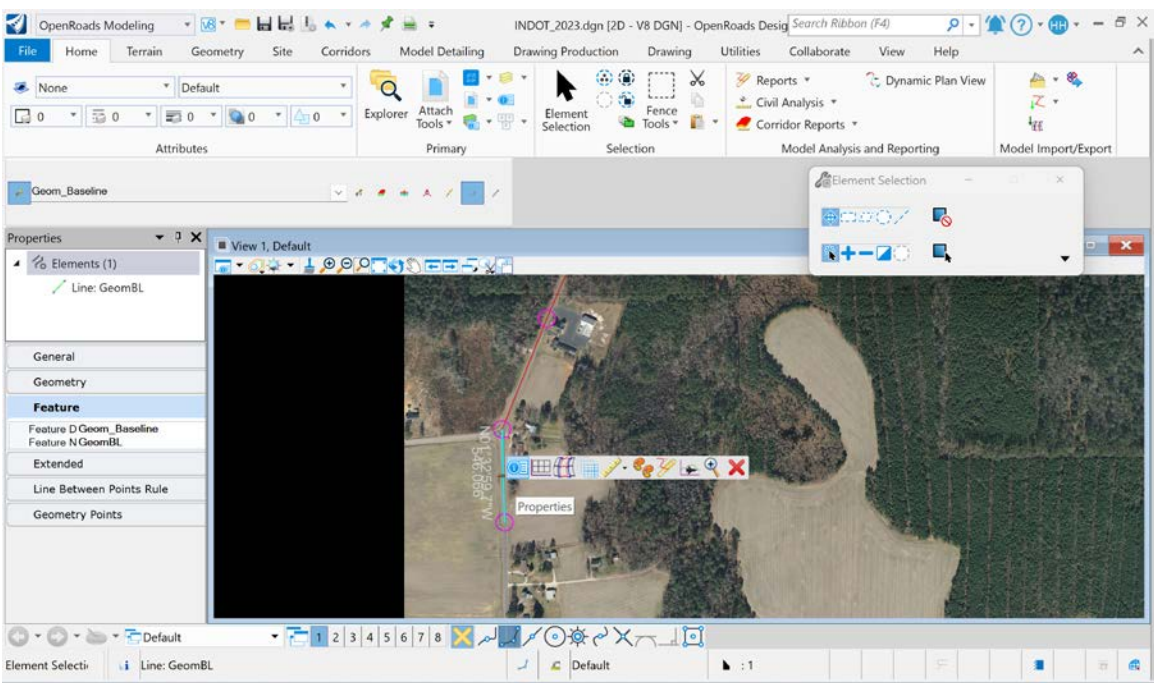


Figure B.53 For reviewing all details, select the “properties.”

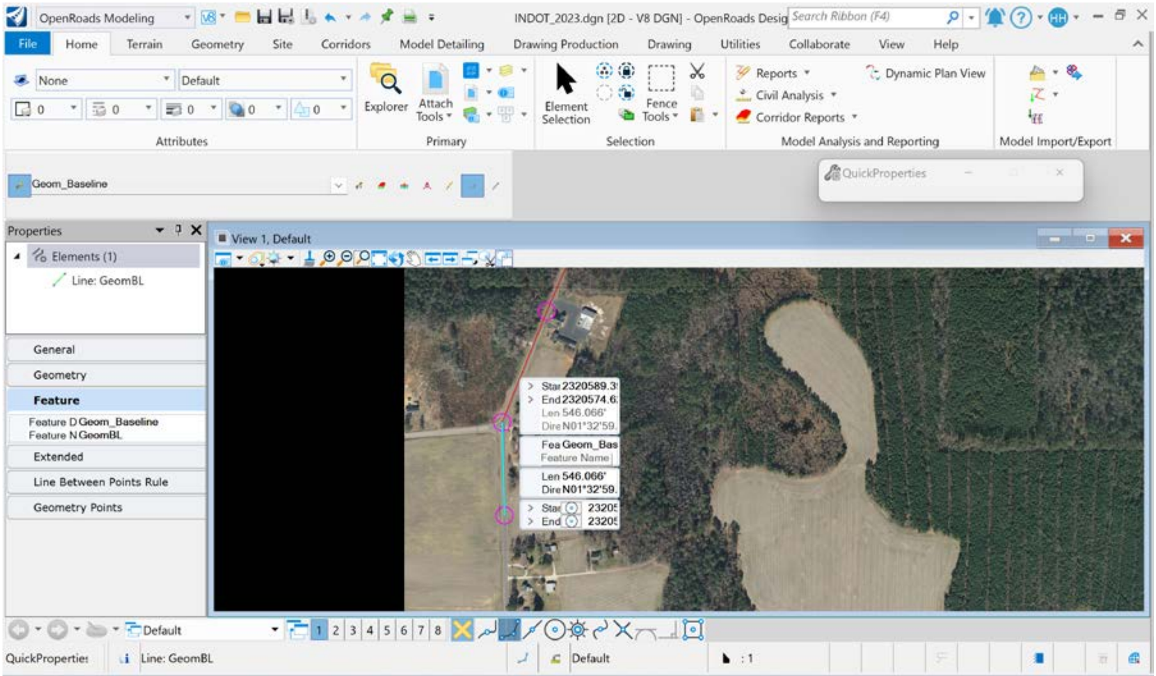


Figure B.54 The properties for the line.

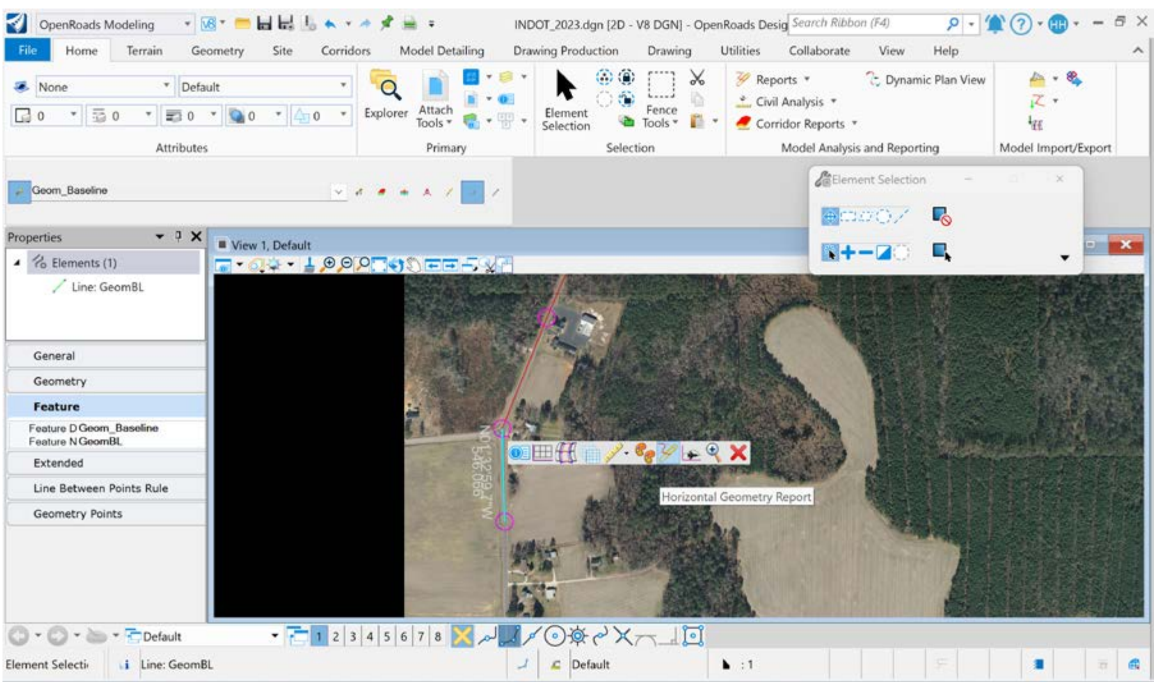


Figure 2.55 Export the "horizontal geometry report."

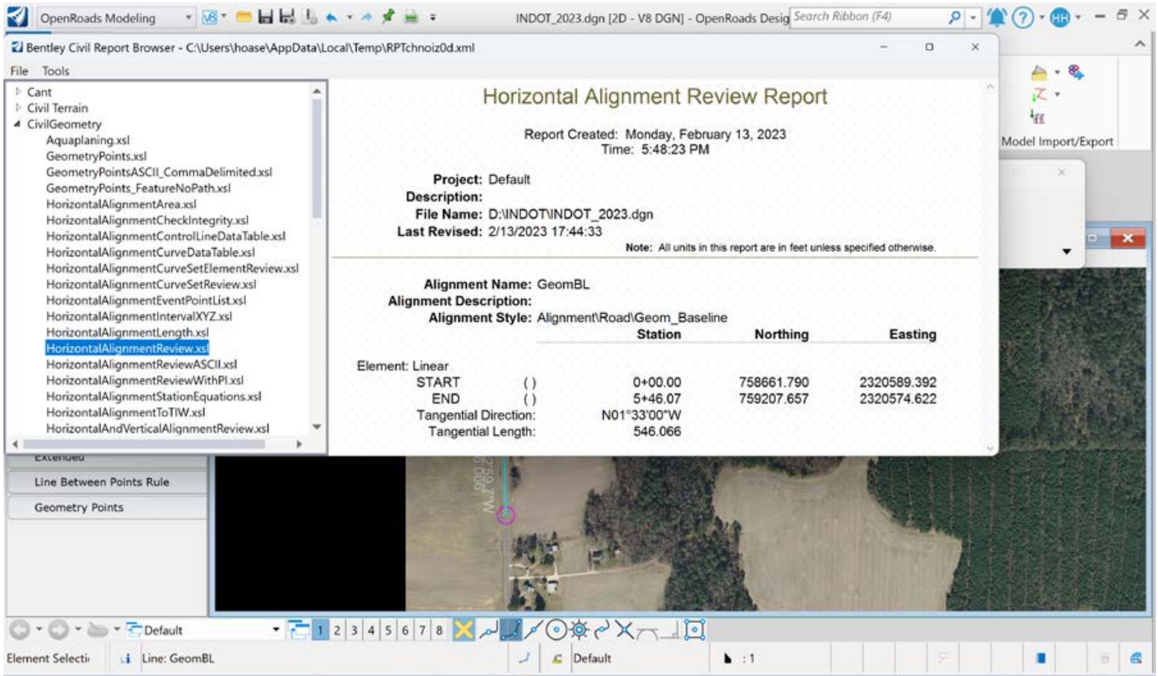


Figure B.56 Interface for the “horizontal geometry report.”

- Draw the arc between the elements: *Geometry Tab>Arcs> Arc Between Elements>Simple Arc*

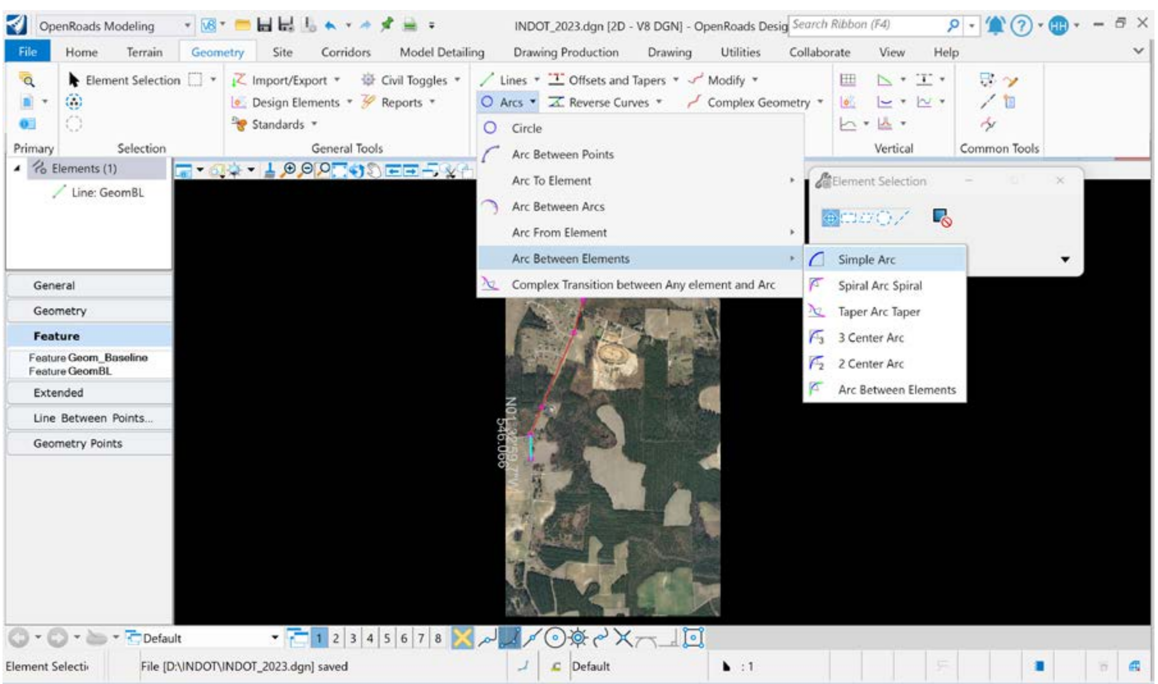


Figure B.57 Draw a simple arc between elements.

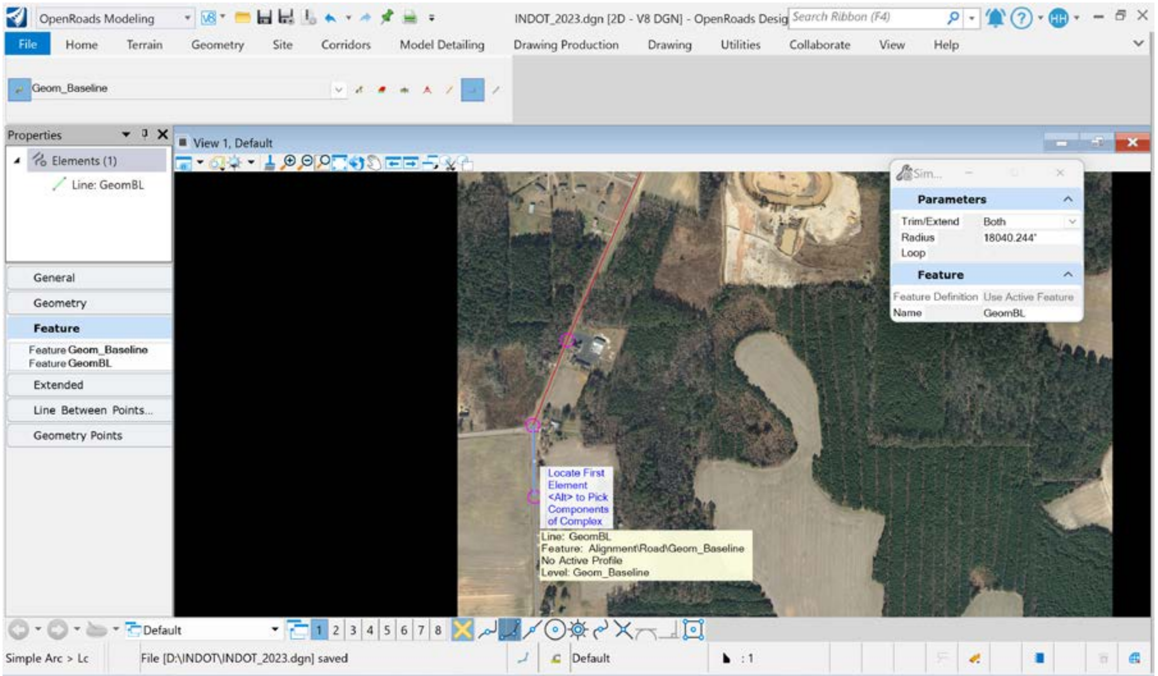


Figure B.58 Select the first element.

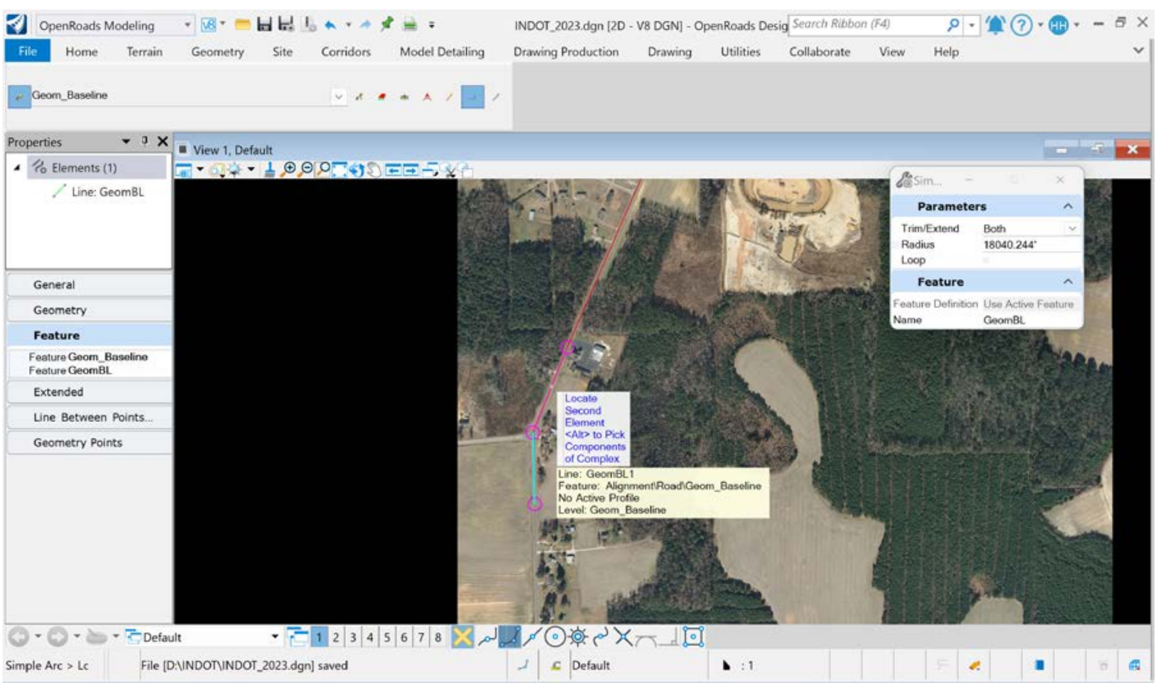


Figure B.59 Select the second element.

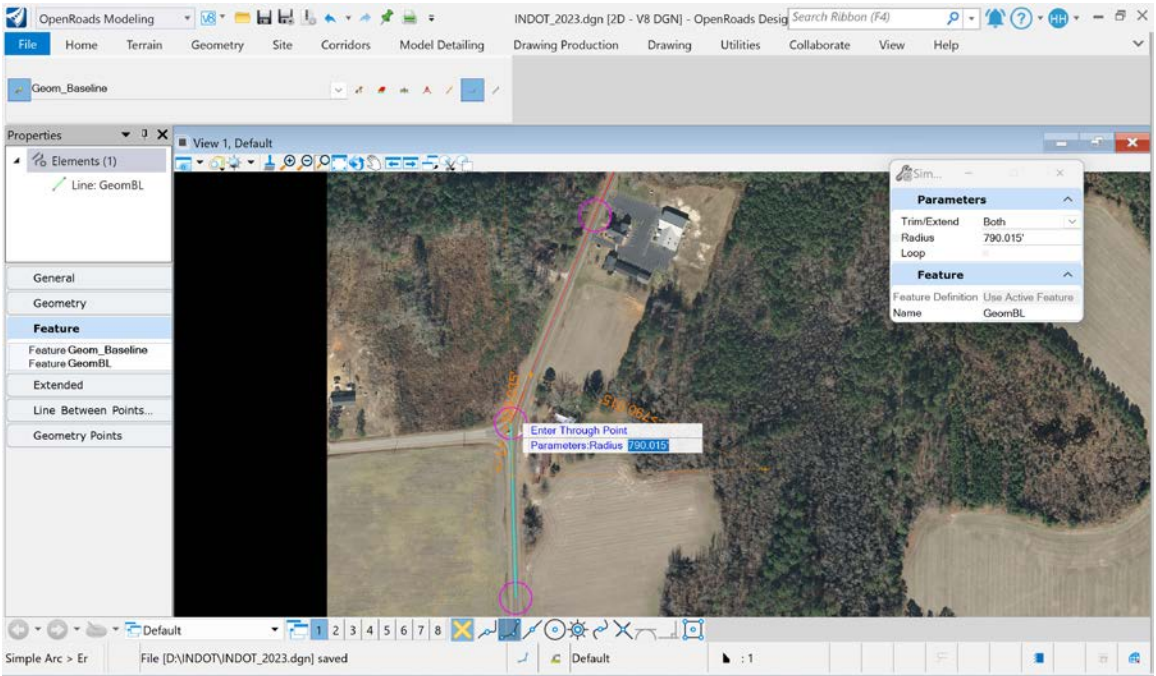


Figure B.60 Define the appropriate radius.

Left click to accept that.

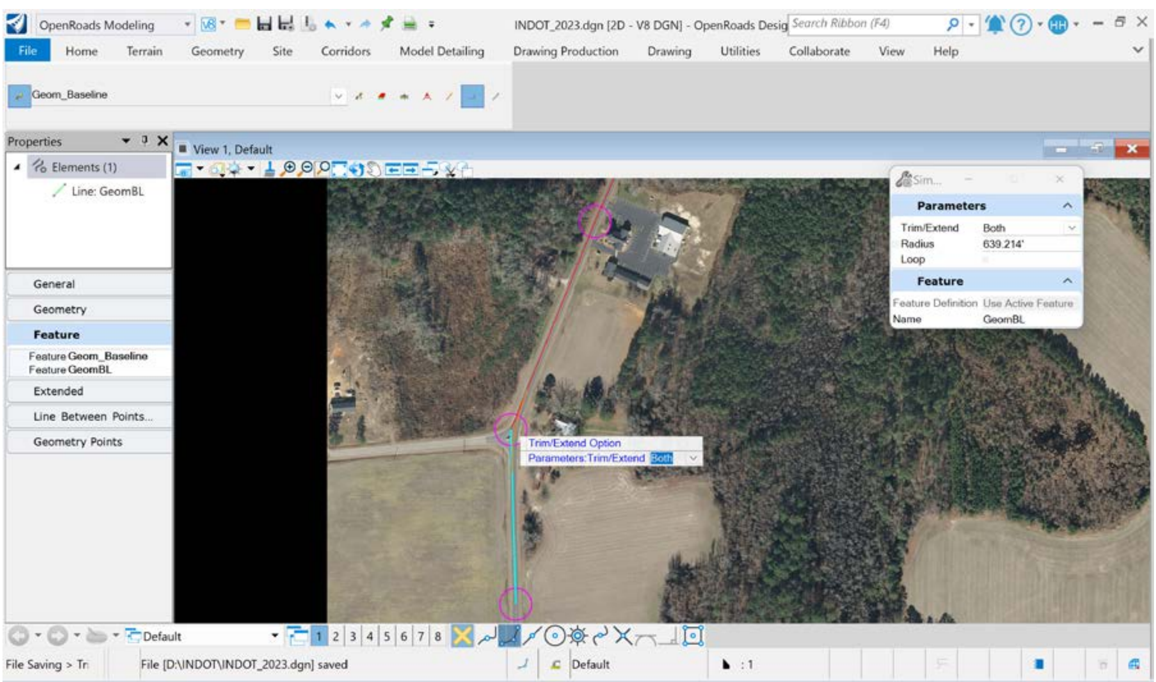


Figure B.61 Trim/extend option (both).

Left click to accept that.

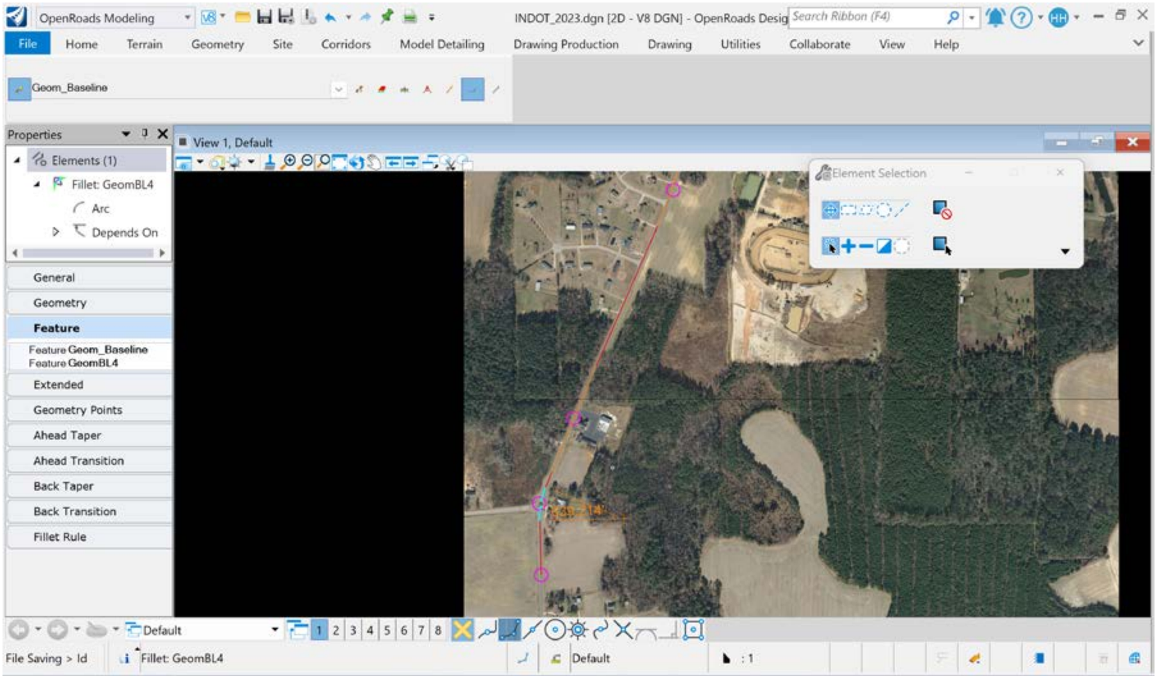


Figure B.62 Complete the arc between all pairs of two elements.

Identify the line as a “complex geometry” to define all lines and arcs as a one line (one element): *Geometry Tab>Complex Geometry> Select the line.*

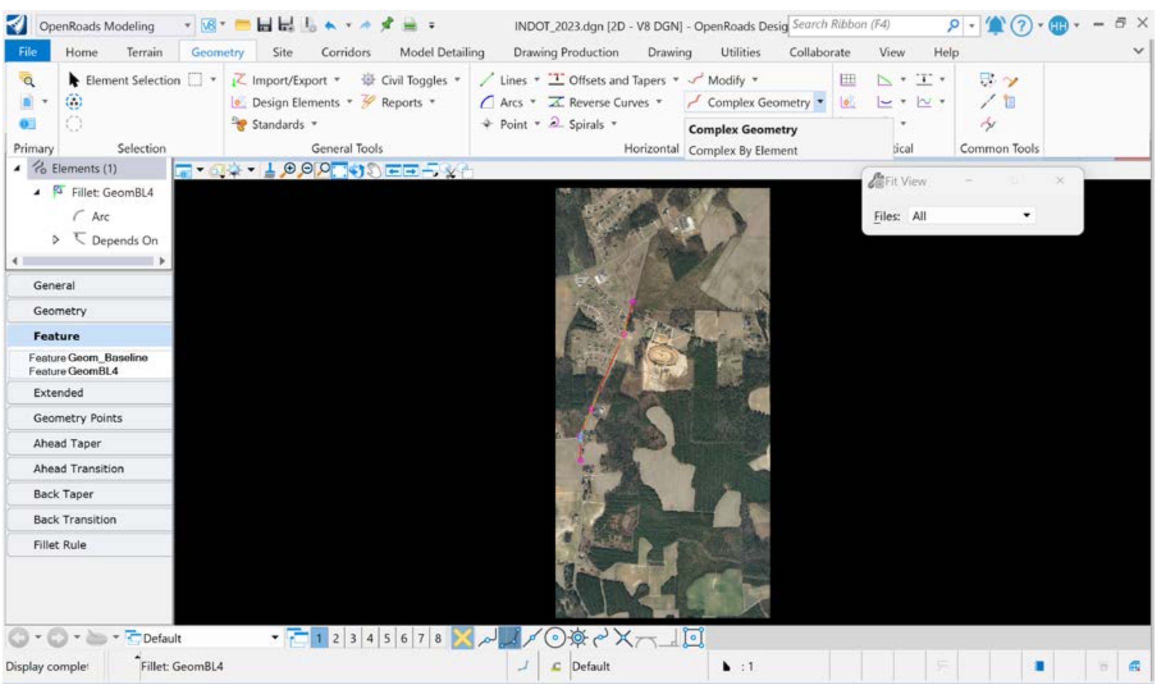


Figure B.63 Choose the “complex geometry.”

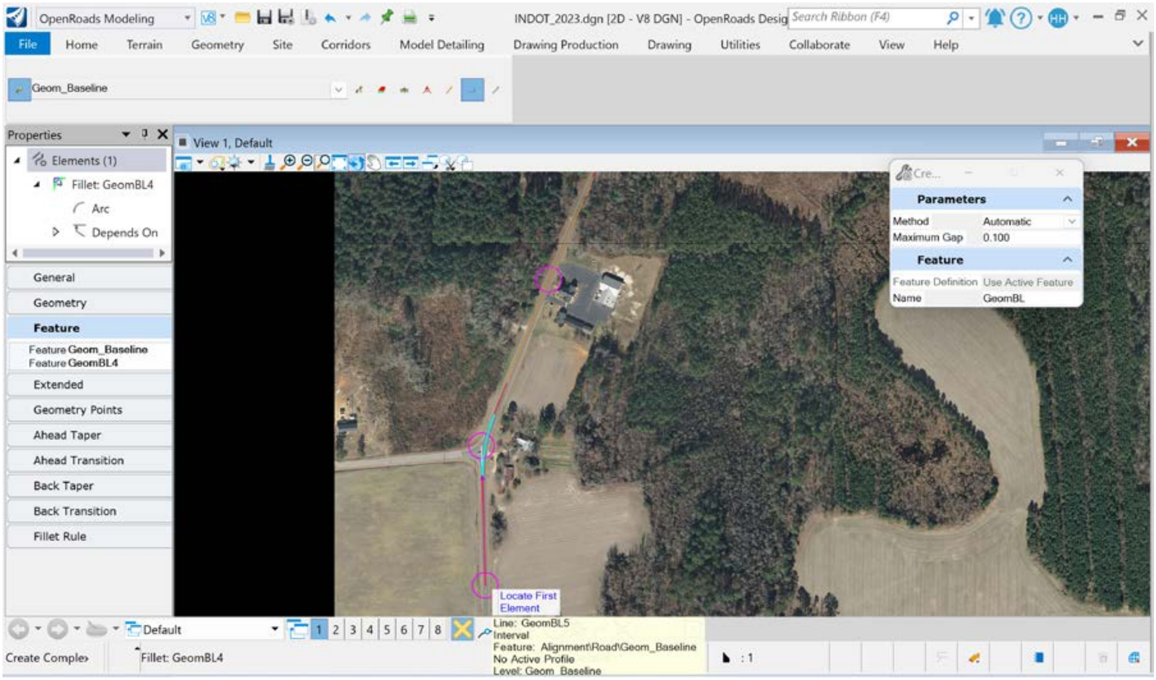


Figure B.64 Select the first element and check the arrow direction.

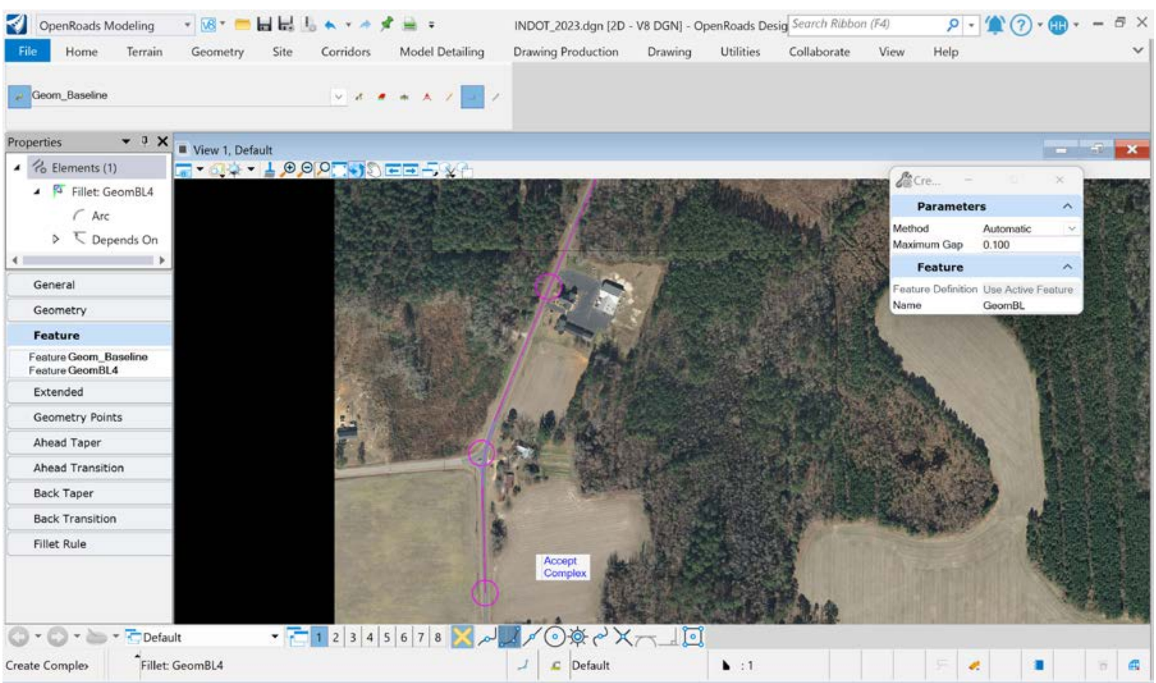


Figure B.65 “Accept complex.”

Right click to accept that.

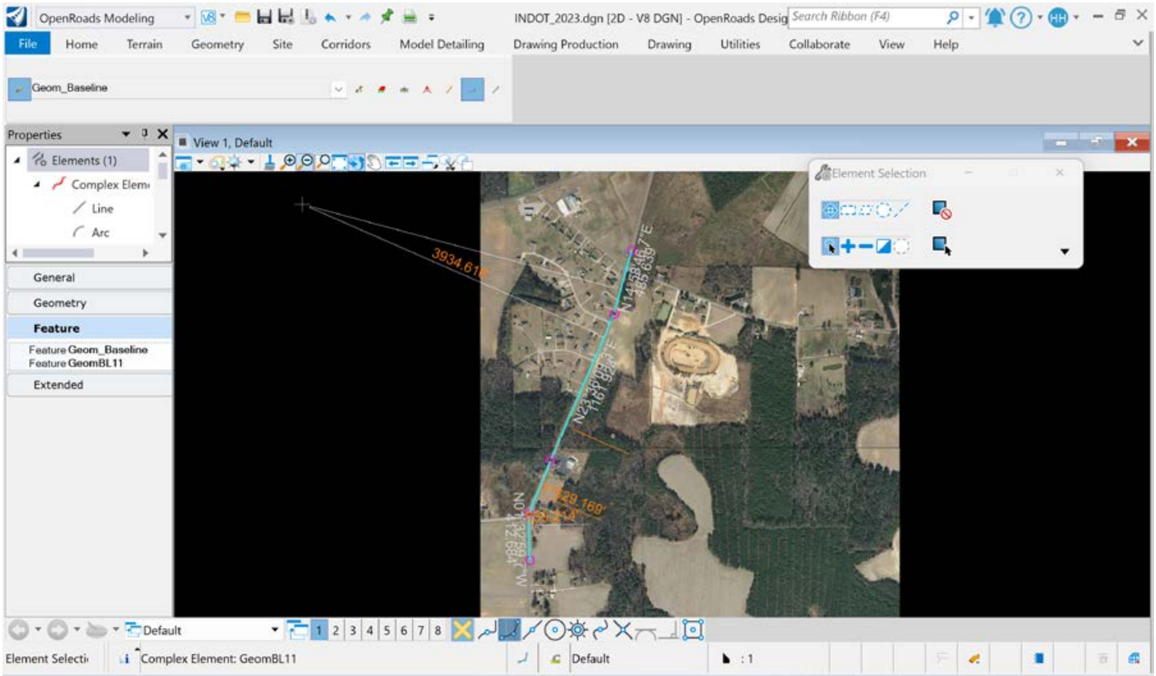


Figure B.66 Interface for the line as a "complex element."

Identify the start station (0.00): *Geometry Tab>Modify>Start Station*

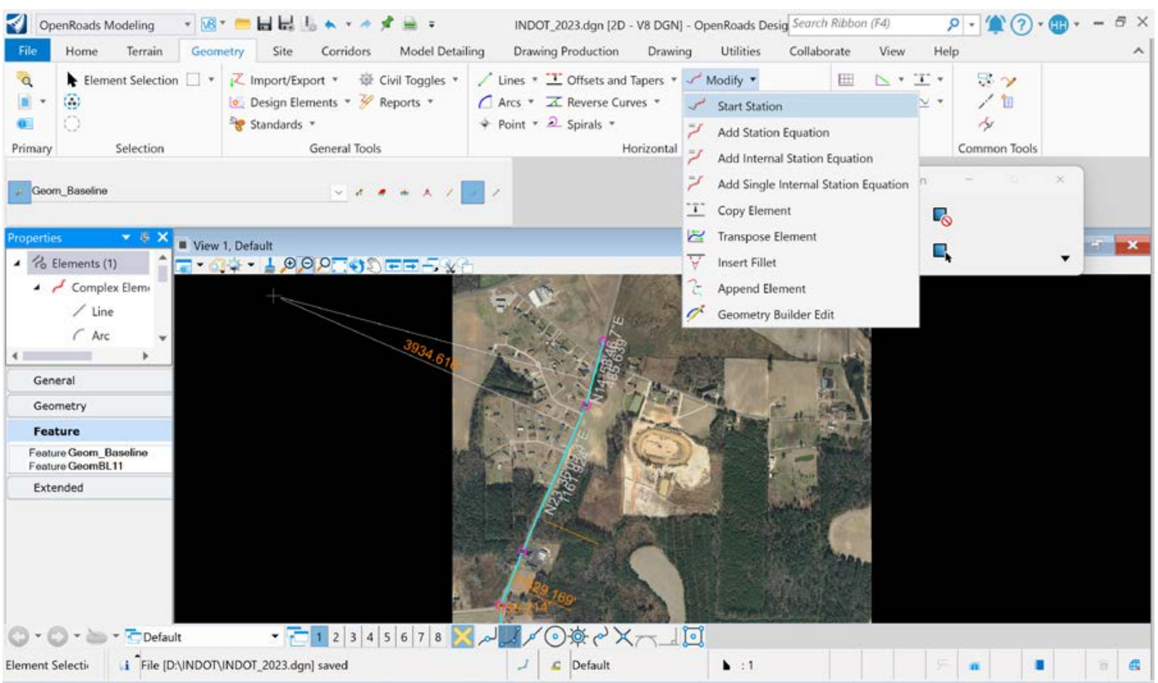


Figure B.67 Choose the "start station."

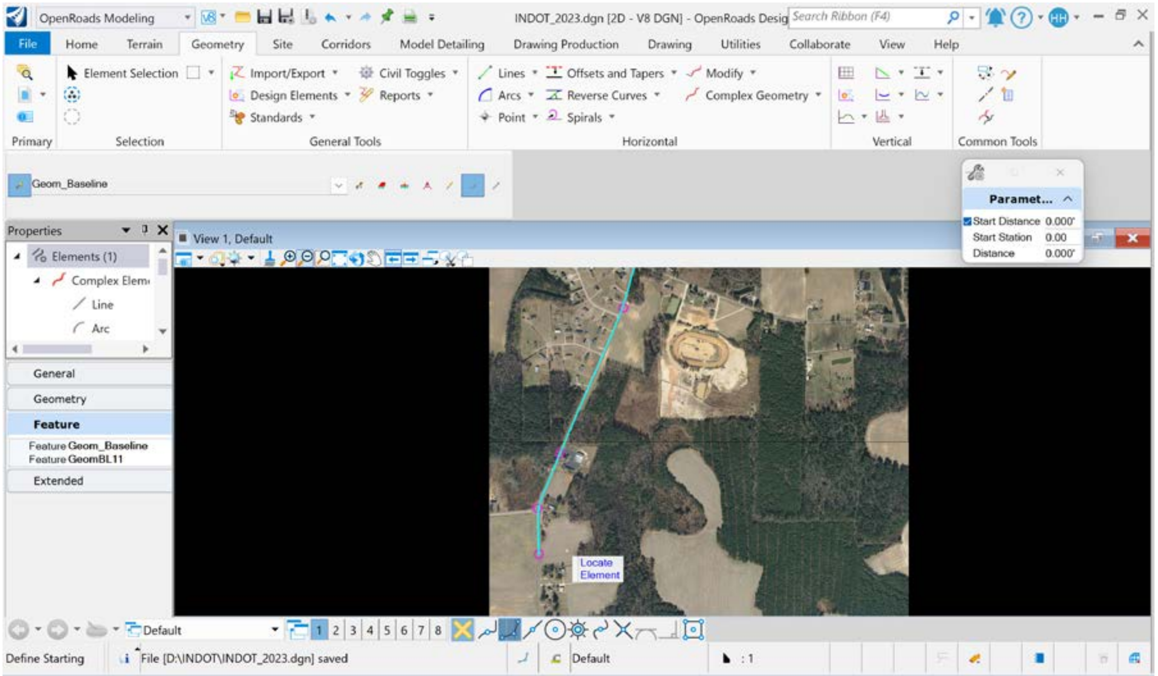


Figure B.68 Select the element (line).

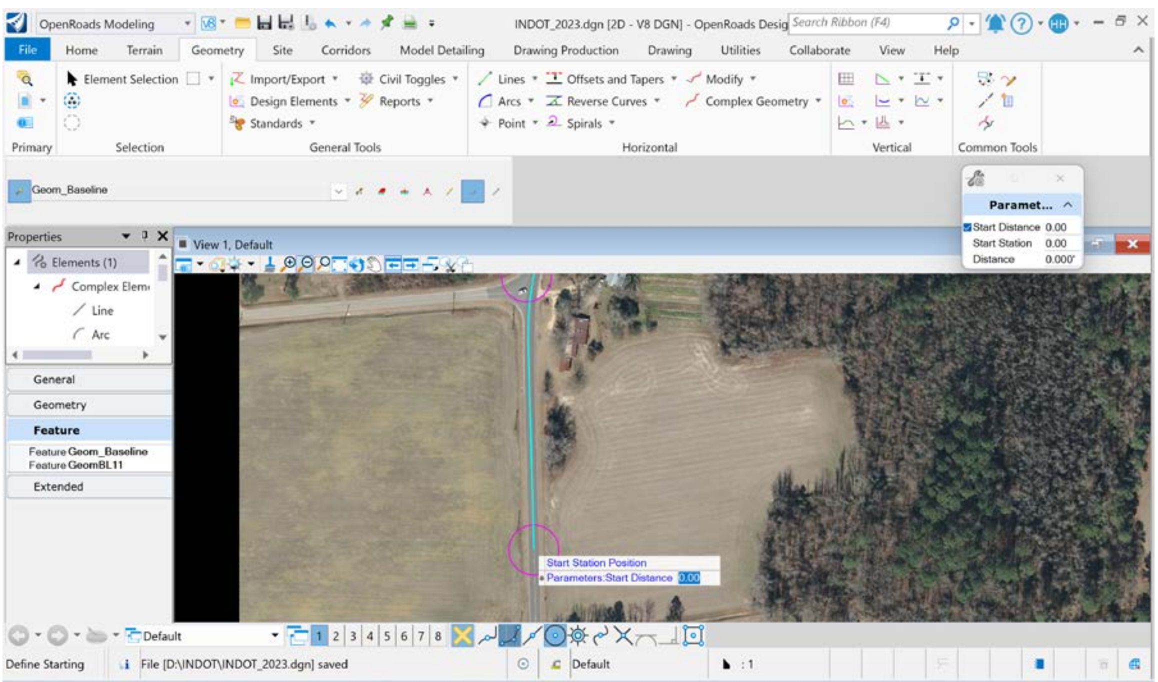


Figure B.69 Define the start station position.

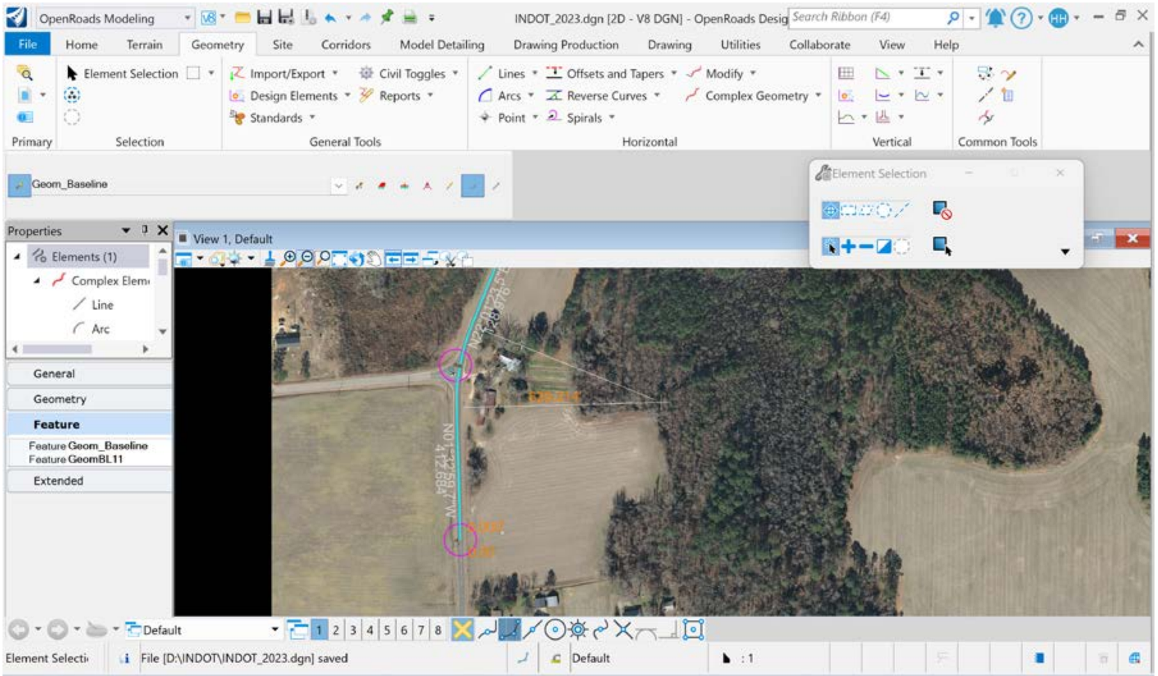


Figure B.70 Interface for the details of the station point and the line.

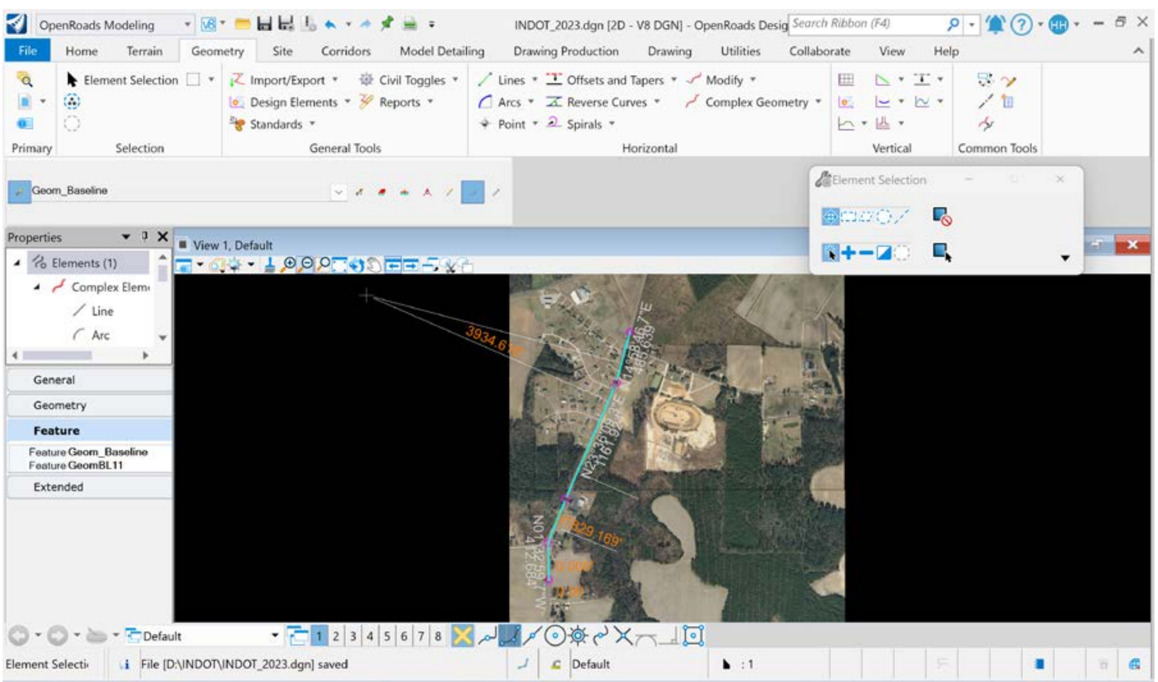


Figure B.71 Interface for the final details of the line.

Attach tools (Geometry and Terrain) as references: Home Tab>Attach Tools> References> References interface>tools>Attach>Select Terrain_Existing

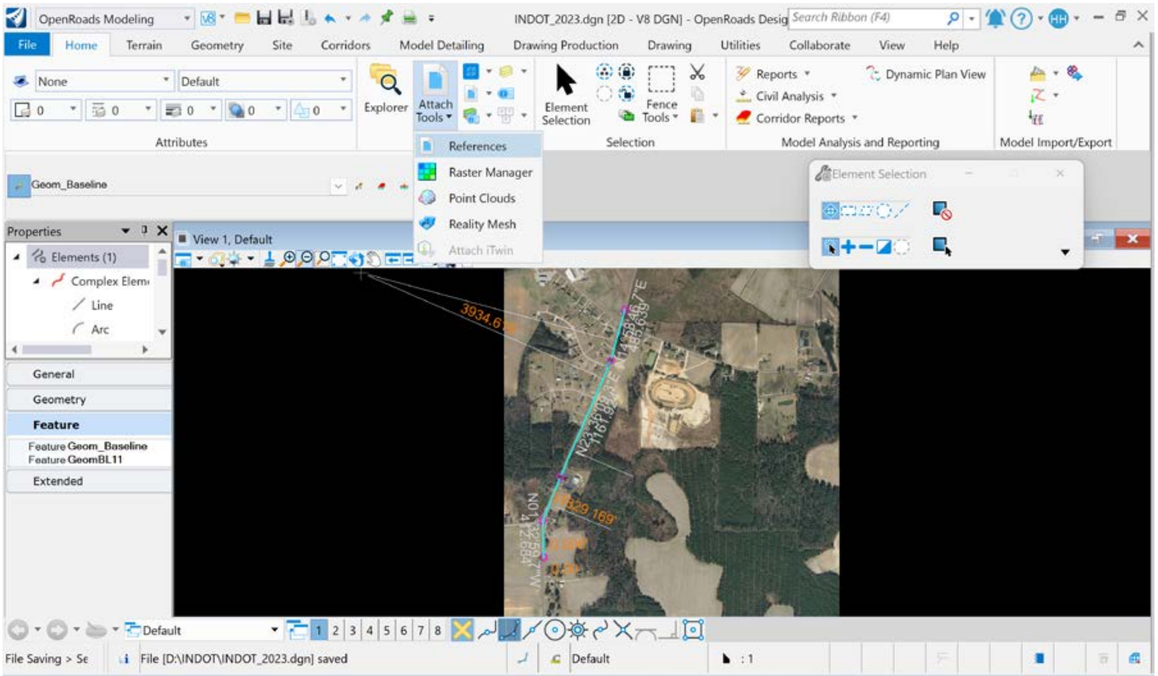


Figure B.72 Choose the “references” from “attach tools” list.

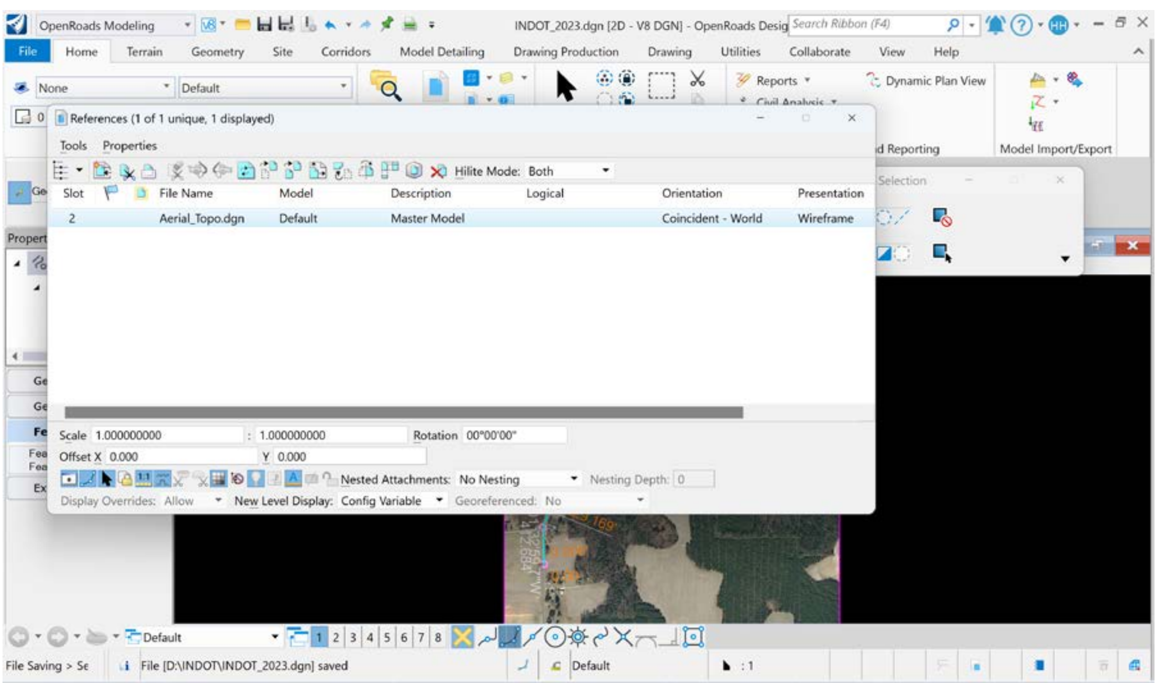


Figure B.73 References dialog.

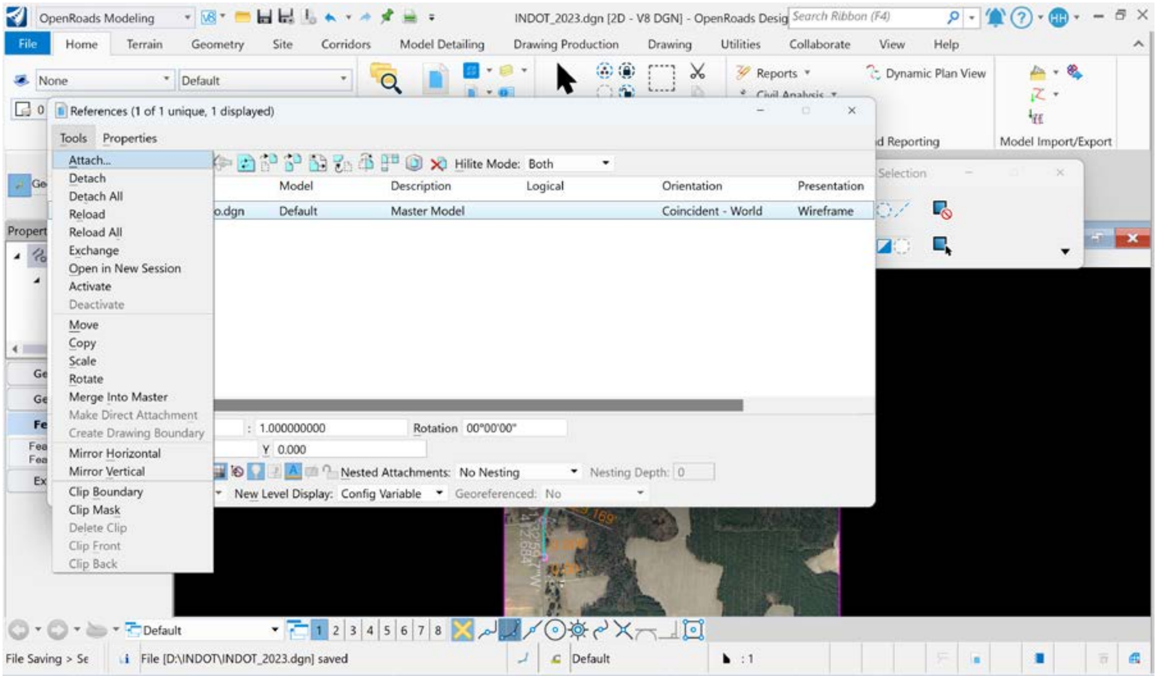


Figure B.74 Select “attach” from “tools” list.

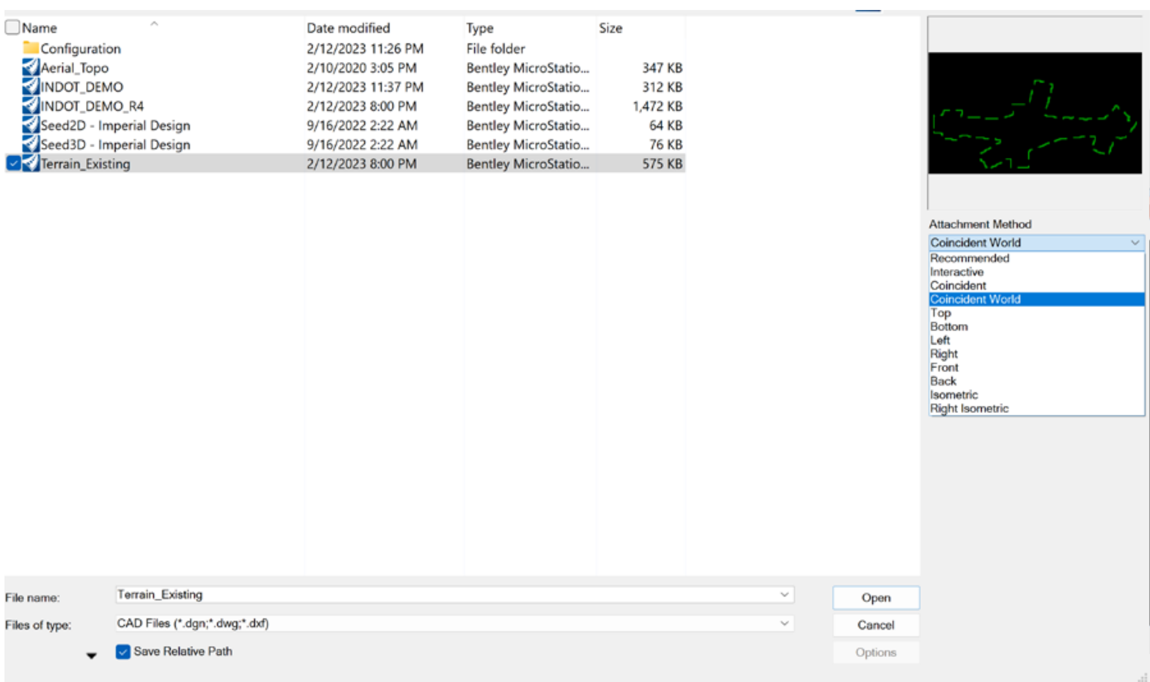


Figure B.75 Select “terrain existing” and check “attachment method” as a “coincident world.”

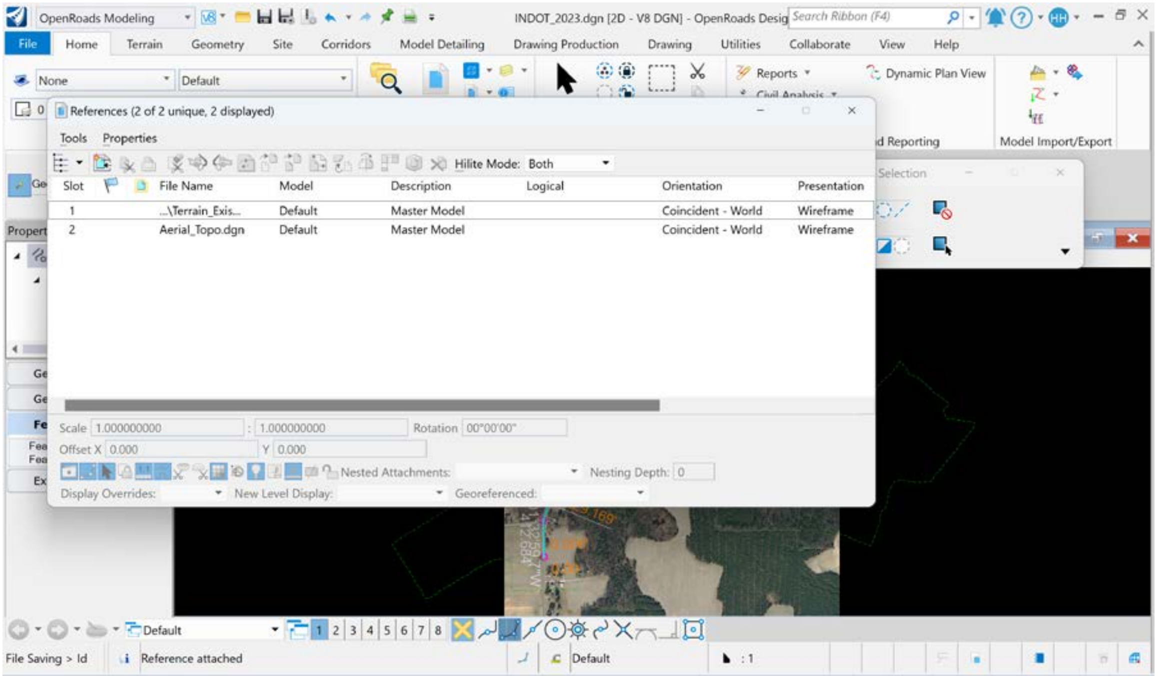


Figure B.76 Interface for the "references" dialog after adding a new reference.

Close the interface.

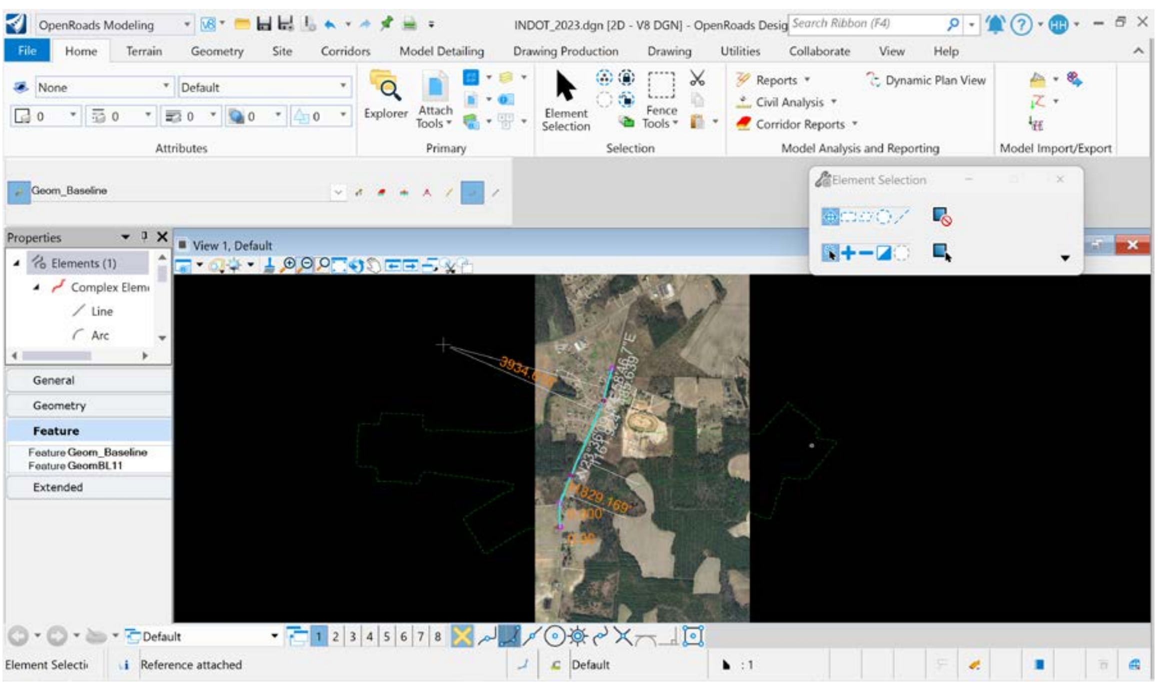


Figure B.77 Interface for the terrain and geometry.

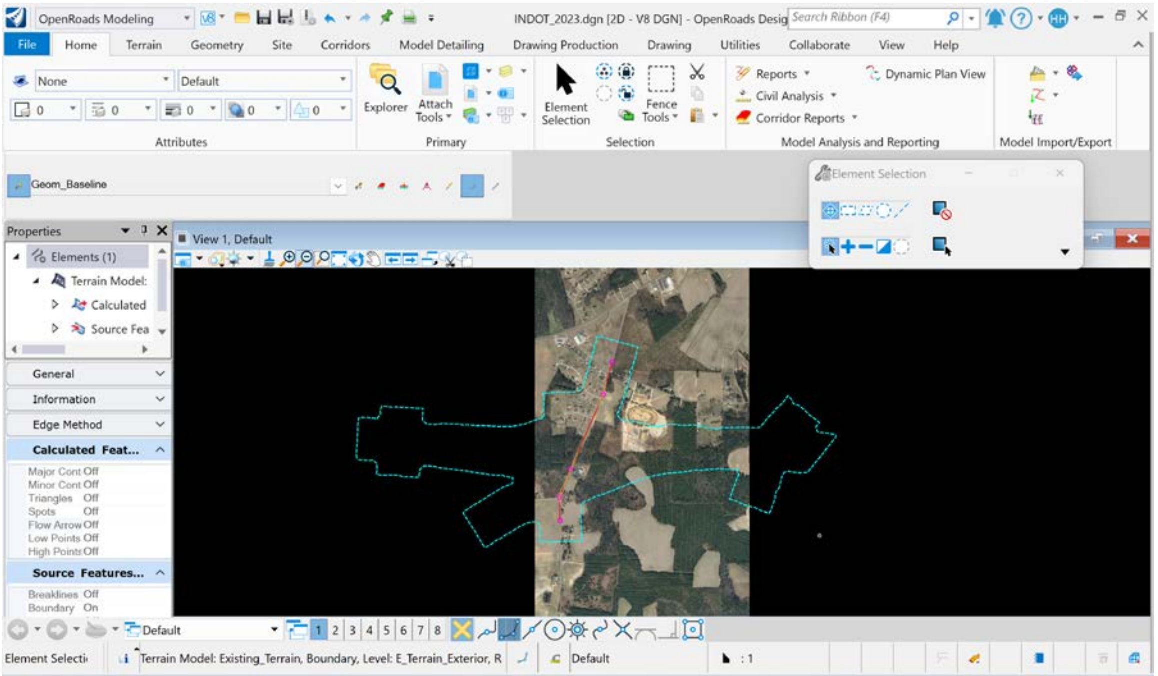


Figure B.78 Interface for the final shape of the terrain and geometry.

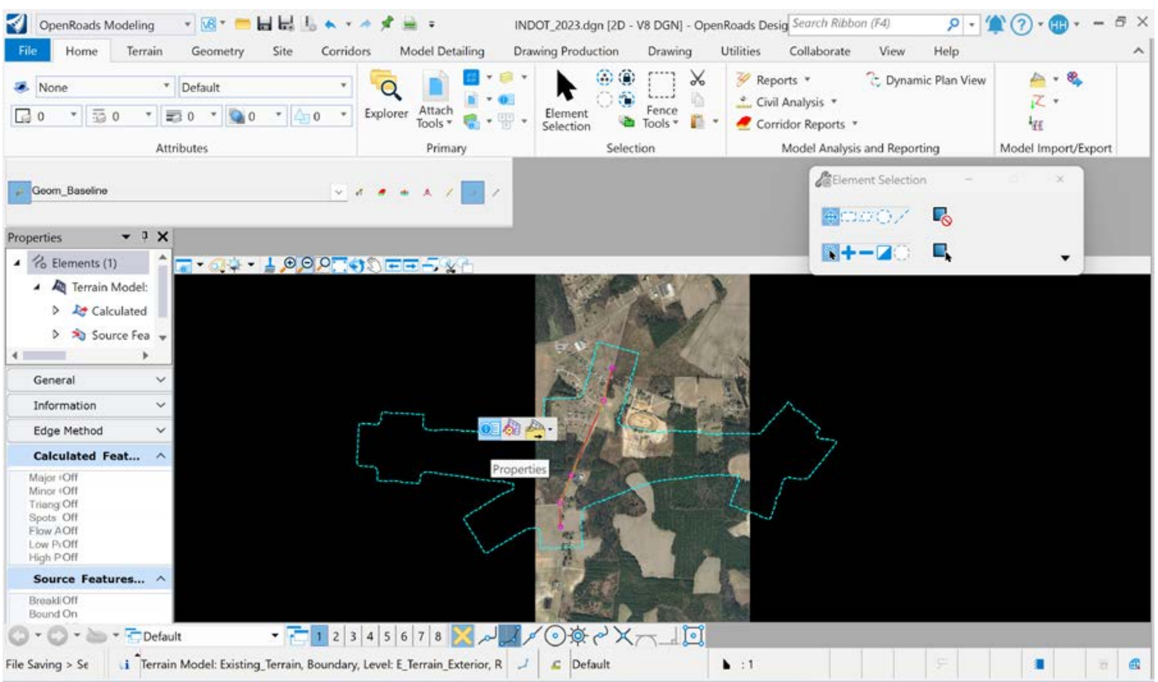


Figure B.79 Click on the edge of the terrain to show the “properties.”

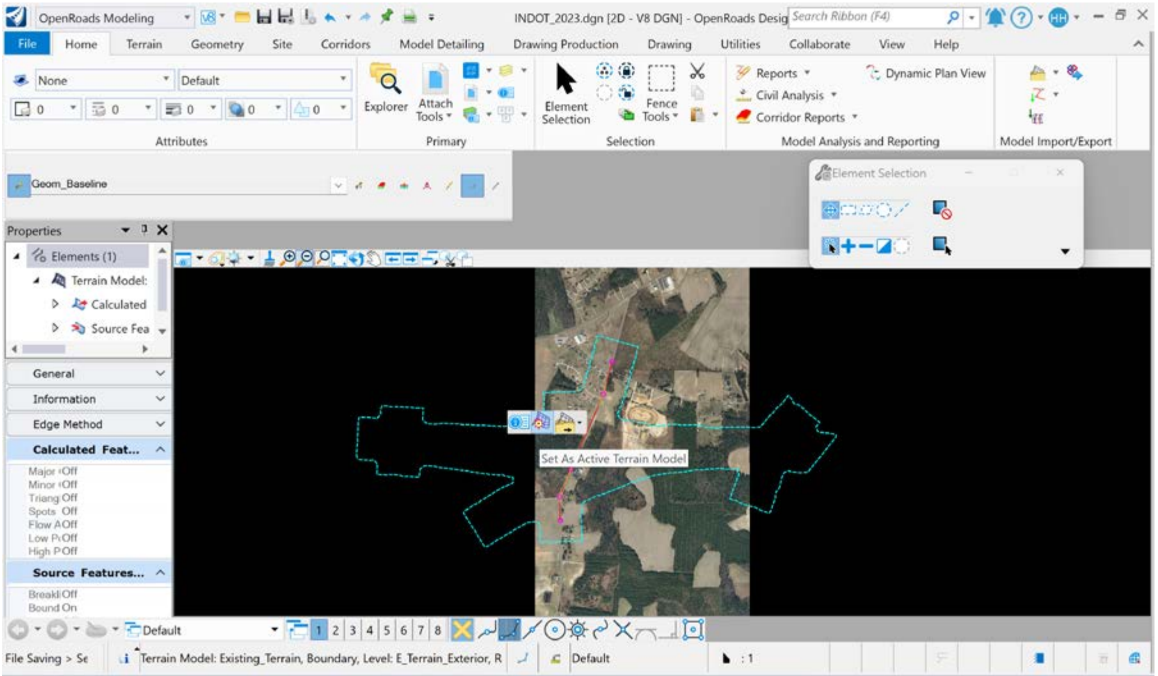


Figure B.80 Click on the terrain to active it—“Set as Active Terrain Model.”

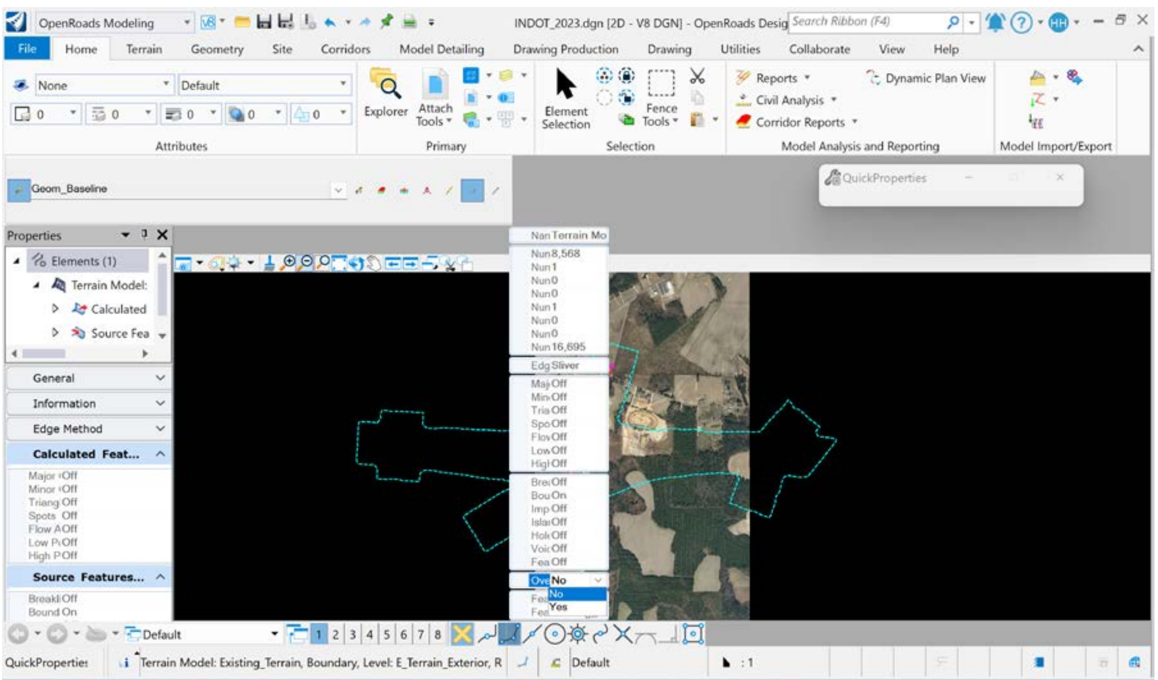


Figure B.81 Properties of the terrain.

Notes: Please select “Yes” to show and control for all features for terrain, then start to show any features (On/Off) as following.

- Users need to click on the Reference>Override Symbol>change from “No” to “Yes.”
- The Calculated Features Display window’s optional arrows (On/Off) will be activated.
- Change the needed options from Off to On.
- The Contours of the terrain will show.

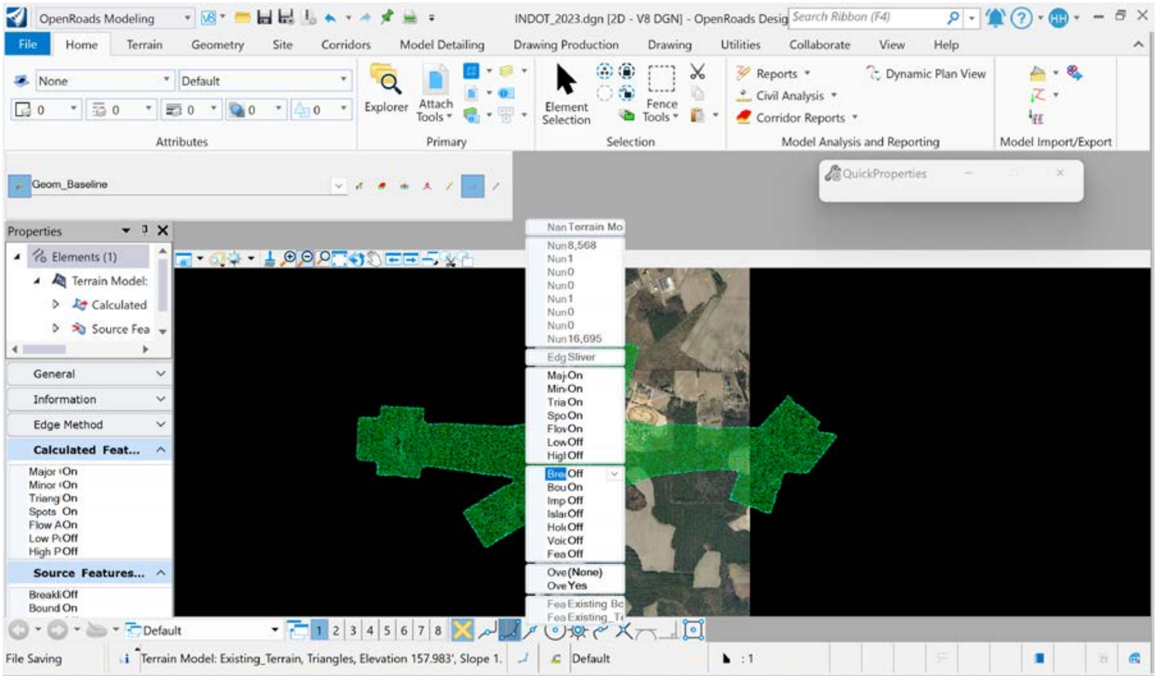


Figure B.82 To show the contours of the terrain.

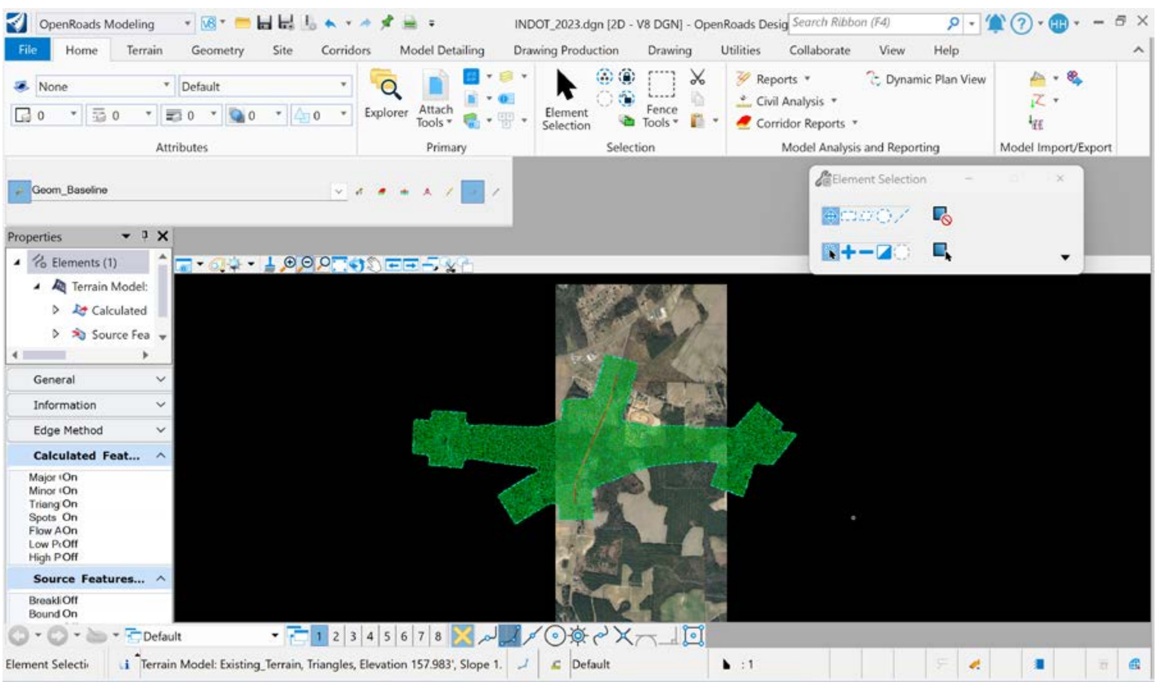


Figure B.83 Contours of the terrain.

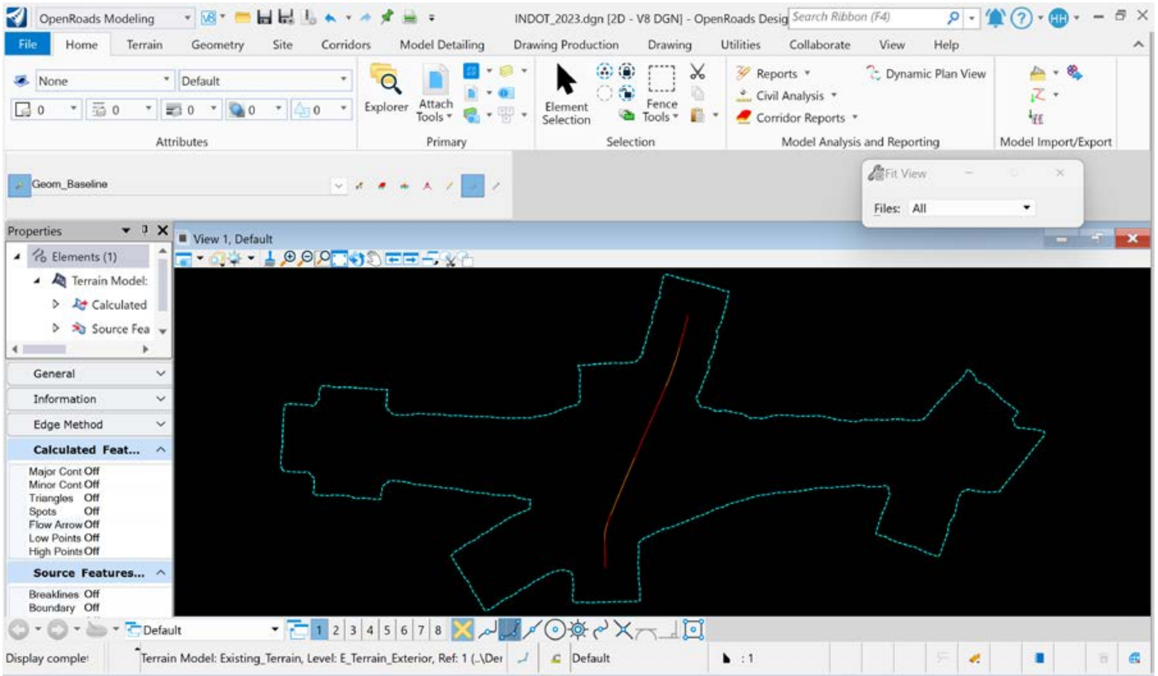


Figure B.84 Interface for the terrain and the line.

Define Annotation to show more details for the profile (Annotations Scale 1″ = 100′)
Drawing Production Tab>Annotations>Annotate Element

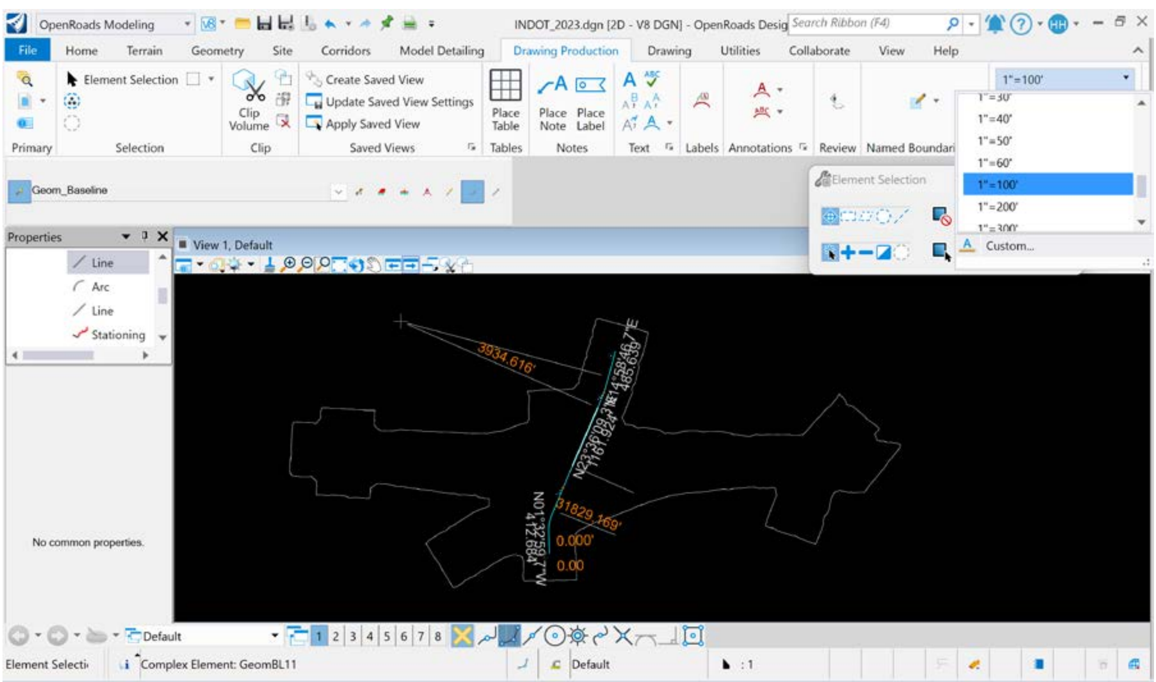


Figure B.85 select the “annotations scale” (1″ = 100′).

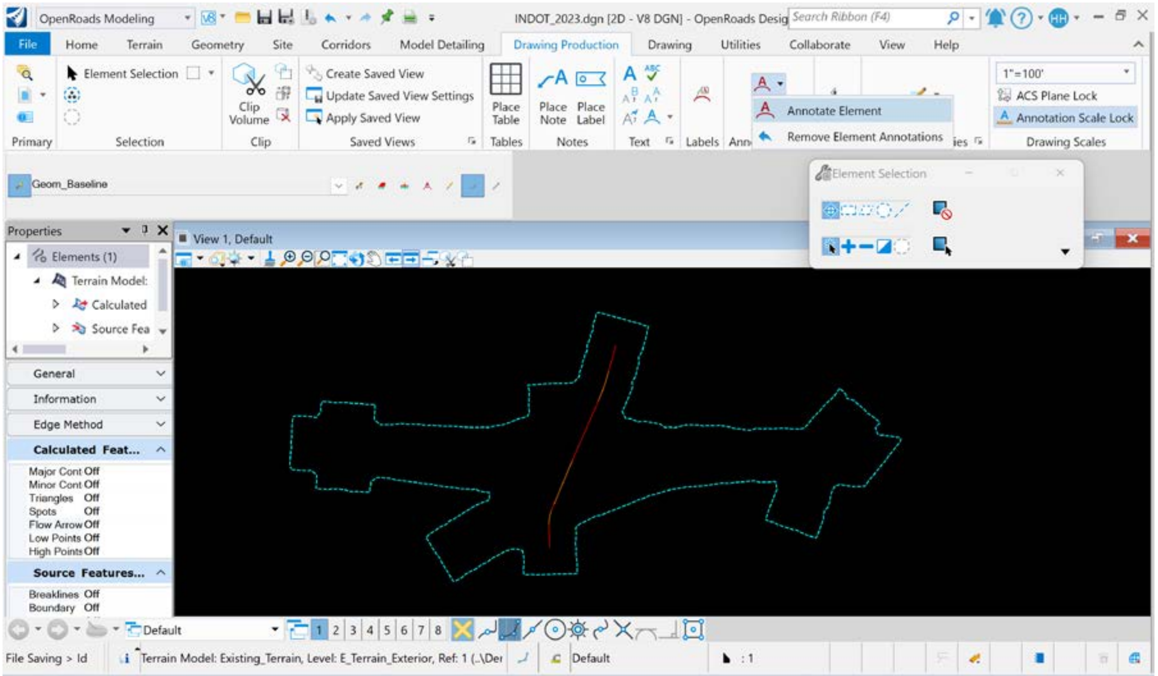


Figure B.86 Select the "annotate element."

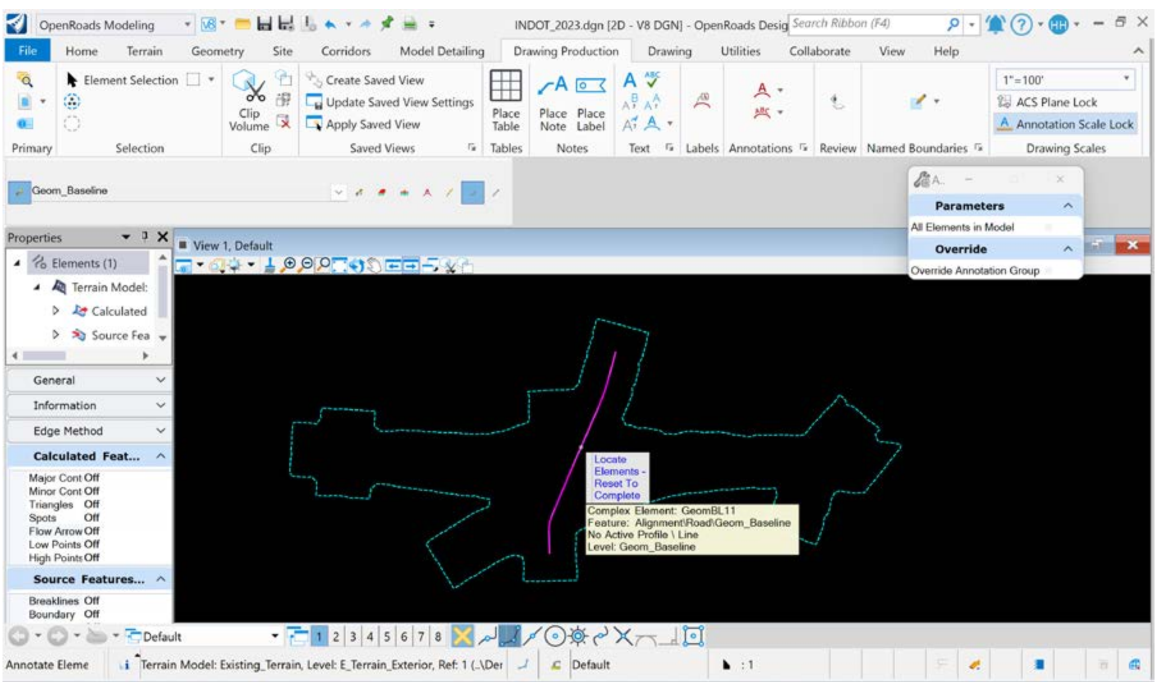


Figure B.87 Select the profile.

Left click to accept.

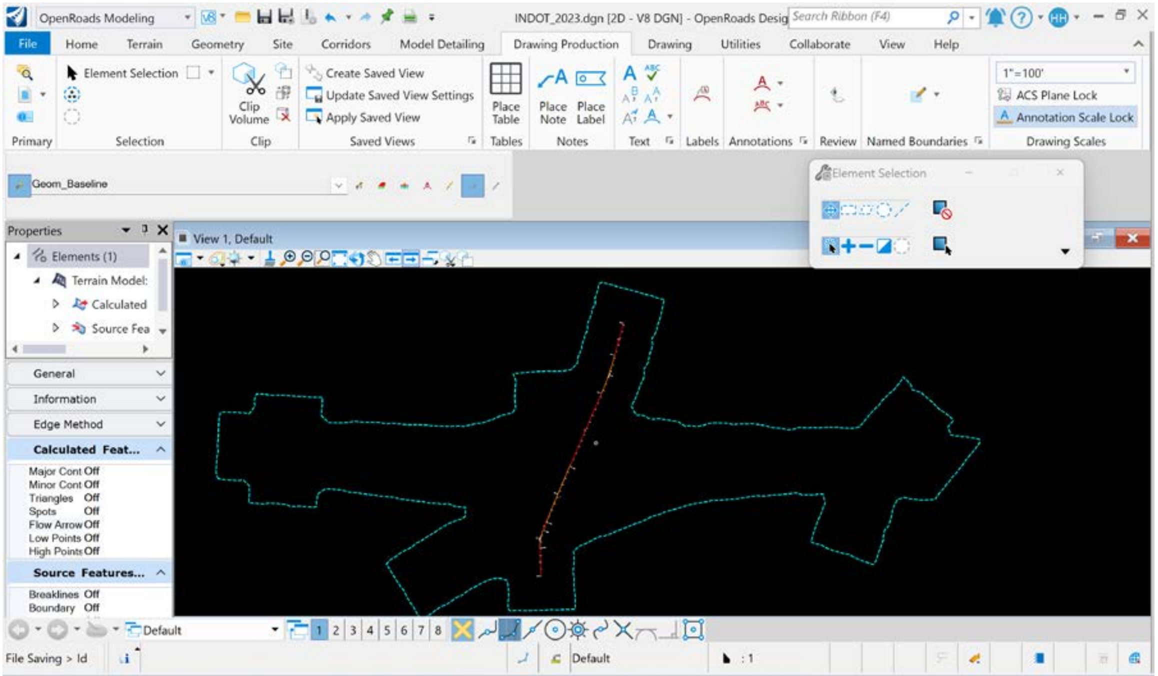


Figure B.88 Interface for the terrain and profile.

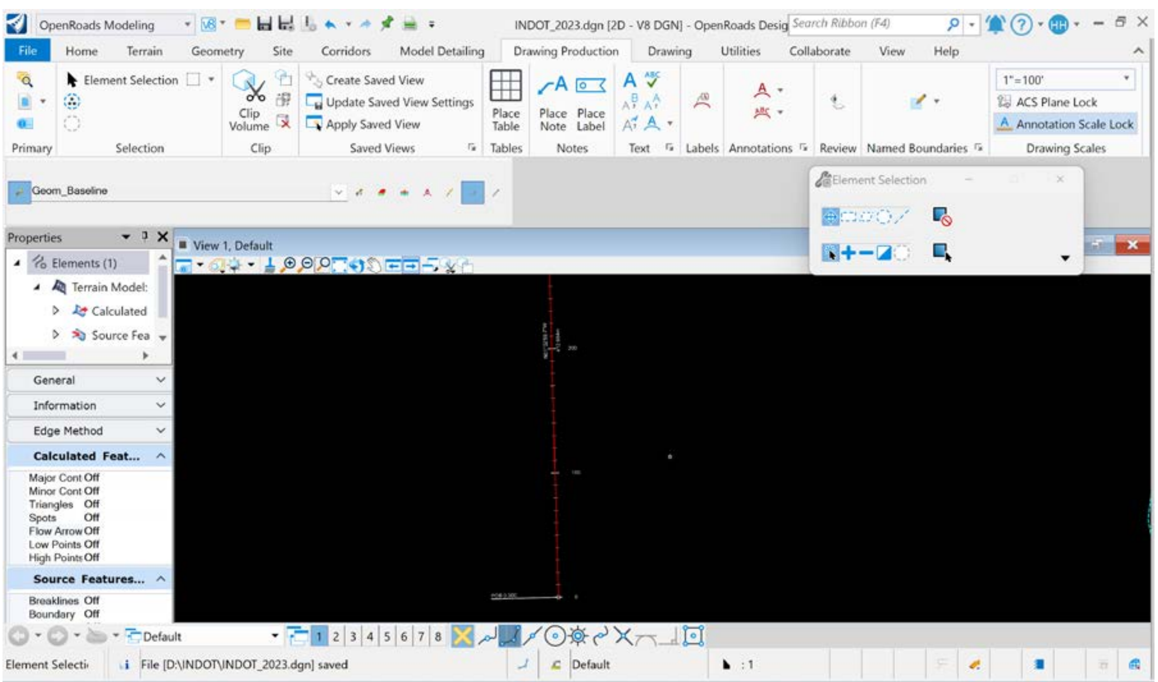


Figure B.89 Interface for more details of the profile.

If you want to show 2D and 3D view: *Right-click >View Control>2 Views Plan/3D.*

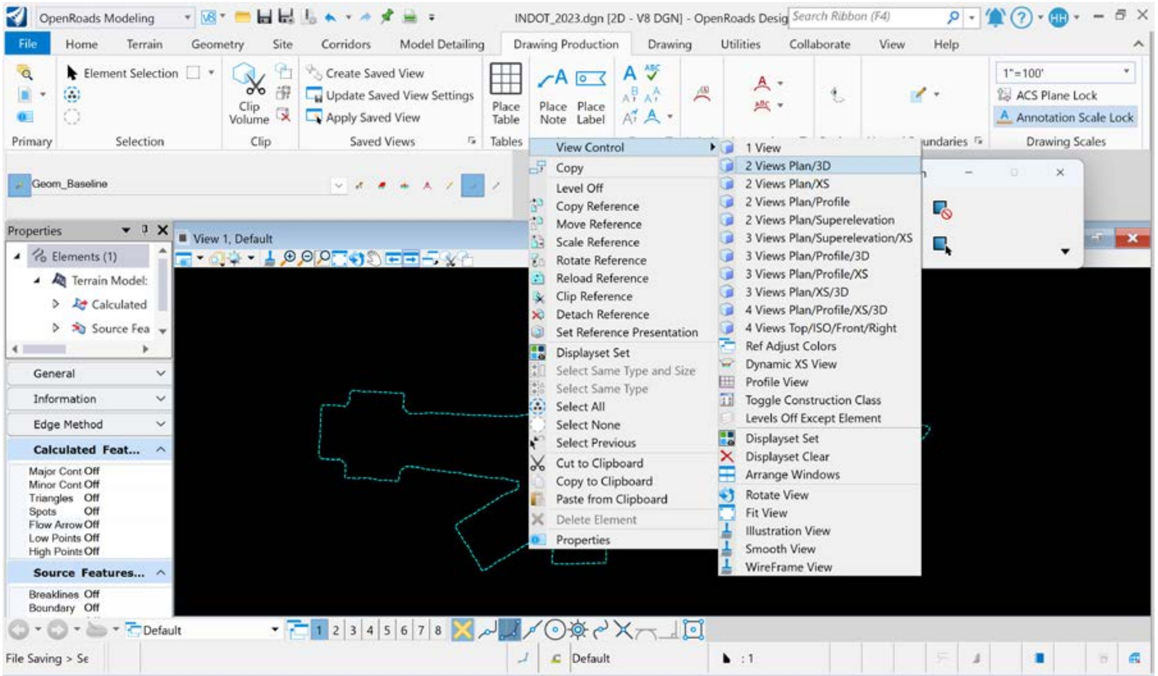


Figure B.90 Interface to show the two views "Plan/3D."

Fourth Step: Define Profile Model View

Home Tab>Element Selection>Select the element>Open Profile Model

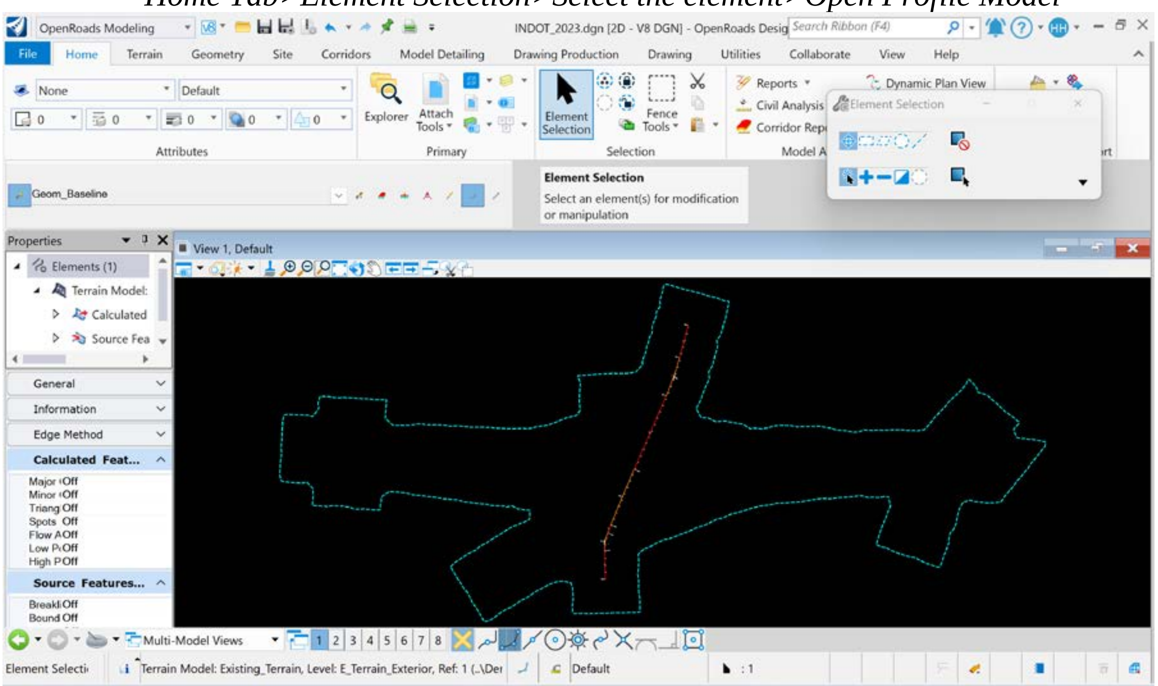


Figure B.91 Select the "element selection."

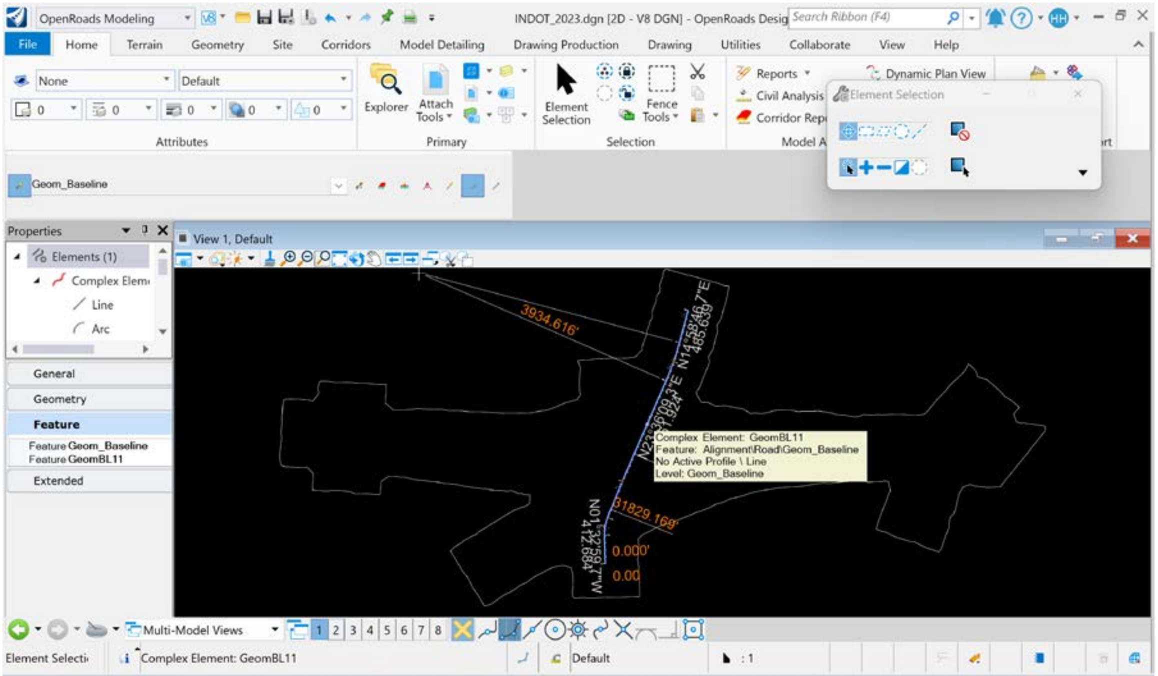


Figure B.92 Select the profile.

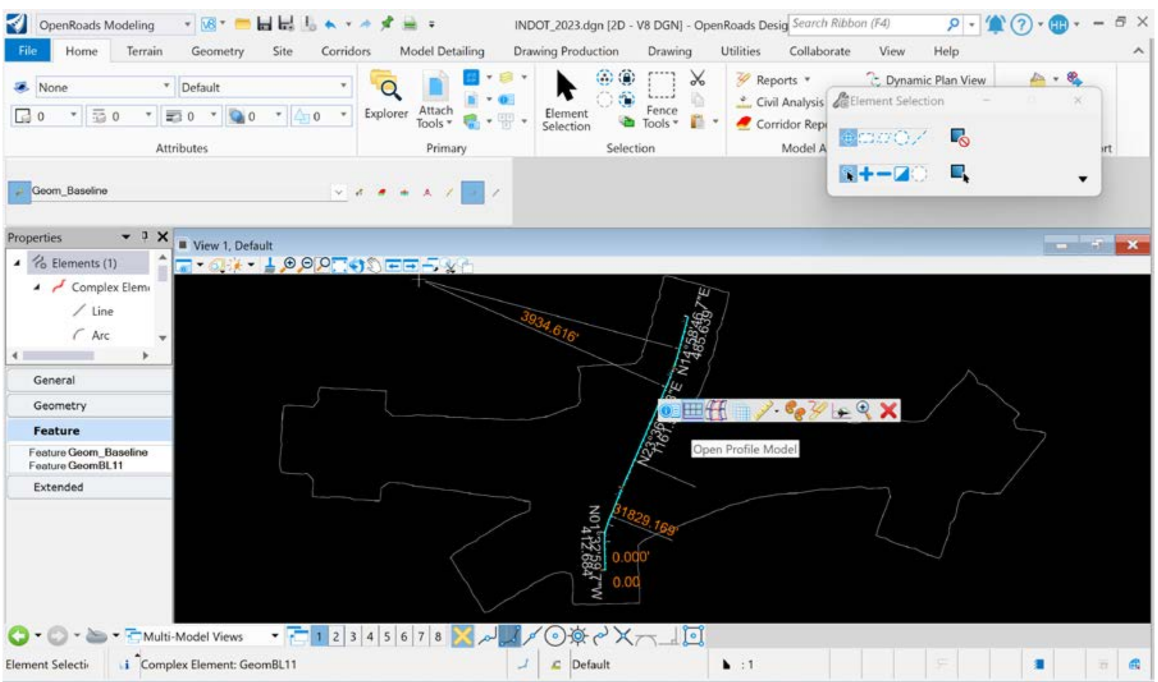


Figure B.93 Select the icon of “open profile model.”

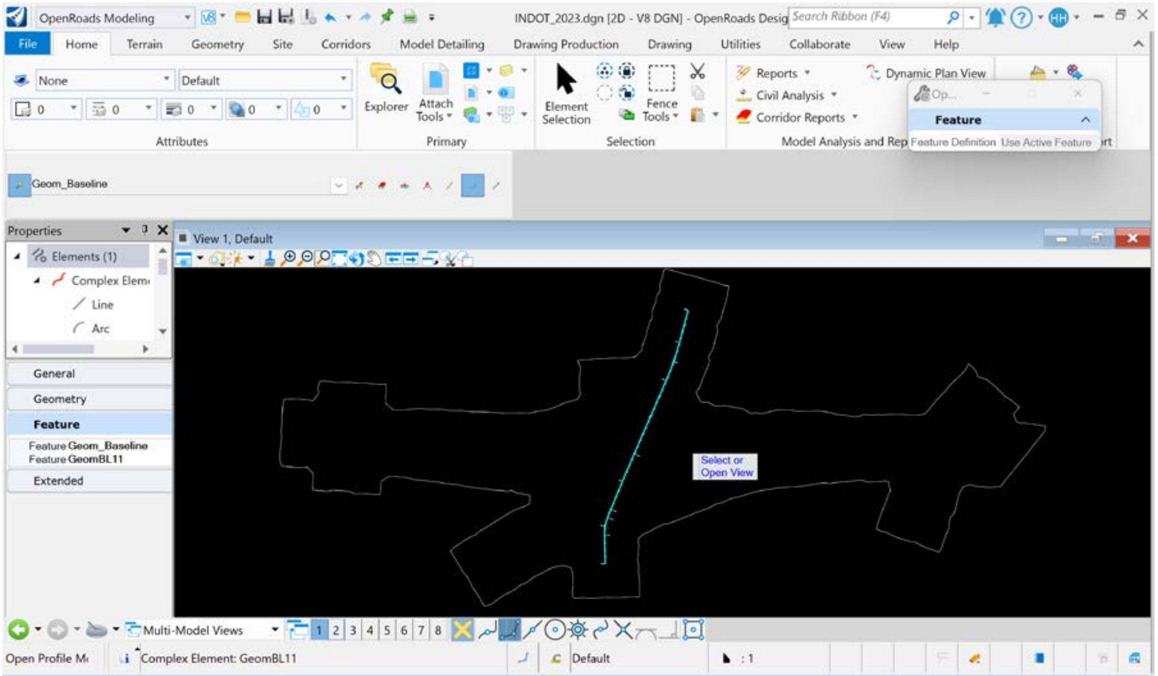


Figure B.94 Select the “open view.”

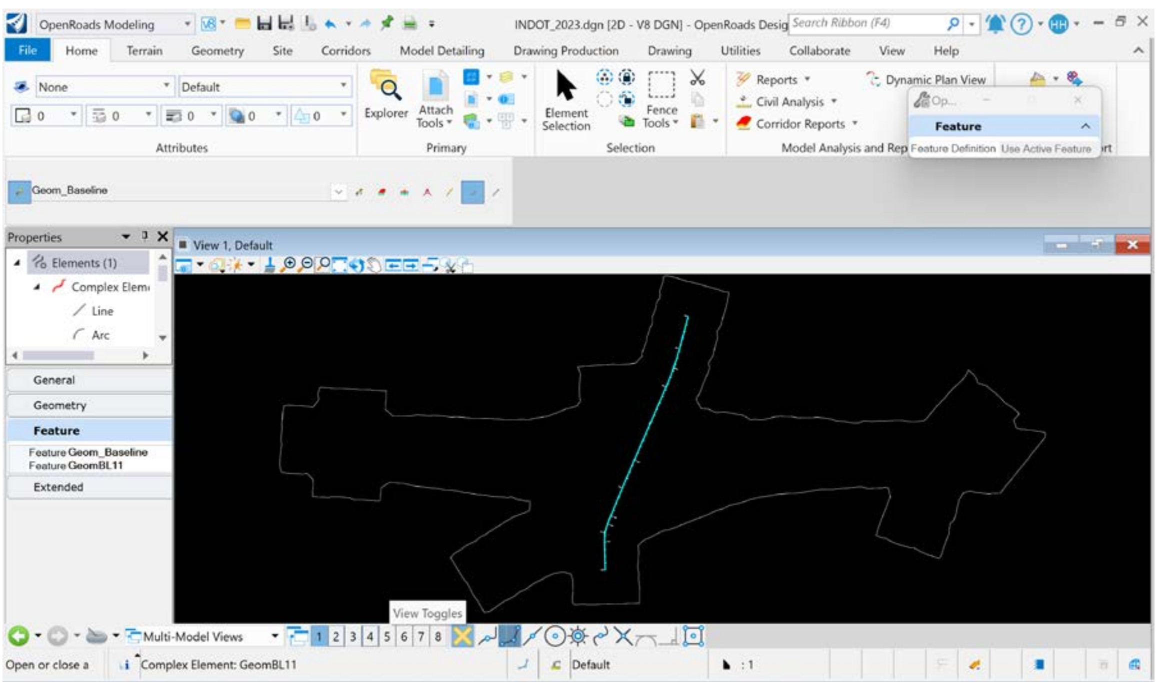


Figure B.95 Select the “view toggles” to show the view for the profile.

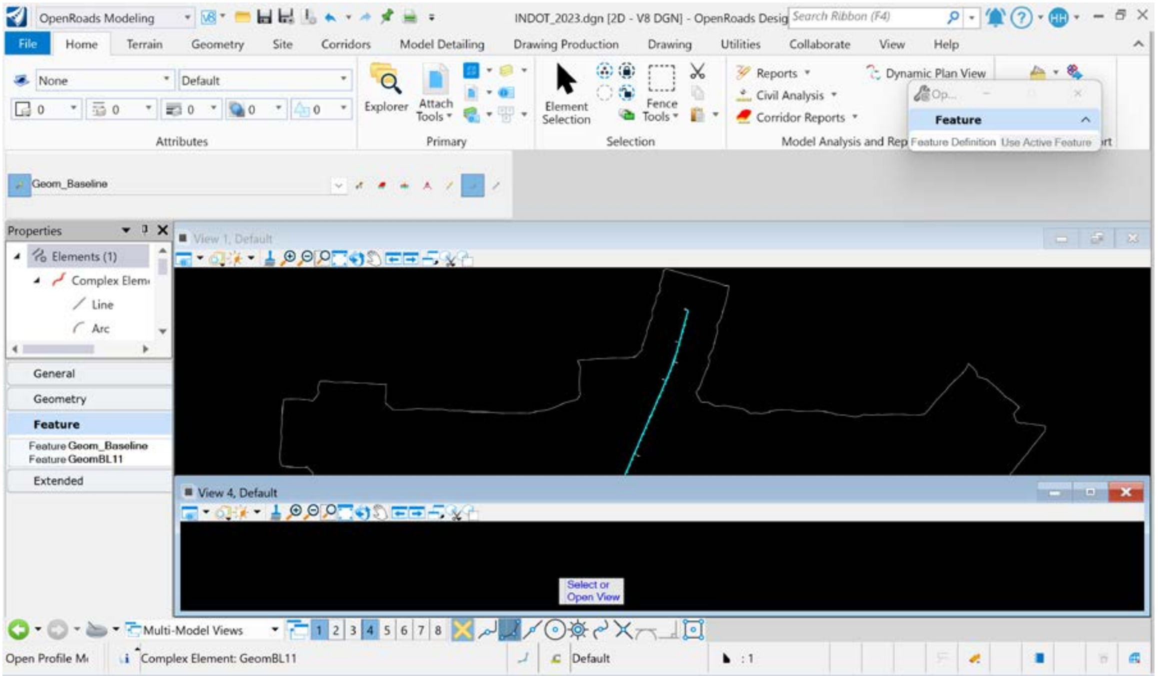


Figure B.96 Interface for the views of 2D and profile.

Notes: If the profile does not appear, please double click in the interface.

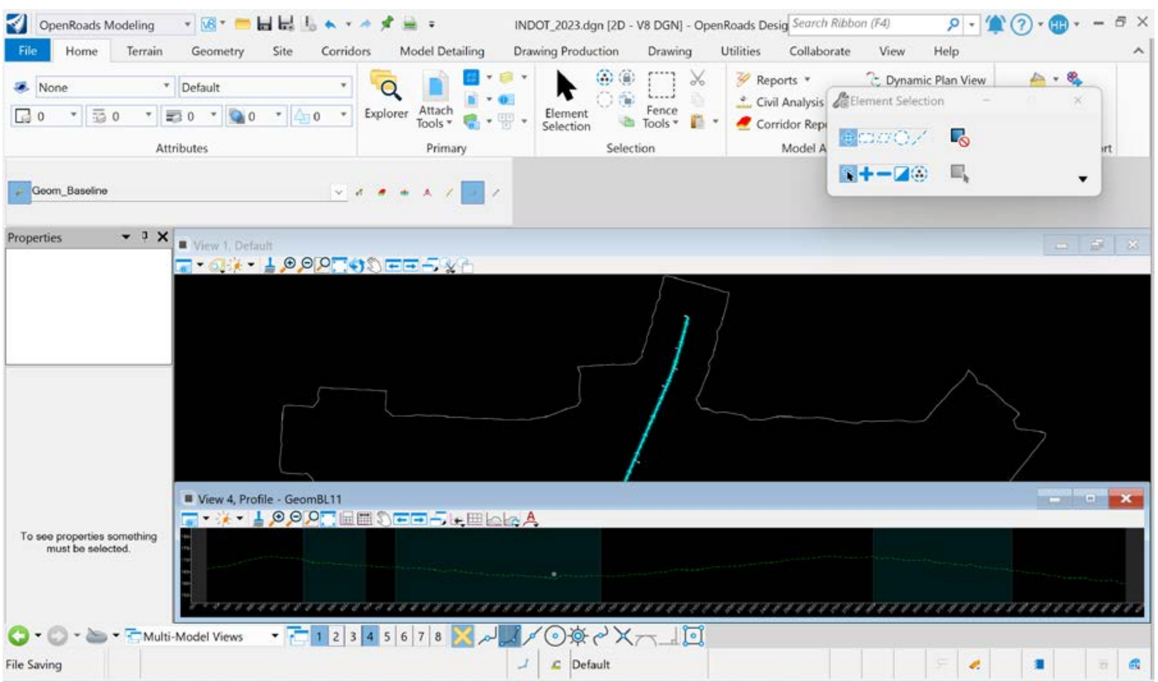


Figure B.97 Interface for the views of 2D and profile.

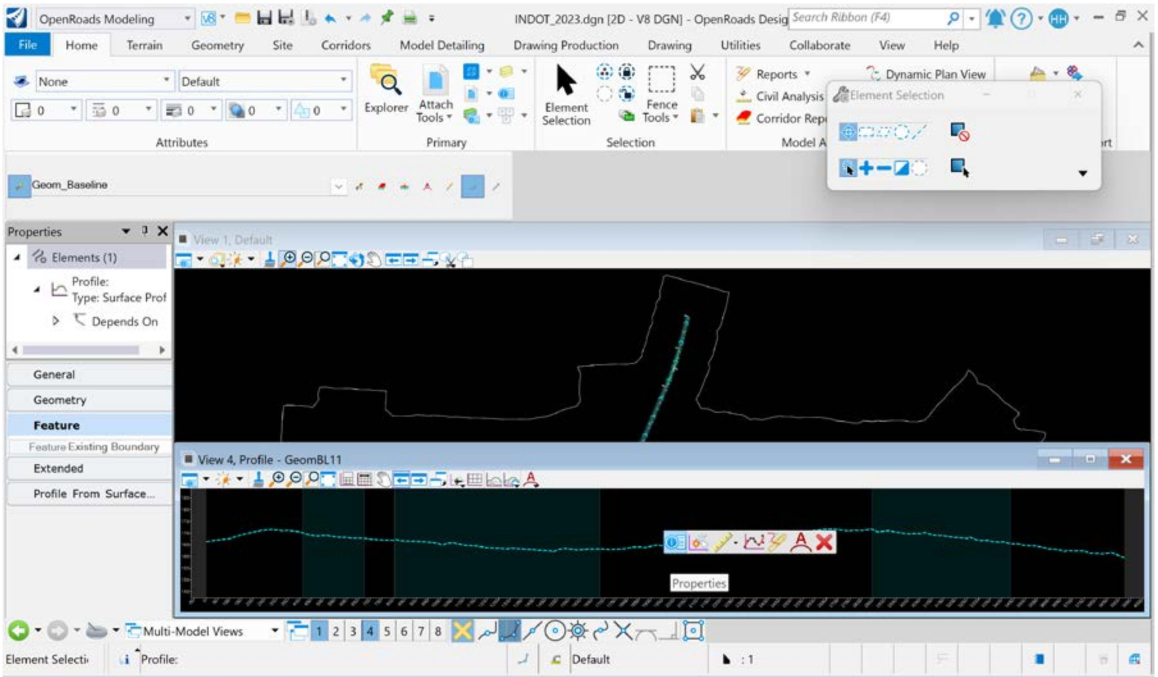


Figure B.98 Click on the profile to show the details.

Create and edit vertical geometry (draw the profile): *Geometry Tab>Vertical>Lines>Profile Line between Points*

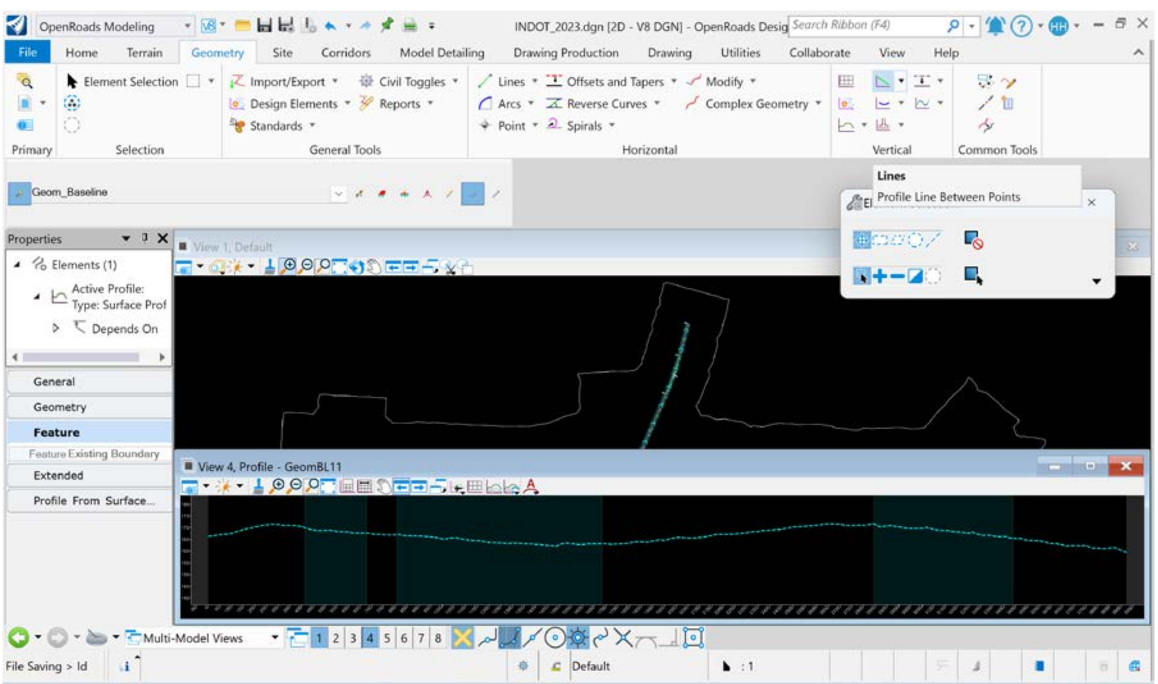


Figure B.99 Select the line from vertical icons.

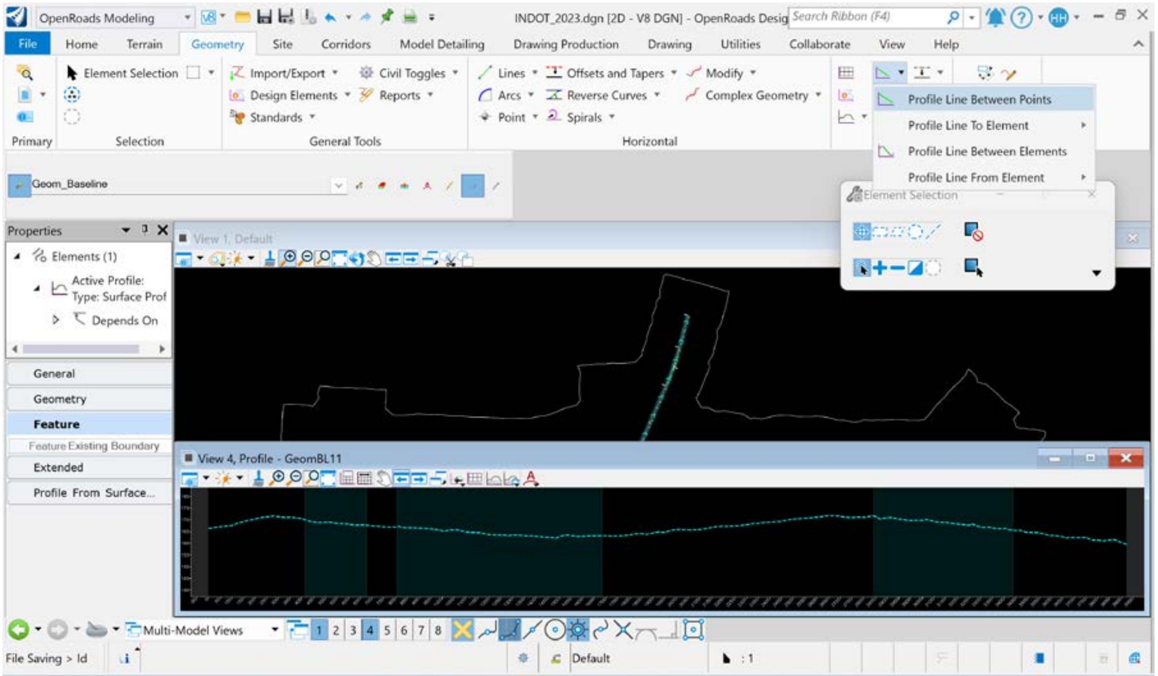


Figure B.100 Select the "profile line between points."

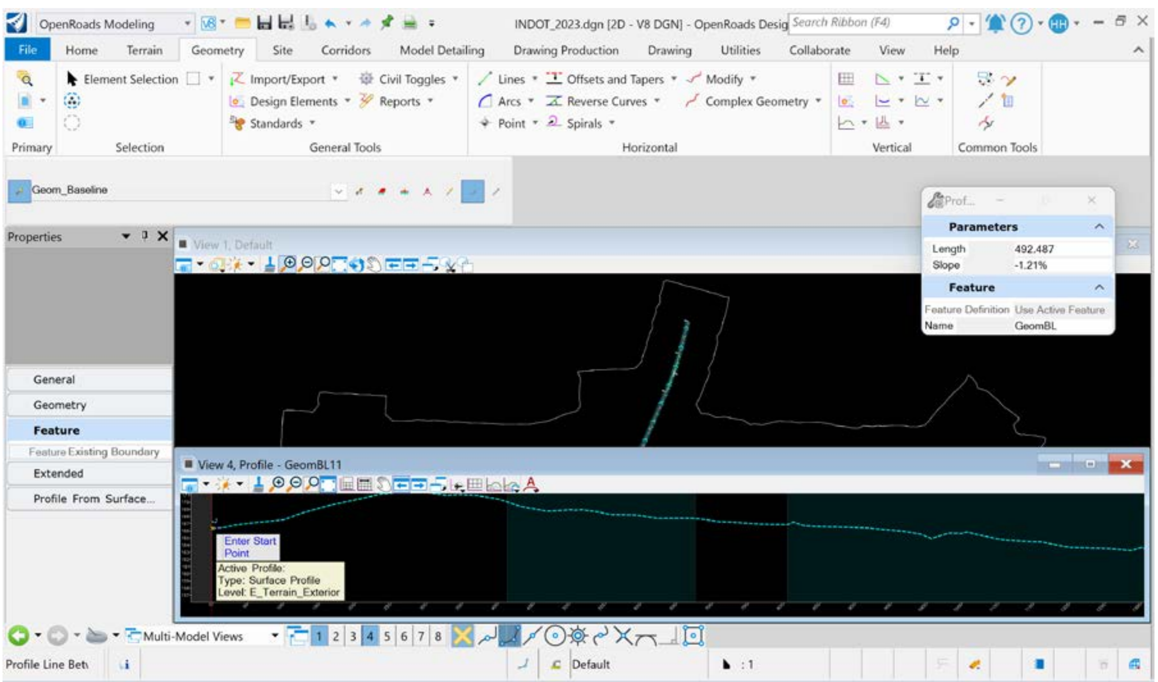


Figure B.101 Start to draw the vertical line "enter start point."

Notes: Please check that we use the feature definition is "Use Active Feature" and the feature name.

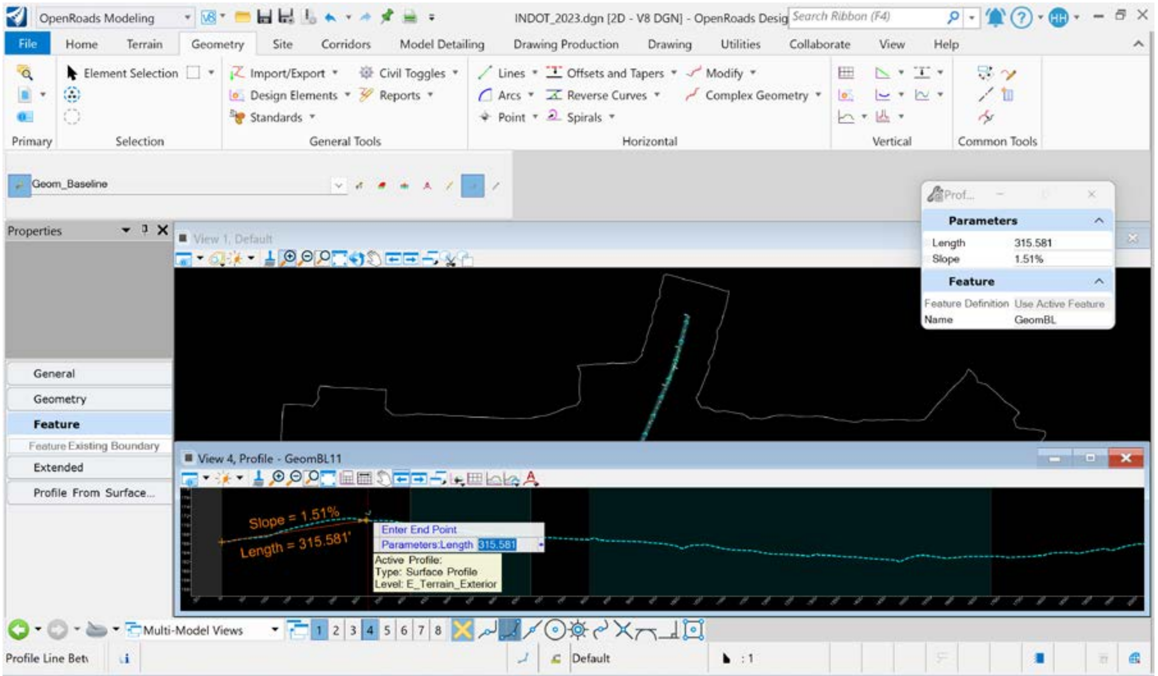


Figure B.102 Complete the line according to length and slope.

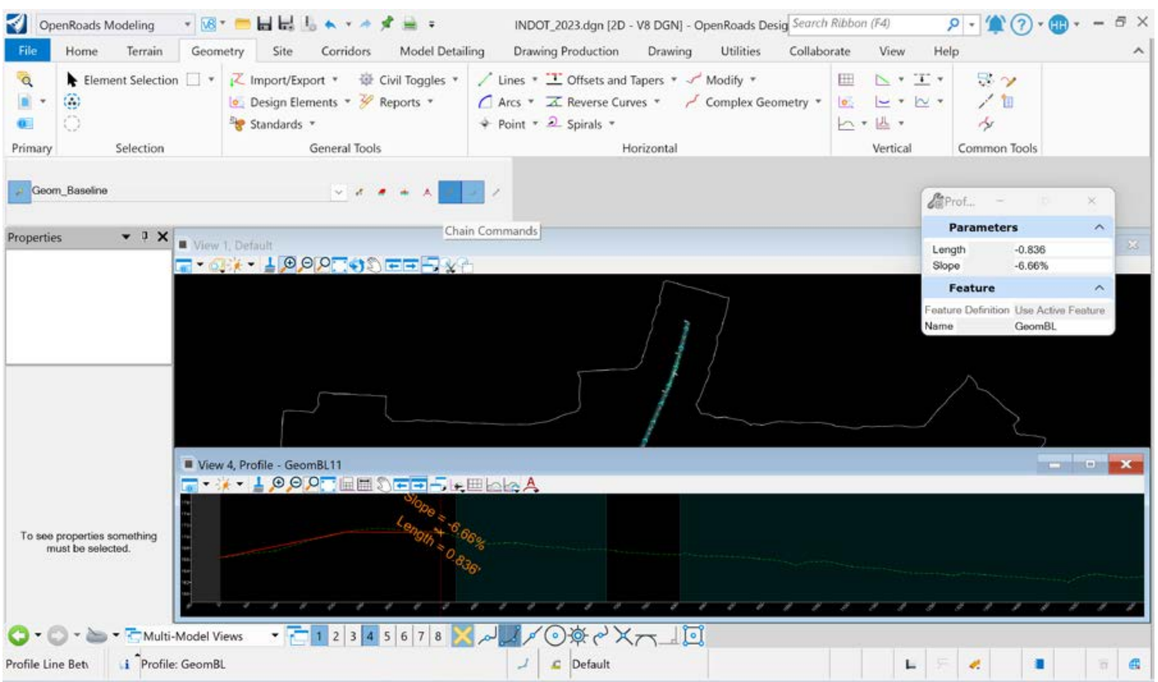


Figure B.103 To continue the line, "chain commands" icon should be active.

Please make sure to complete the line!

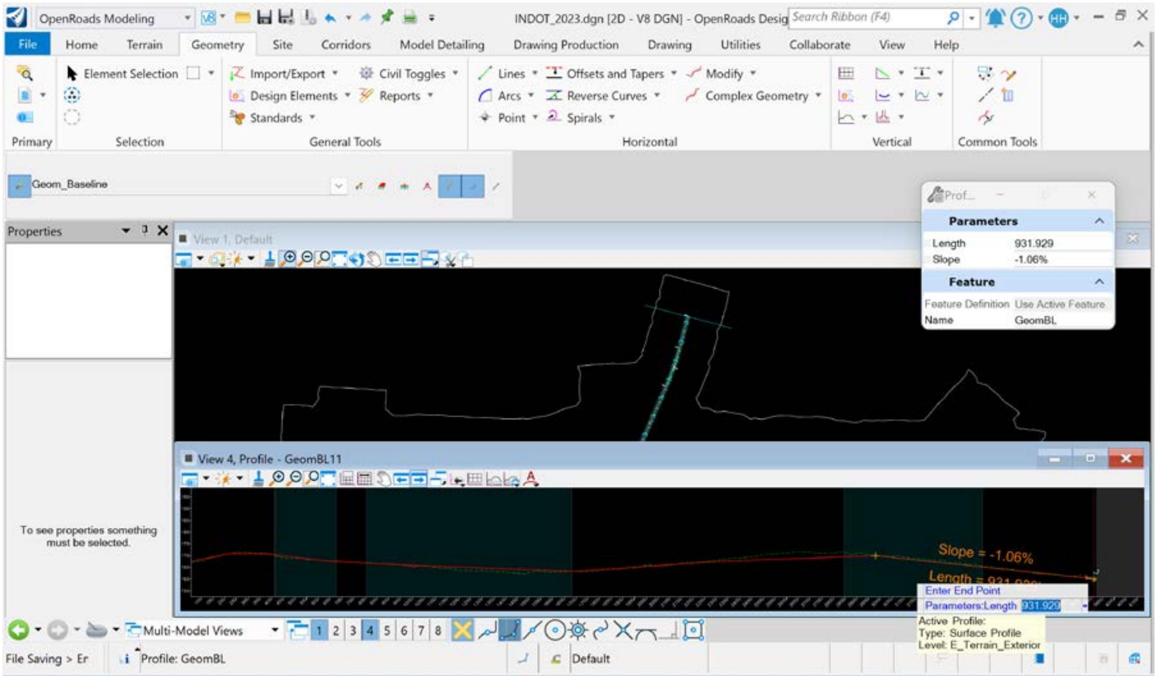


Figure B.104 Complete the profile.

Create and edit vertical geometry (Draw the arc between lines): *Geometry Tab>Vertical>Curves>Profile Curve Between Elements> Parabola between Elements*

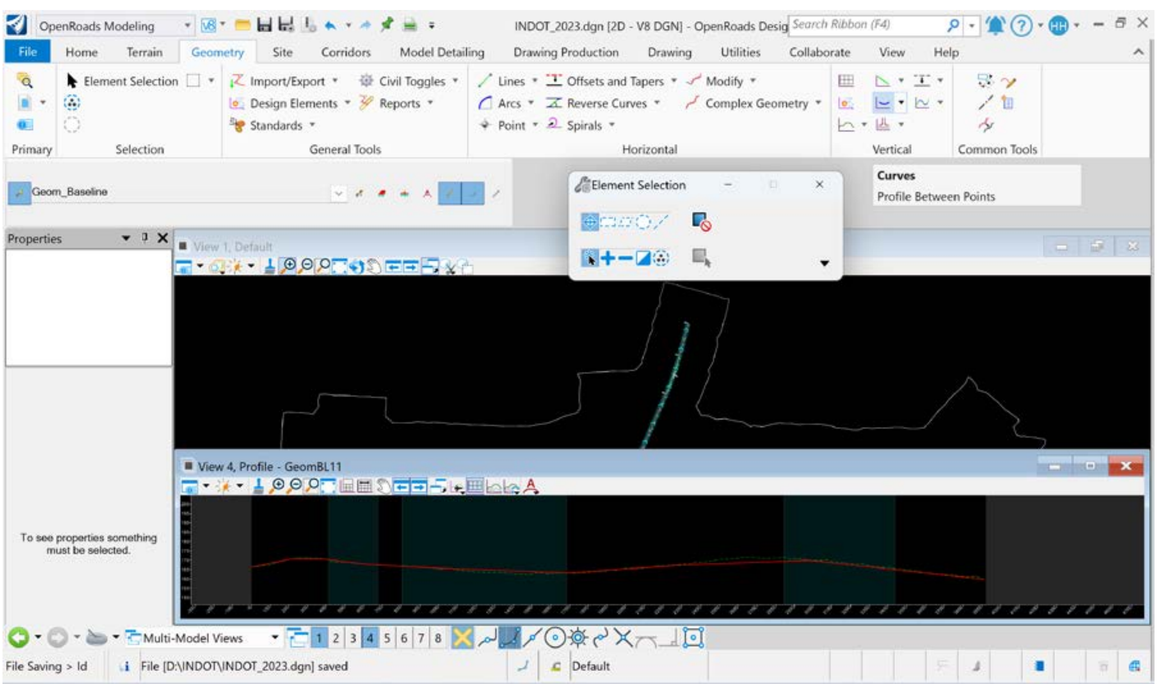


Figure B.105 Select the curve icon.

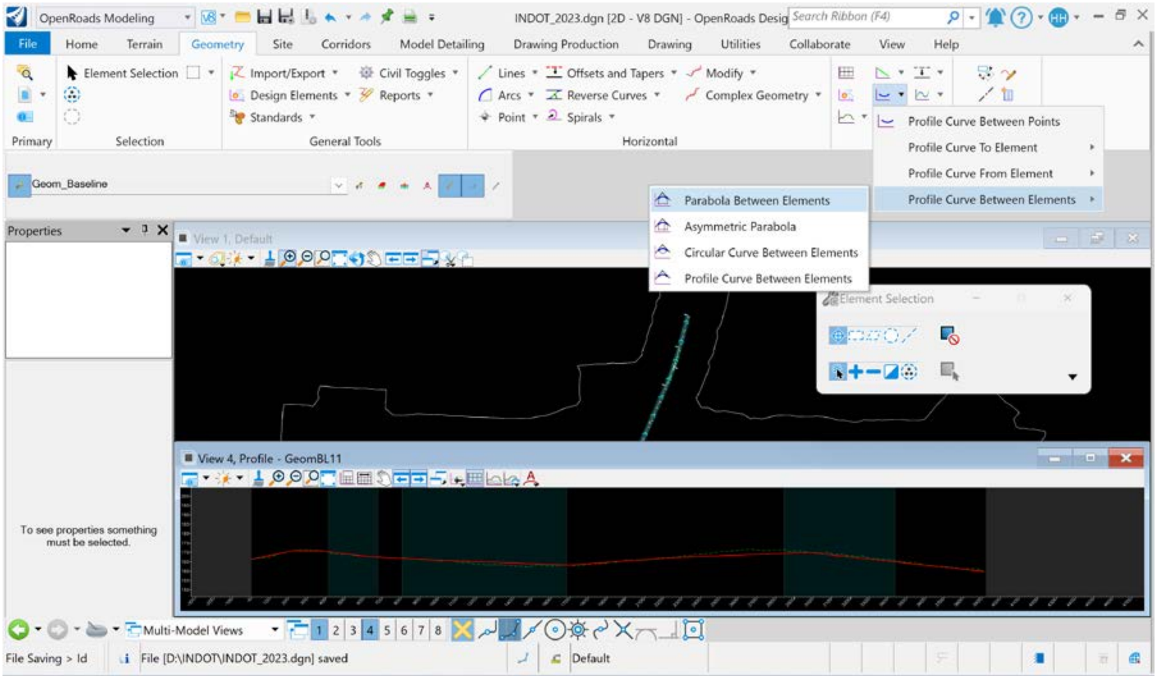


Figure B.106 Select the “parabola between elements.”

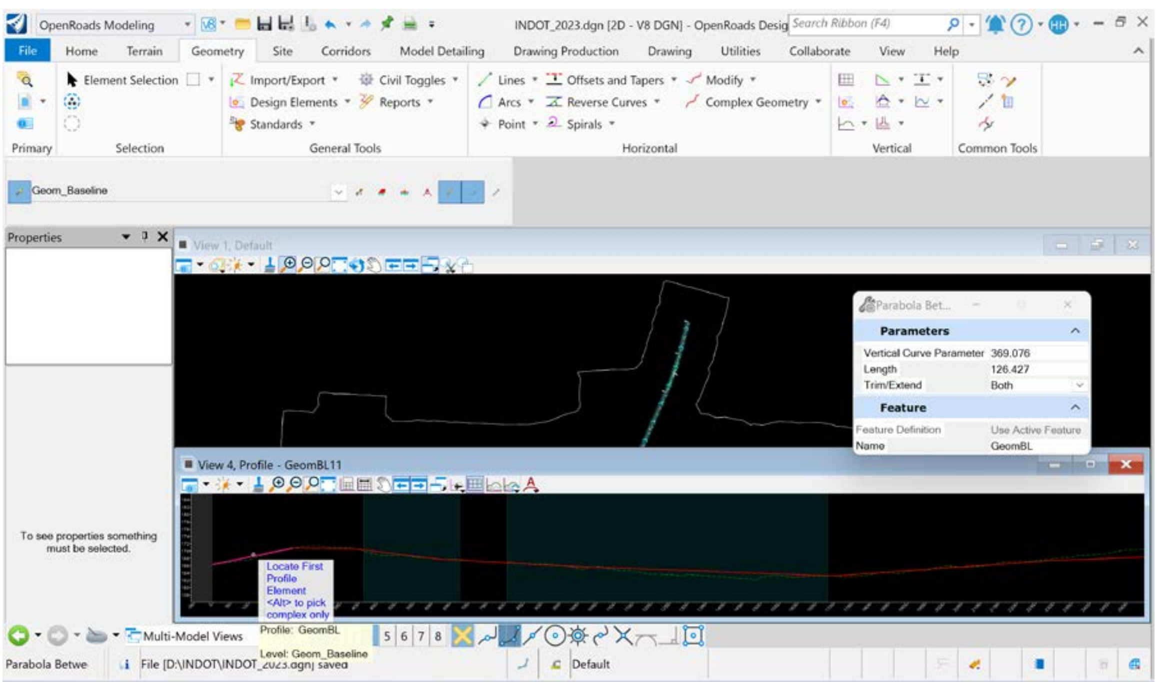


Figure B.107 Start to draw the parabola between elements (select the first element).

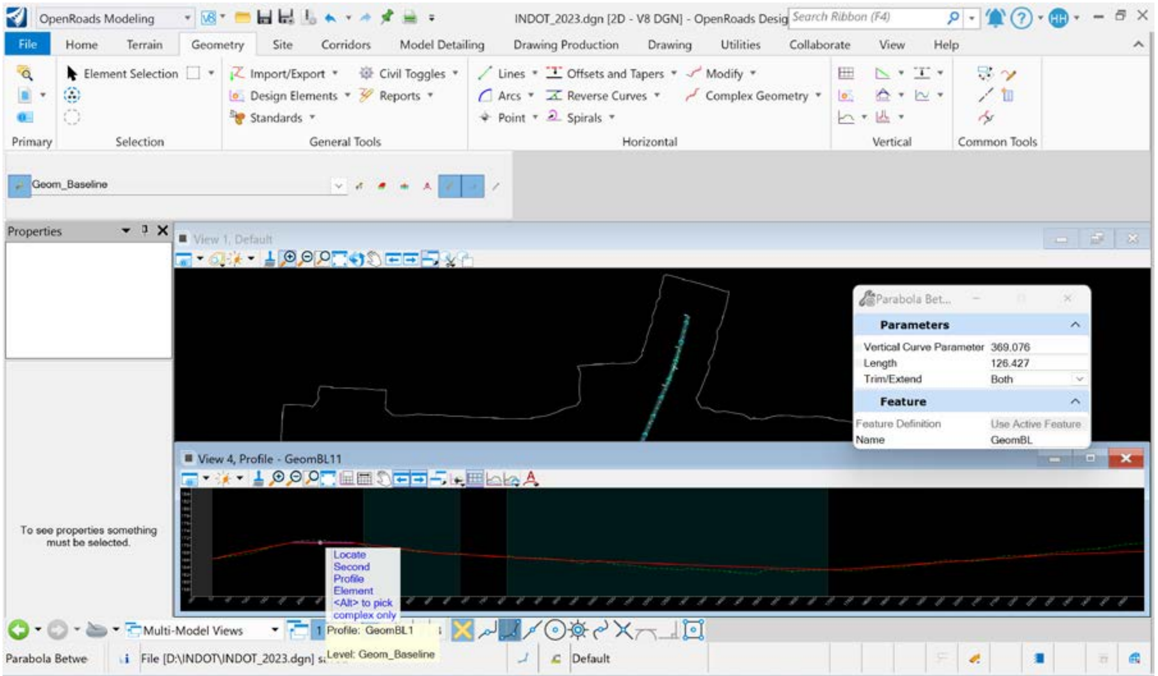


Figure B.108 Start to draw the parabola between elements (select the second element).

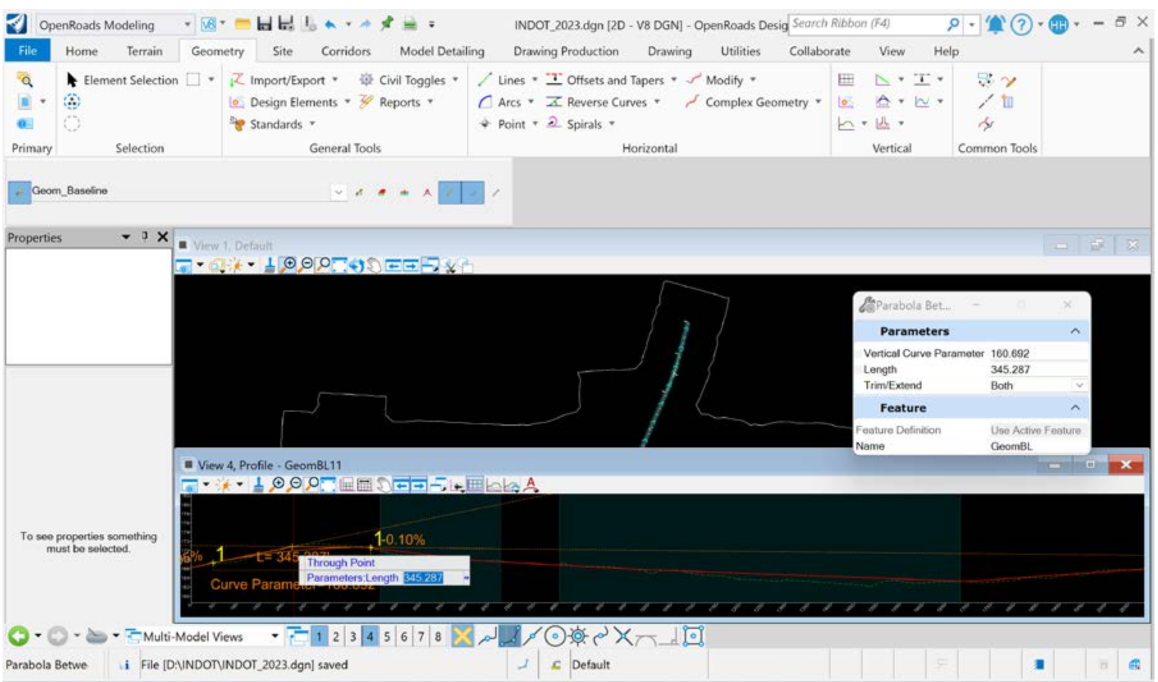


Figure B.109 Start to draw the parabola between elements (identify the length).

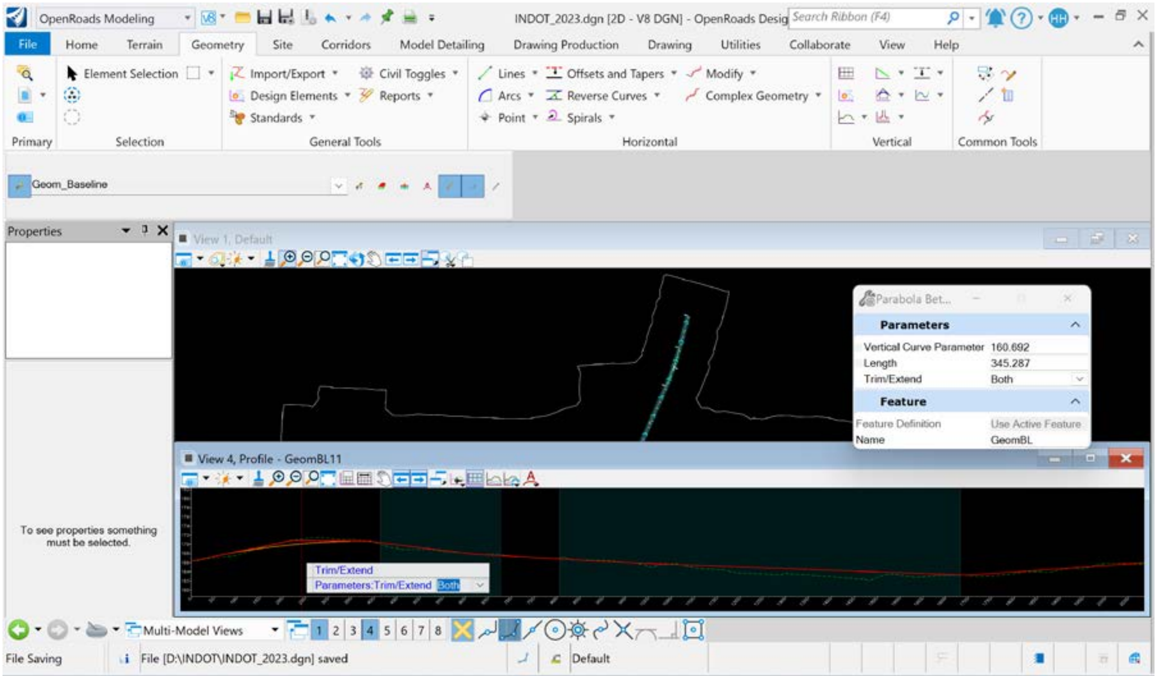


Figure B.110 Start to draw the parabola between elements (trim/extend).

Please remember to Left-Click to accept!

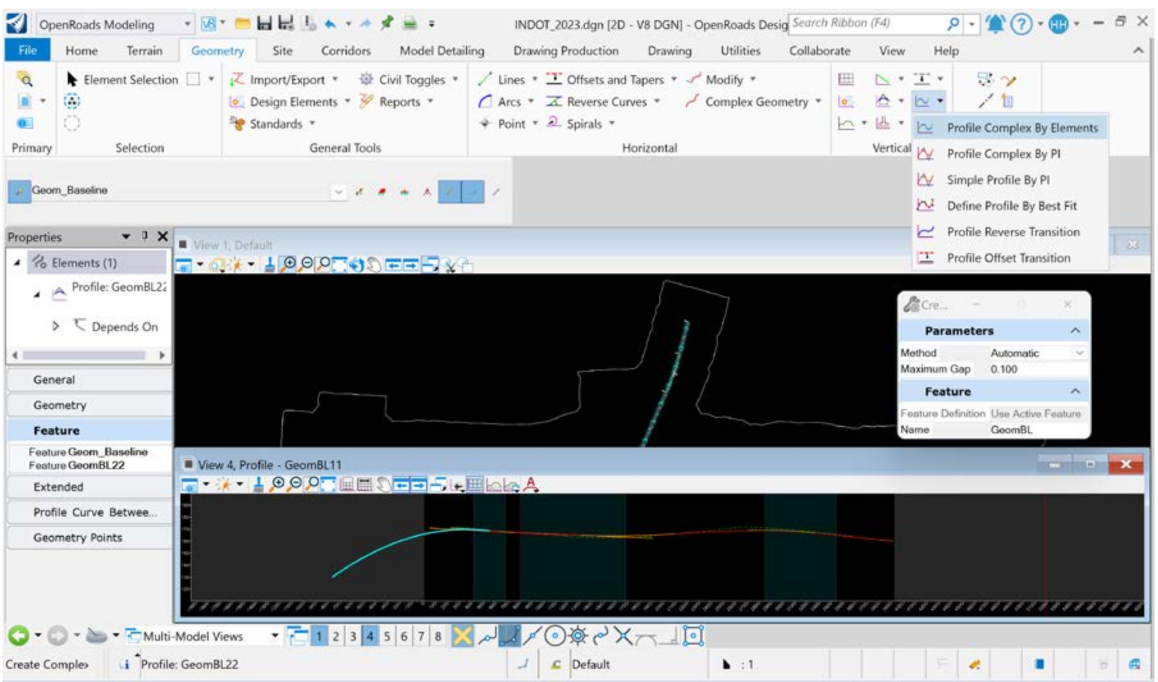


Figure B.111 Select the “profile complex by elements.”

Note: The method in the (complex dialogue) should be as “automatic.”

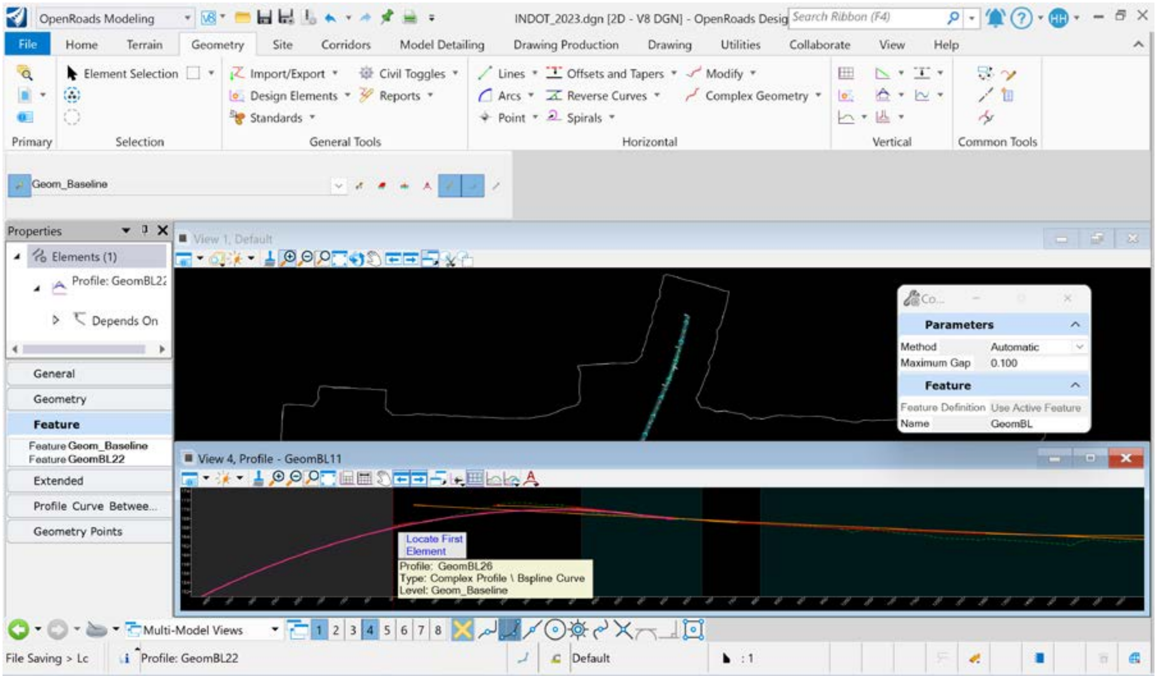


Figure B.112 “Locate first element.”

Note: After that please left click to “accept.”

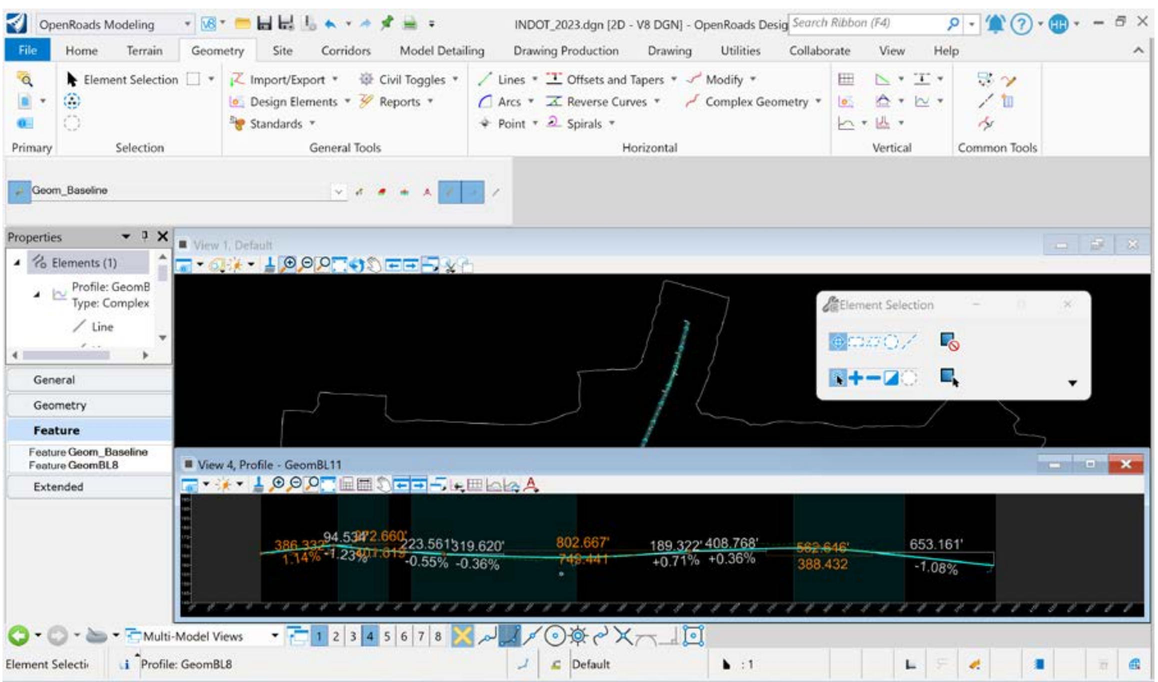


Figure B.113 Set the profile “as active profile”—details for slope and length of profile.

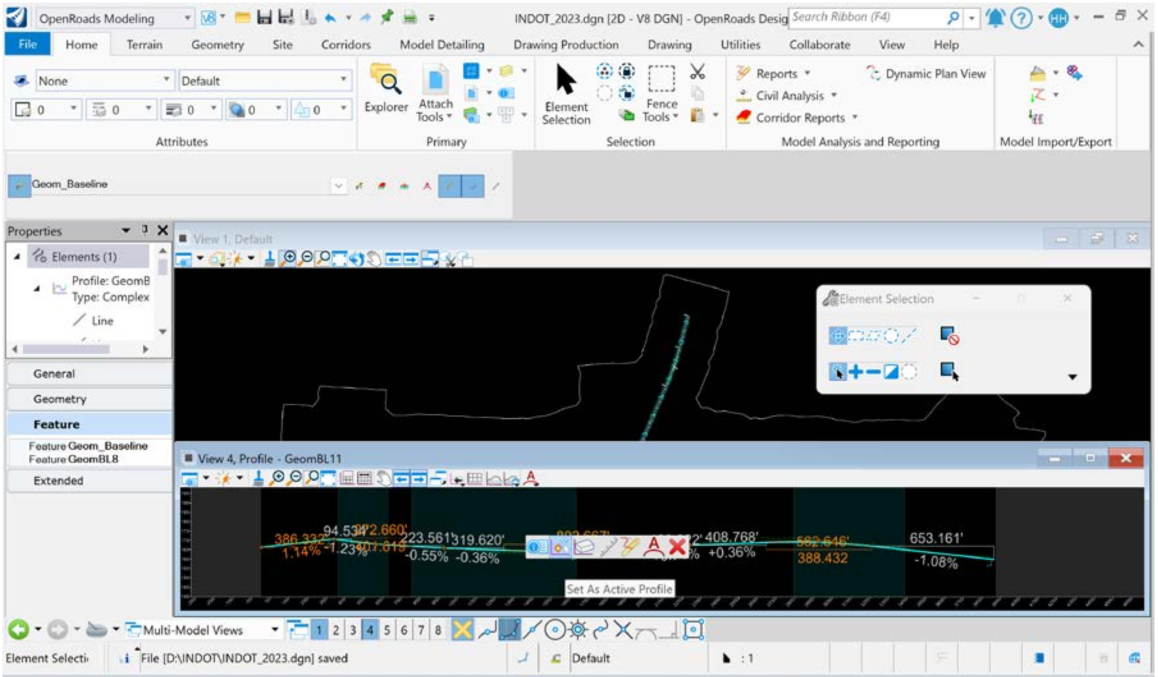


Figure B.114 Set the profile “as active profile.”

Vertical report (left click on profile>profile report).

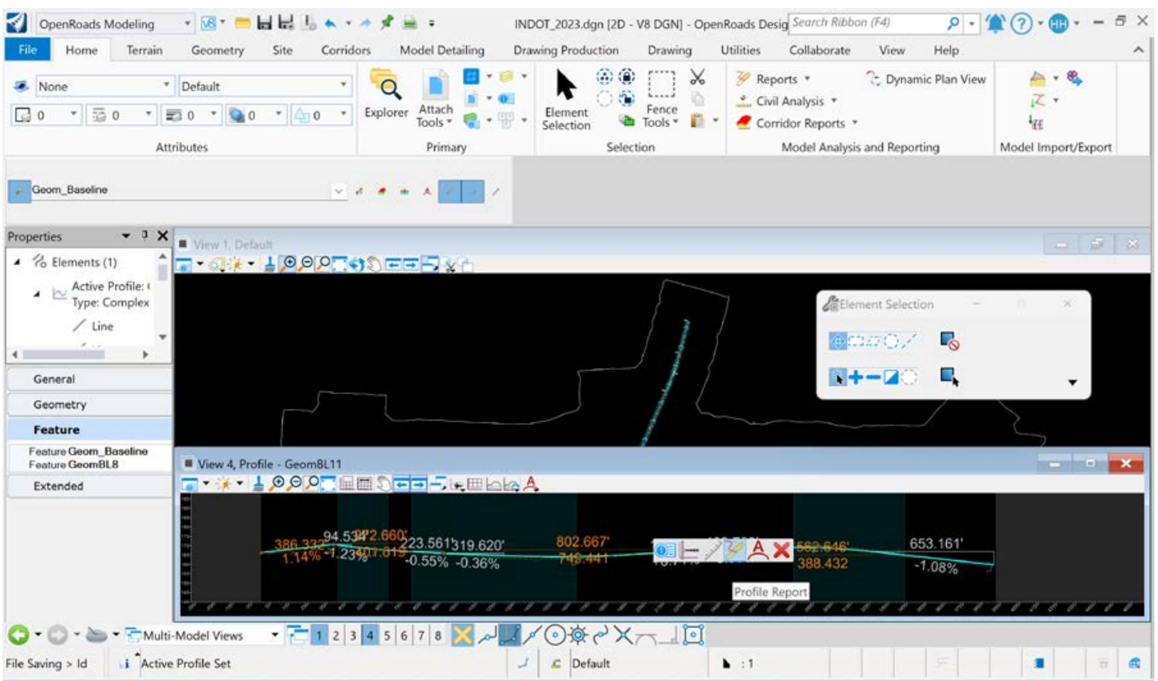


Figure B.115 Show the “profile report.”

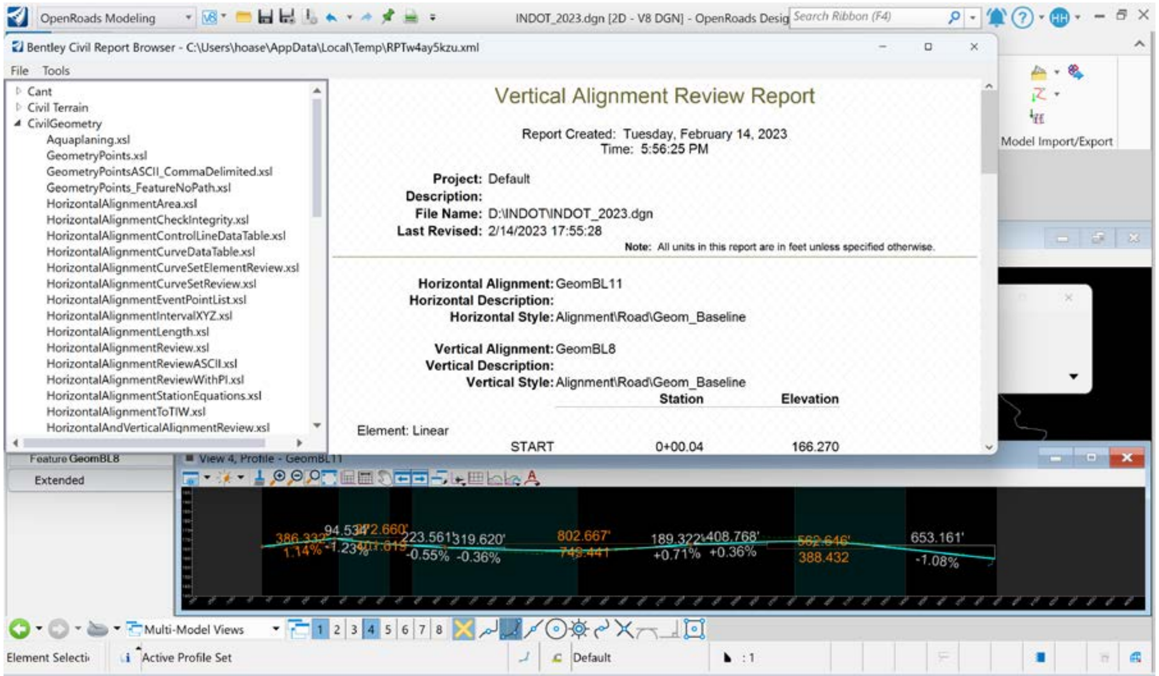


Figure B.116 Interface for “vertical profile report.”

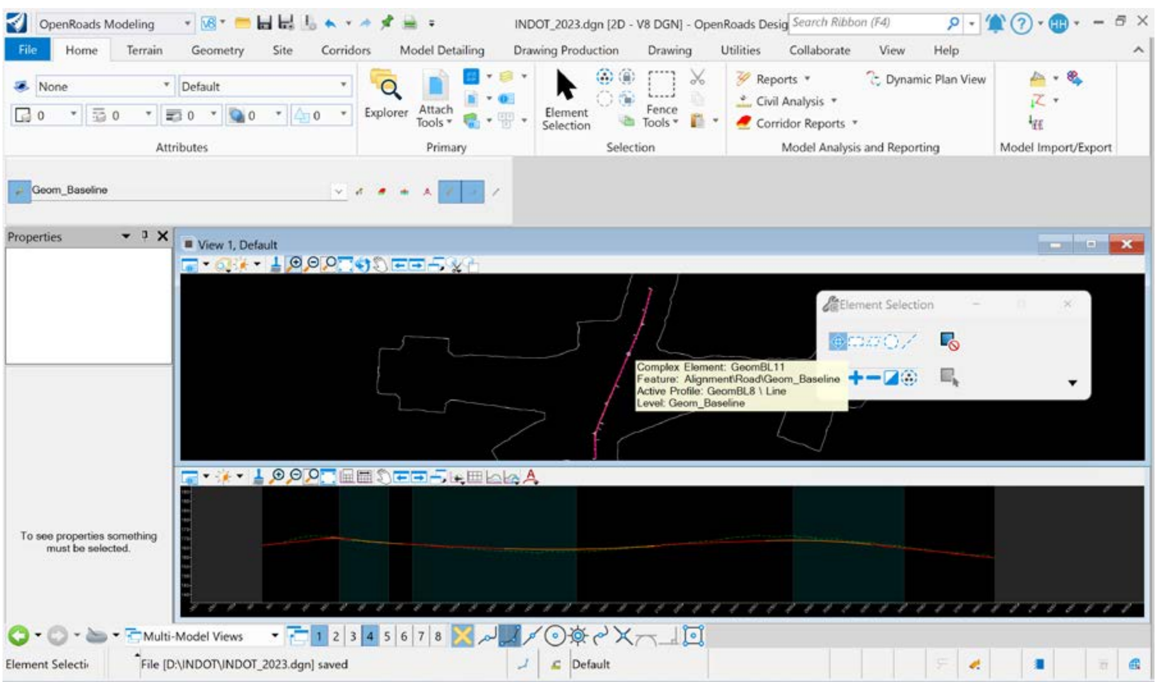


Figure B.117 Interface for the final profile.

Right-click on the screen “View 1.”

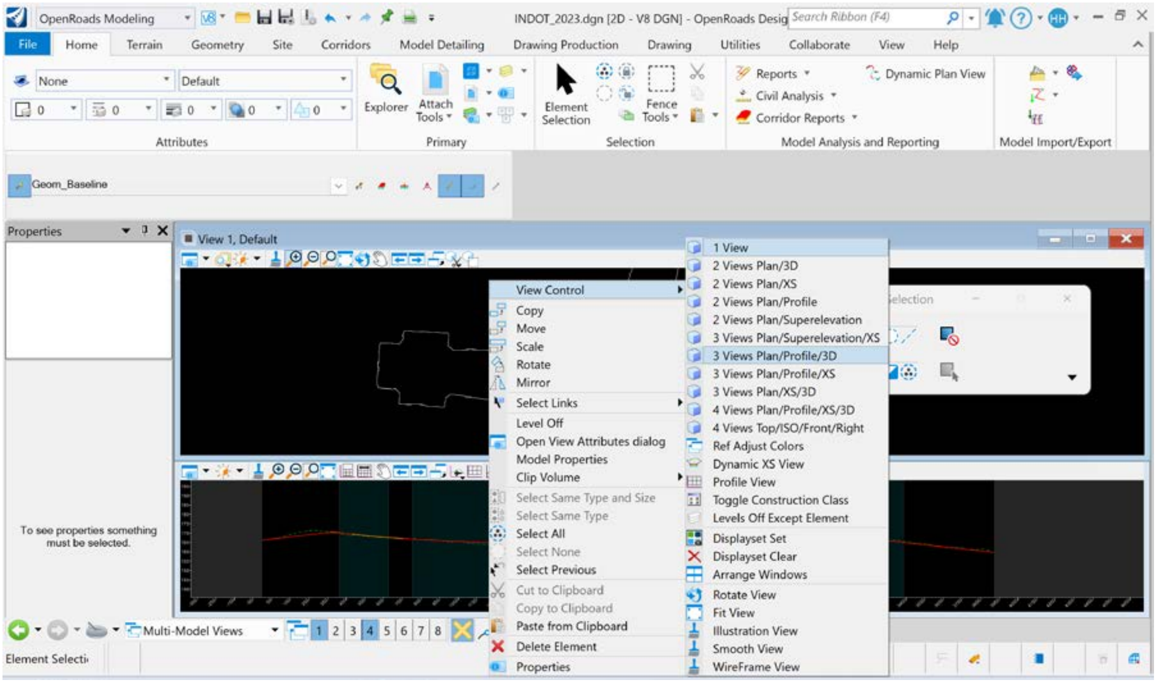


Figure B.118 Interface for the “view control” to show “3 views.”

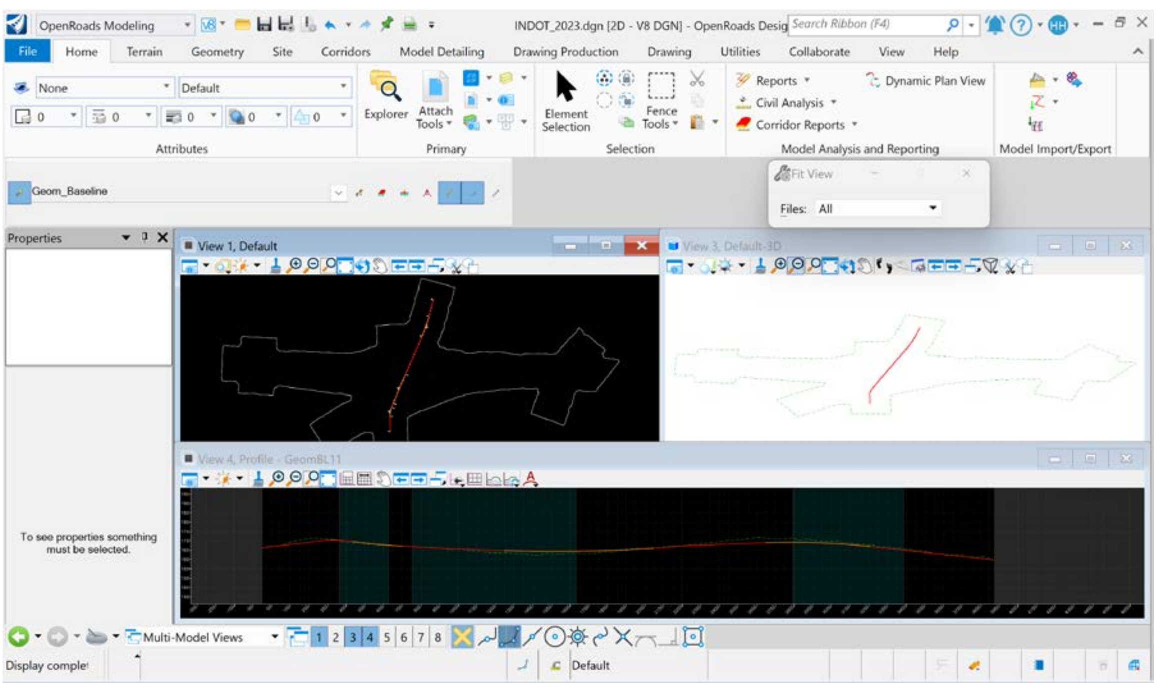


Figure B.119 Interface for 2D/3D/Profile.

Fifth Step: Typical Section (Concrete Pavement).

Corridors and Cross-section: According to *INDOT Standards and Design Manual*, we created the following cross sections (*Corridors> Create>Template> Create Template*):

- Concrete pavement sections with concrete curb (4 in.).
- Concrete pavement sections with concrete curb (6 in.).
- Concrete pavement sections with full-depth concrete shoulder (4 in.).

- Concrete pavement sections with full-depth concrete shoulder (6 in.).
  - PCCP Section with PCC Shoulder: Detailing full-depth concrete pavement sections with full-depth concrete shoulder.

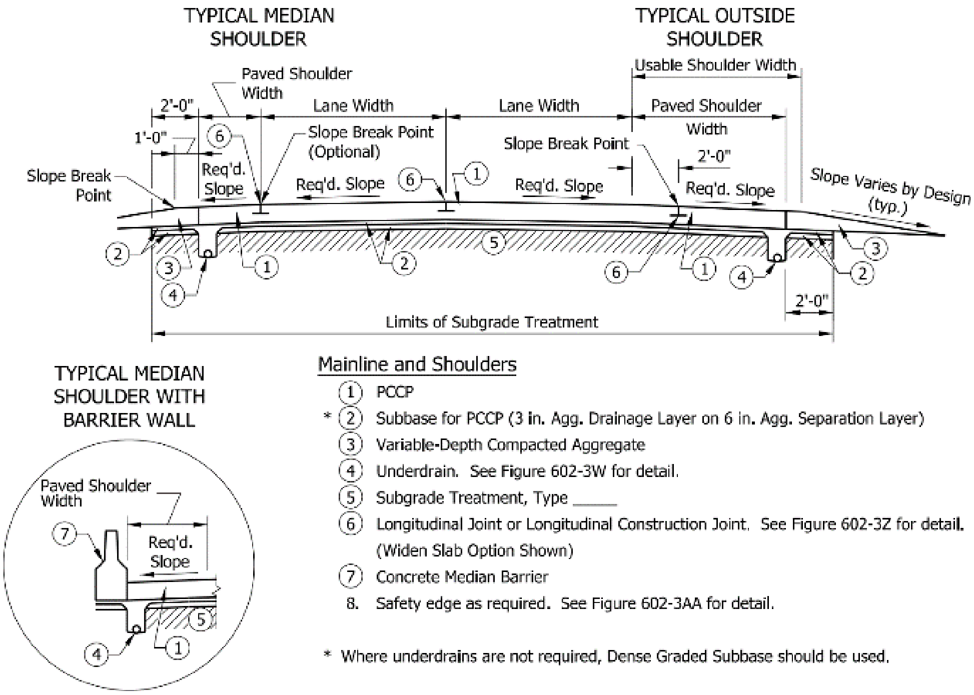


Figure B.120 Cross-section details for PCCP section with PCC shoulder (INDOT, 2022a).

  - PCCP with Concrete Curb: Detailing full-depth concrete pavement sections with concrete curb.

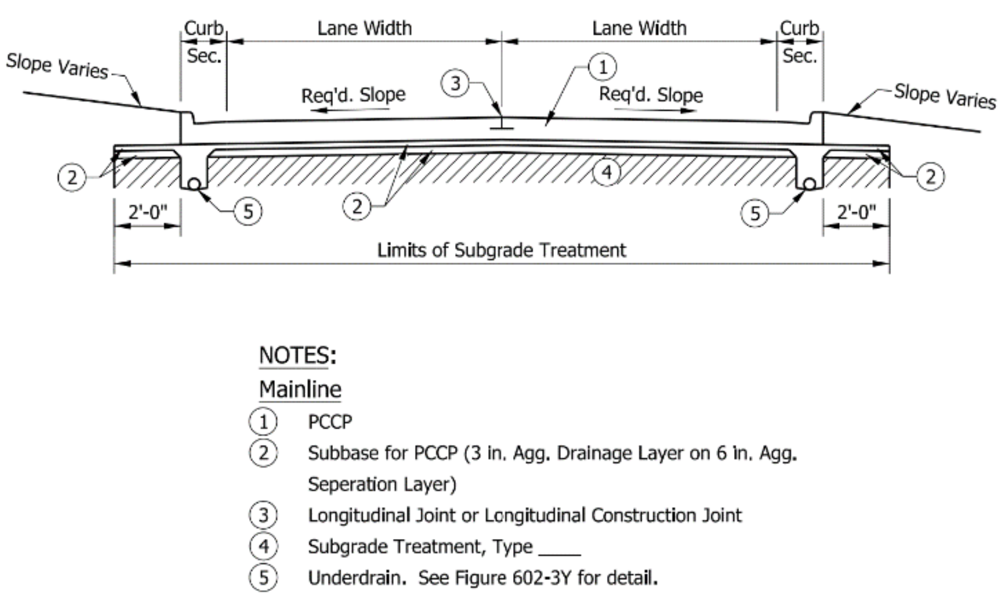


Figure B.121 Cross-section details for PCCP section with concrete curb (INDOT, 2022a).

Create Cross-Section*: Corridors Tab>Create>Template>Create Template>File>Open>Template-Imperial*

(C:\ProgramData\Bentley\OpenRoads Designer CE 10.11\Configuration\Organization-Civil_Civil Default Standards - Imperial\Template Library)> OpenRoads Templates Imperial.itl Notes: The file depends on the default installation of the software. In the companion digital package it is located in "Configuration\Organization-Civil_Civil Default Standards - Imperial\Template Library"

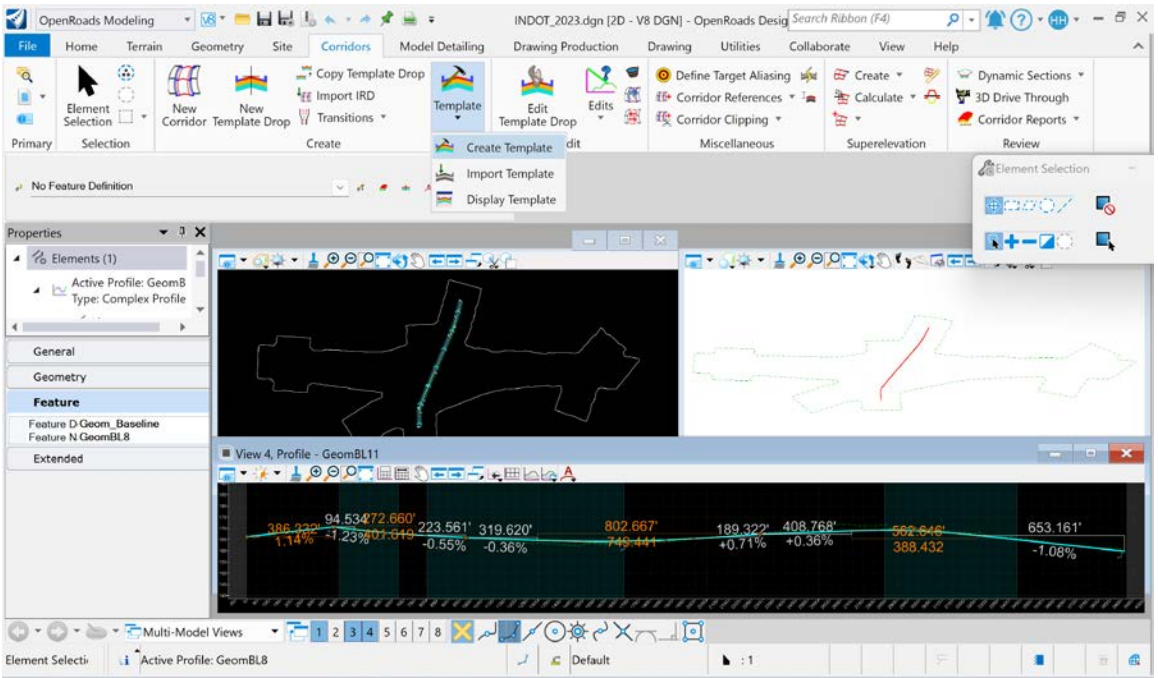


Figure B.122 Select "create template."

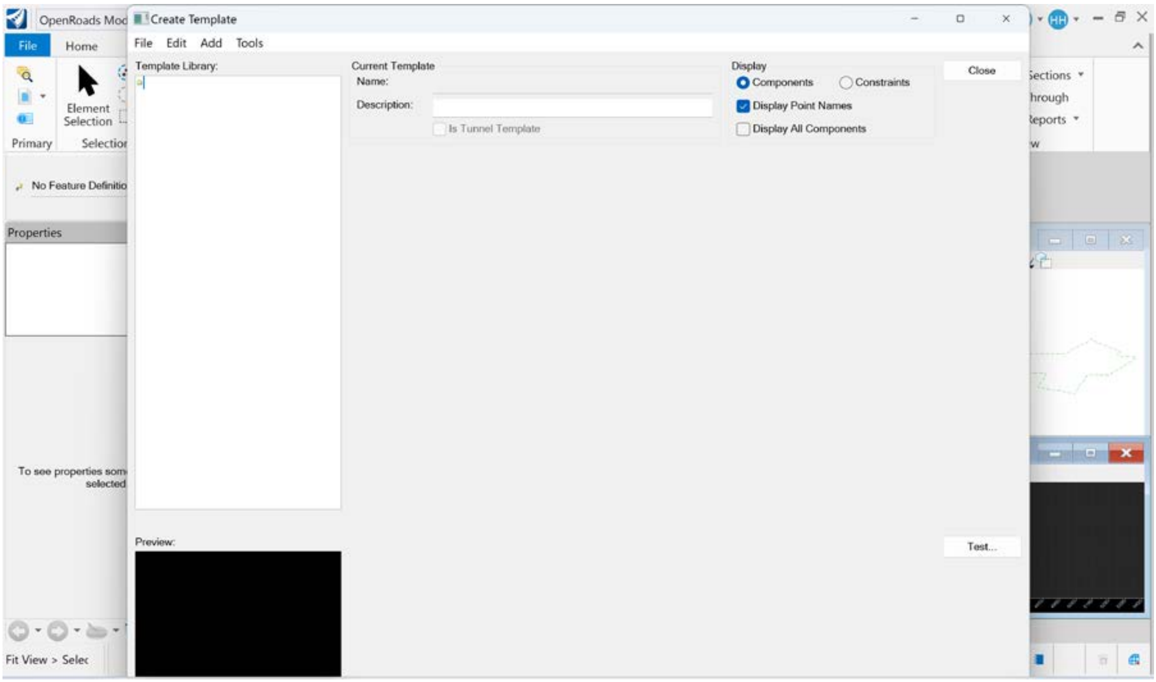


Figure B.123 Interface for “create template.”

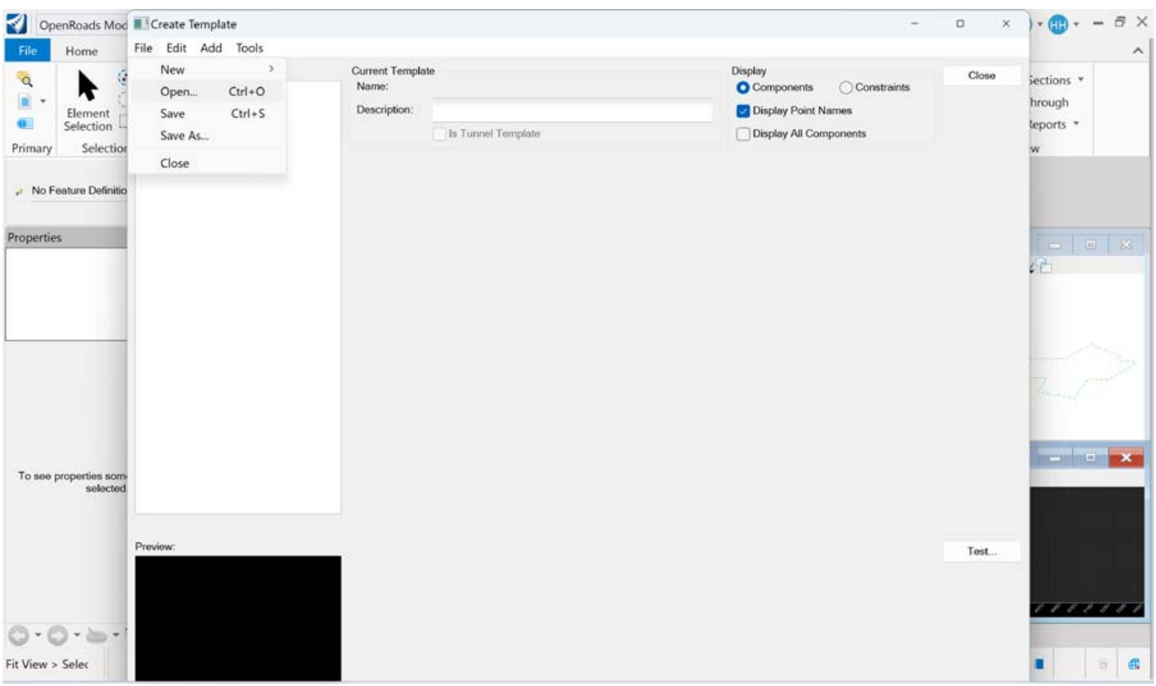


Figure B.124 Select “open” to choose the templates.

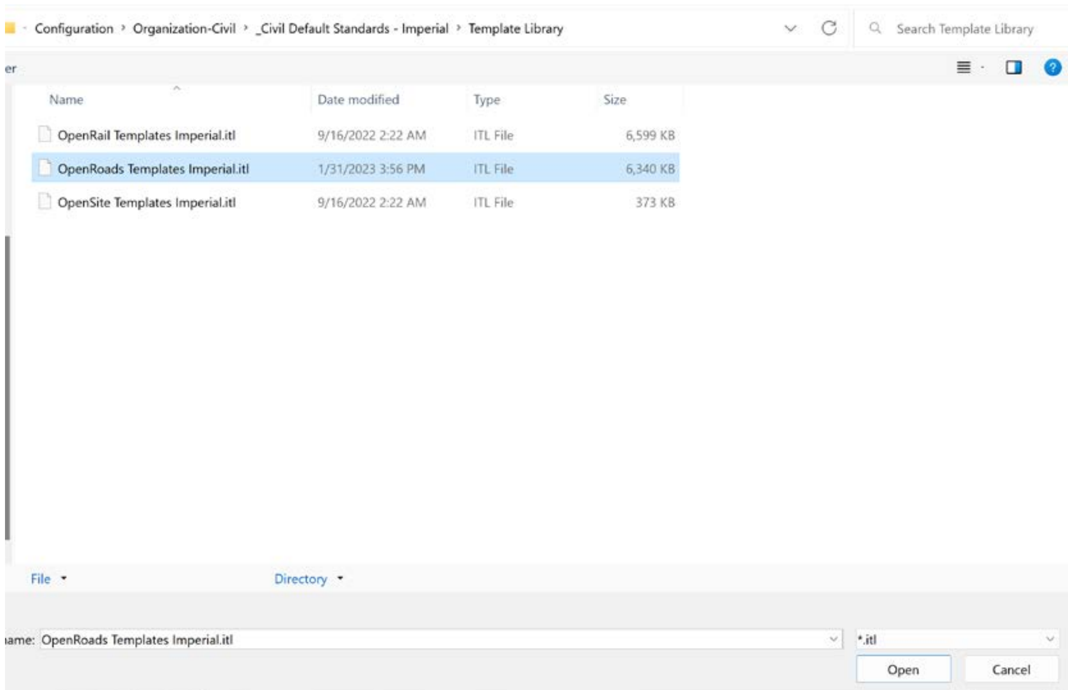


Figure B.125 Choose "templates-imperial.itl."

Note: In the cross-section template: When we create a new template for cross-section, we should choose "OpenRoads Templates Imperial."

Corridors and Cross-Section: According to *INDOT Standards and Design Manual*, we created the following cross sections (*Corridors> Template> Create Template*):

- Concrete pavement sections with concrete curb (4 in.)
- Concrete pavement sections with concrete curb (6 in.)
- Concrete pavement sections with full-depth concrete shoulder (4 in.)
- Concrete pavement sections with full-depth concrete shoulder (6 in.)
    - PCCP Section with PCC Shoulder: Detailing full-depth concrete pavement sections with full-depth concrete shoulder.

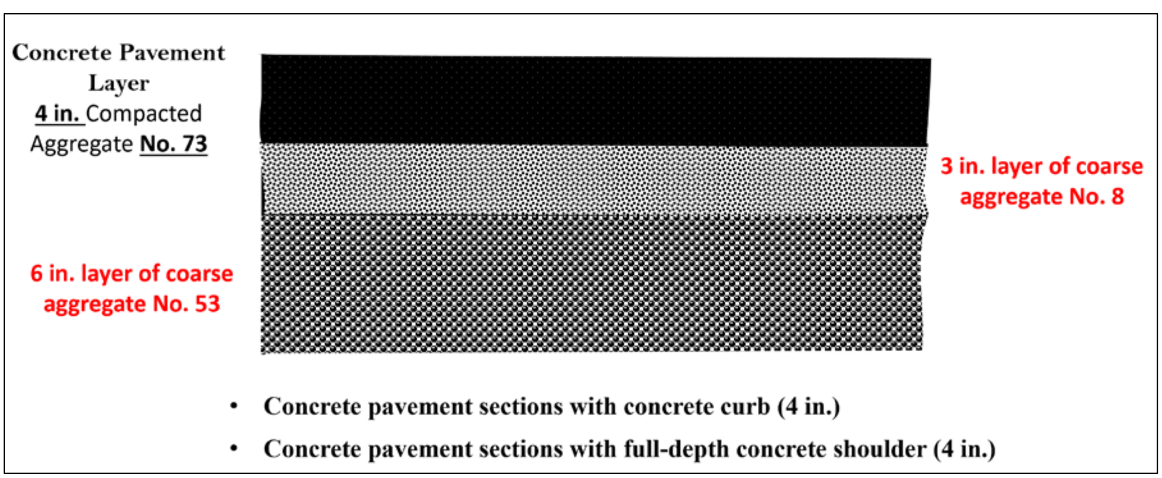


Figure B.126 Details for the cross section (4 in.).

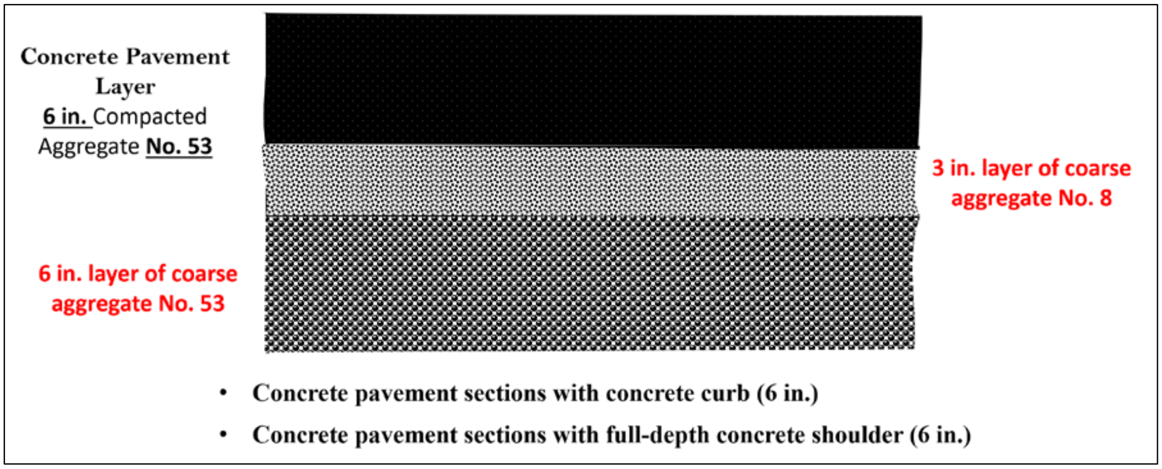


Figure B.127 Details for the cross section (6 in.).

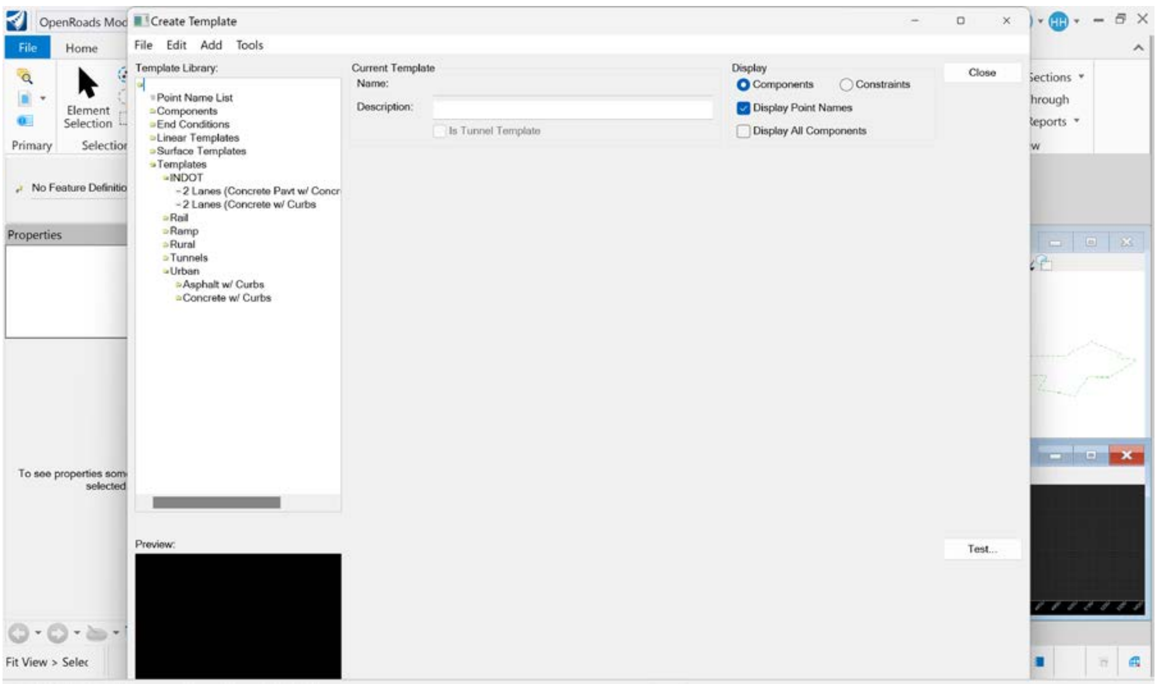


Figure B.128 Interface for the “create template”—“template library.”

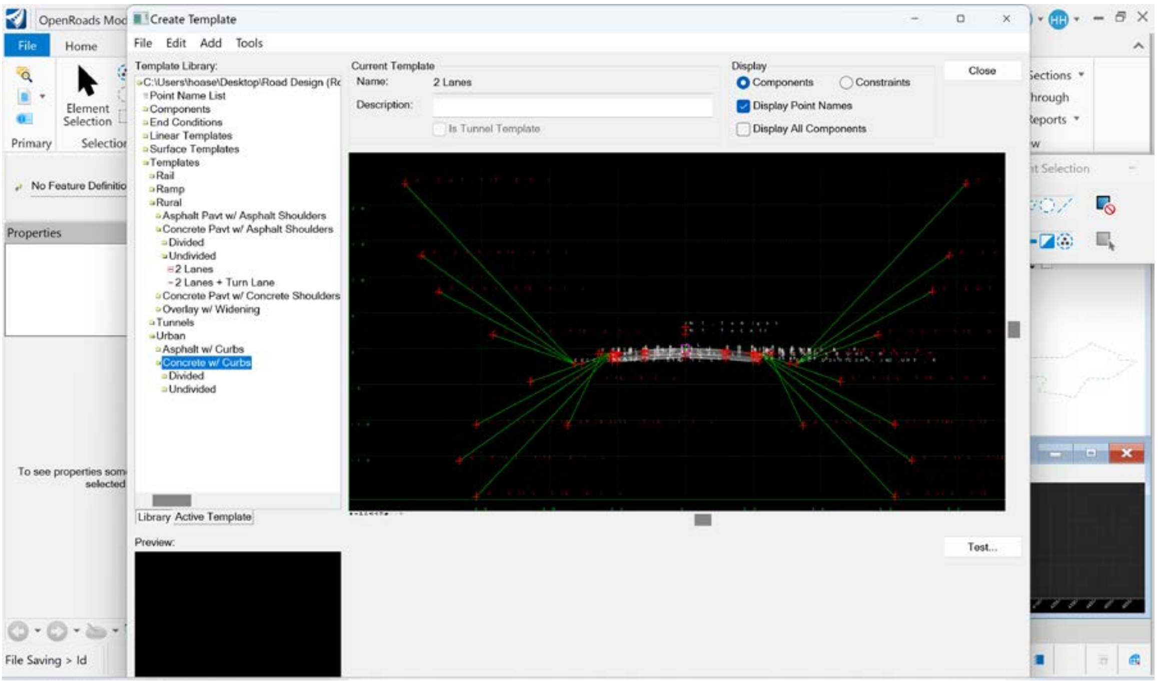


Figure B.129 Example for the “concrete w/ curbs” template.

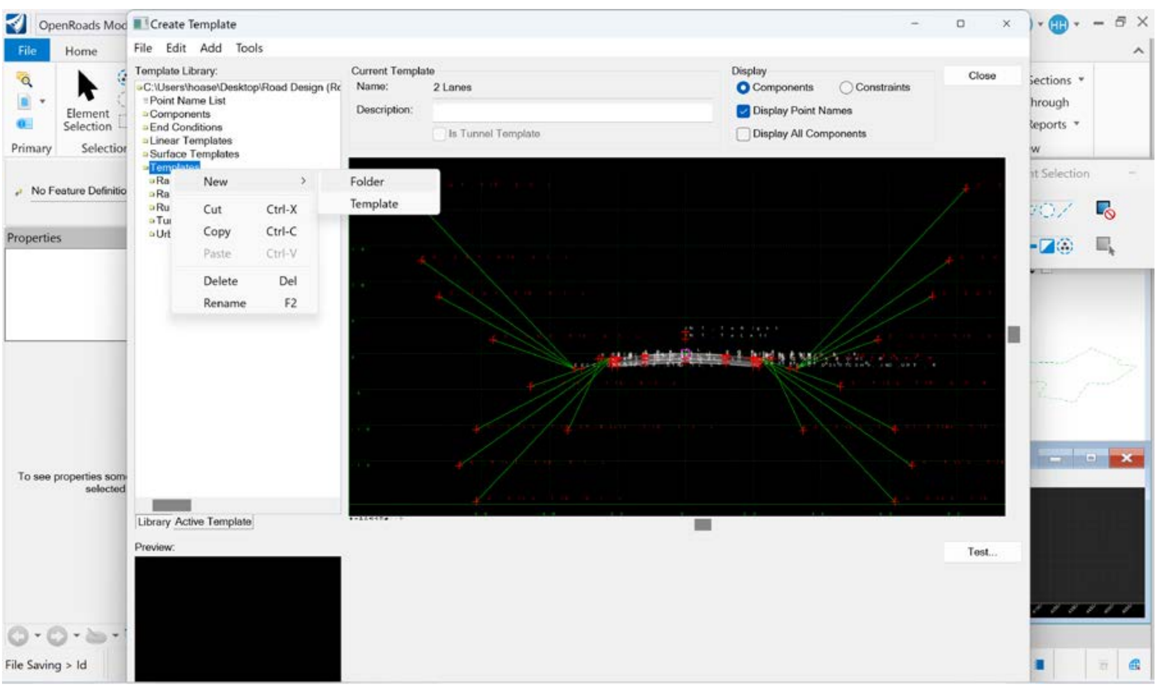


Figure B.130 Right-click on the “template” to create new folder.

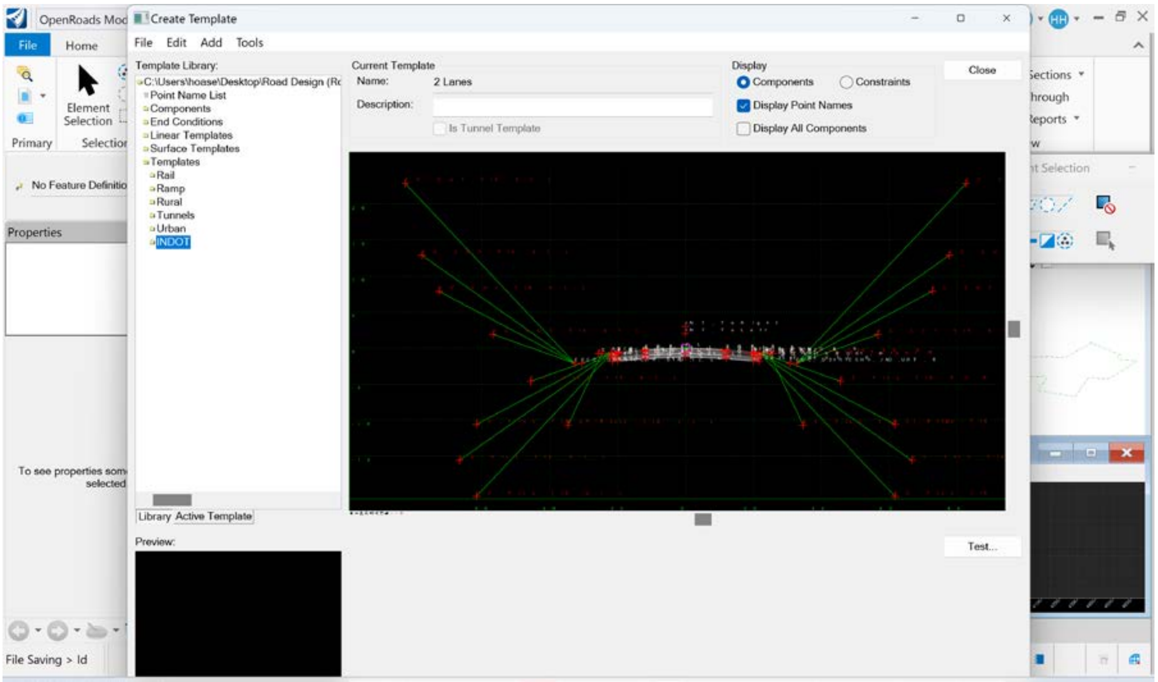


Figure B.131 Create new folder "INDOT."

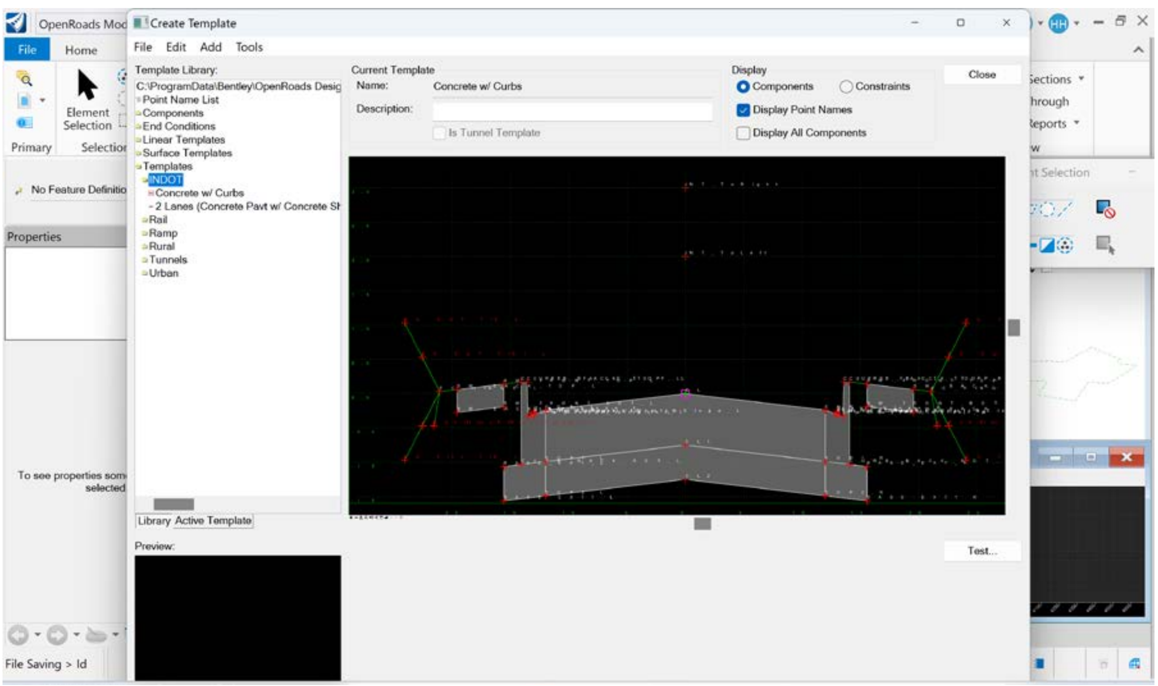


Figure B.132 Copy and paste samples from "template" for "concrete w/ curbs" and "concrete pavt w/ concrete shoulder."

Save As: File>Save As
(C:\ProgramData\Bentley\OpenRoads Designer CE 10.11\Configuration\WorkSpaces\INDOT_2023\WorkSets\INDOT_2023\Standards\Template Library\ INDOT Templates - Imperial)

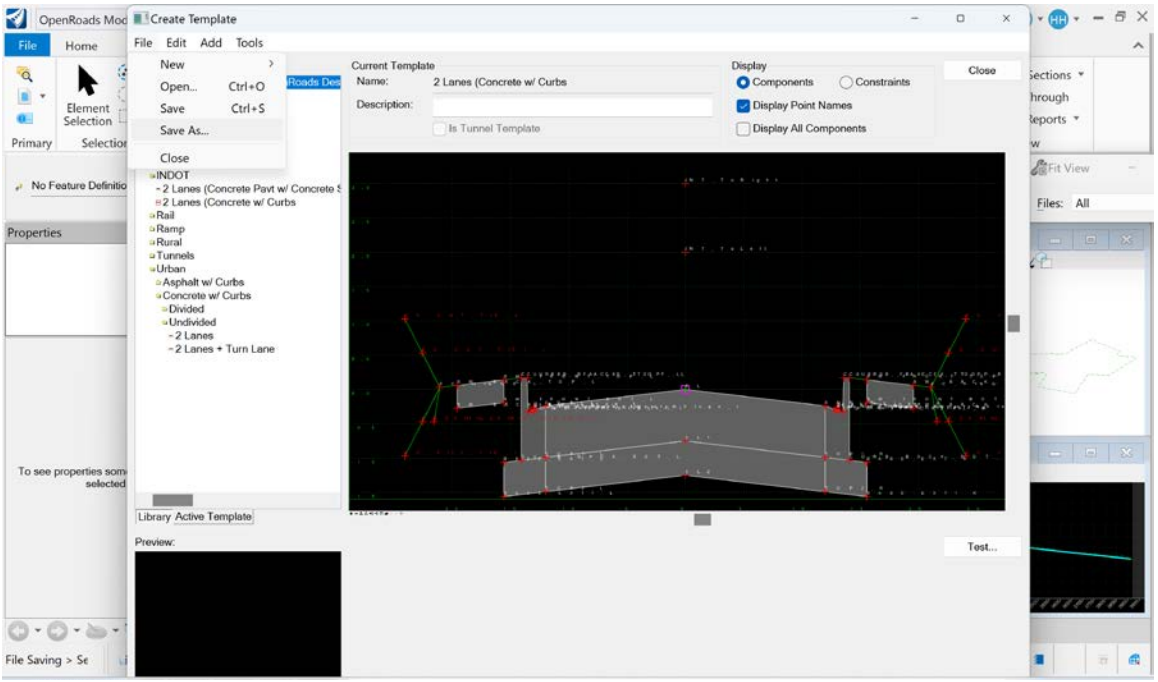


Figure B.133 Select "save as."

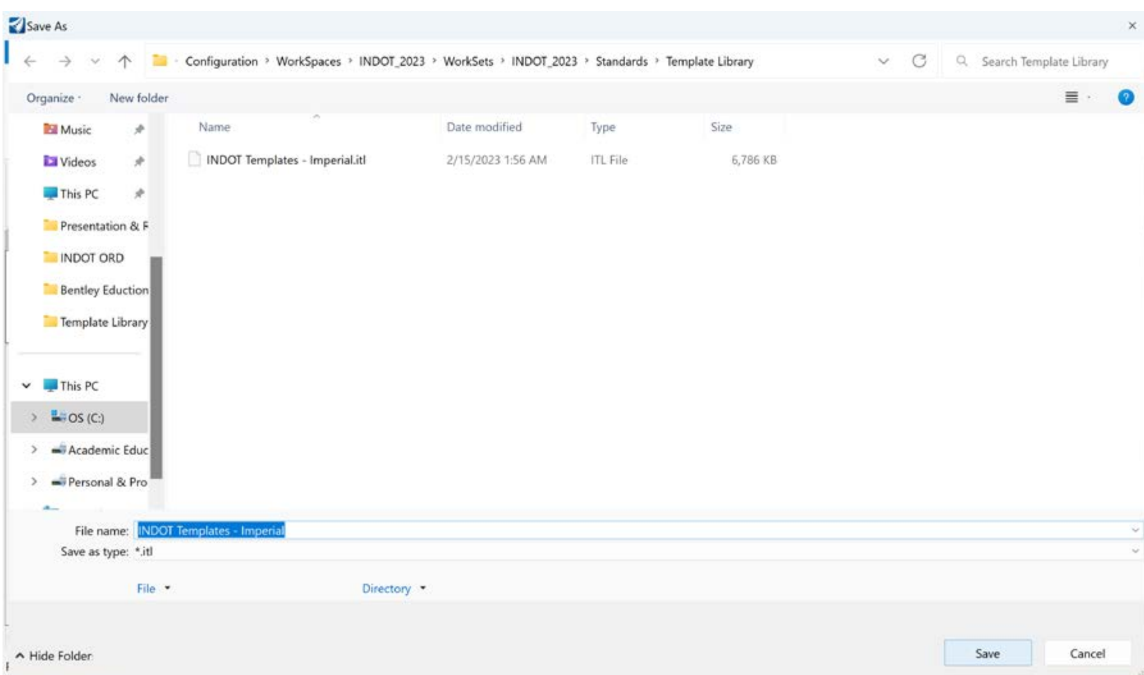


Figure B.134 Create name for the template according to the project.

Create Template “Typical Section.”

From “Components,” we can copy the samples (2 Lanes Curbs and 2 Lanes Shoulders) for the templates and then edit it according to the details and specifications of the project.

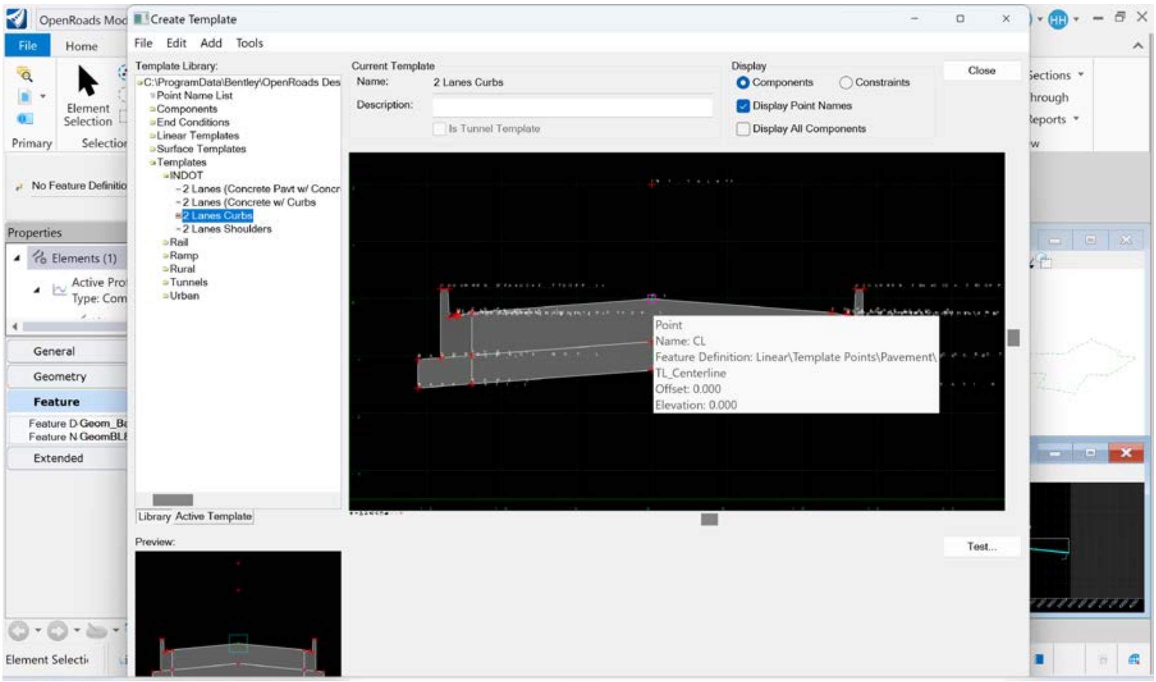


Figure B.135 Check the details for the points.

Double click.

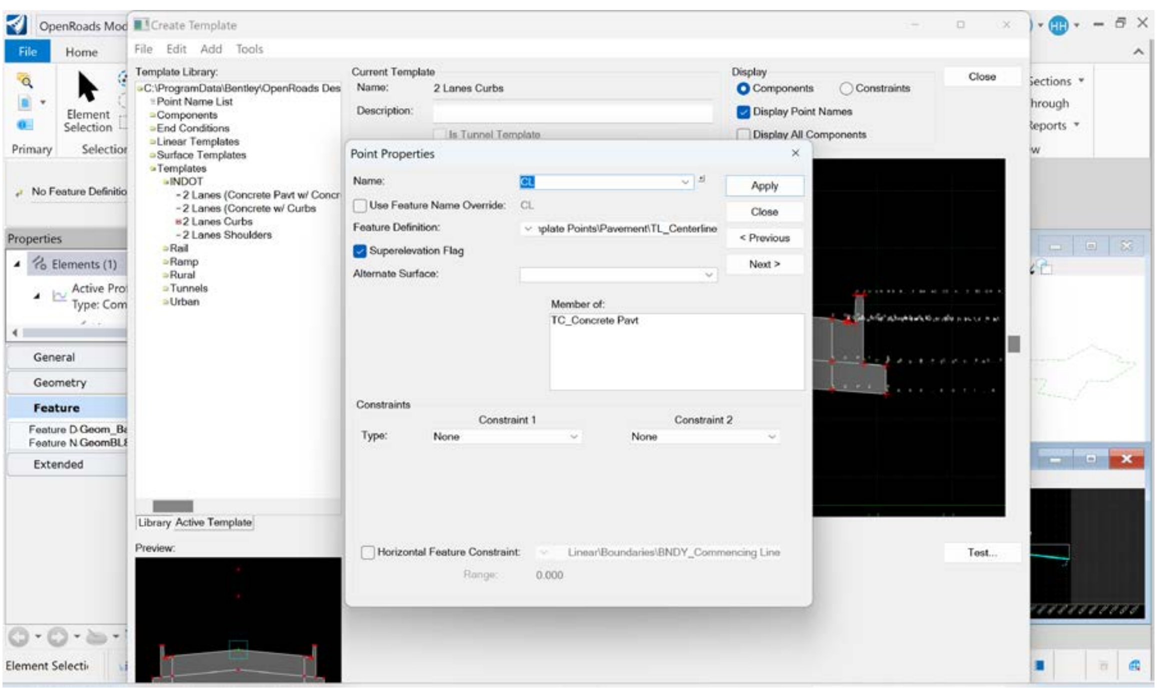


Figure B.136 Interface for the “point properties” and from this dialog we can edit the details for the point.

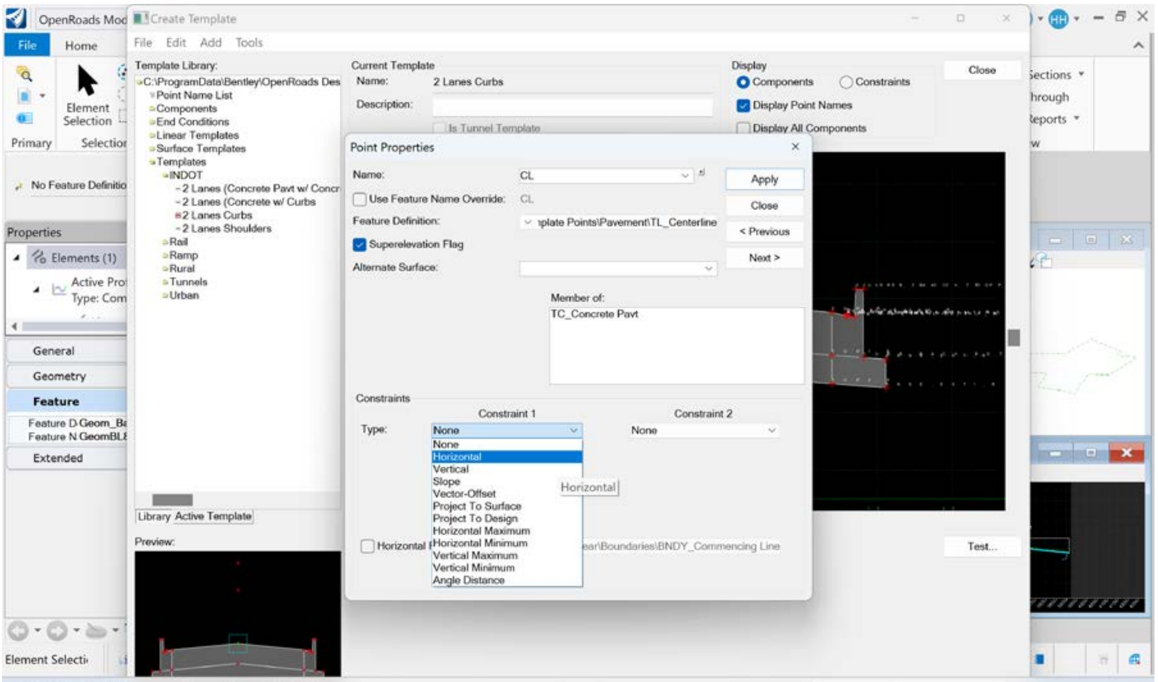


Figure B.137 Define the constraints for the point (constraints 1).

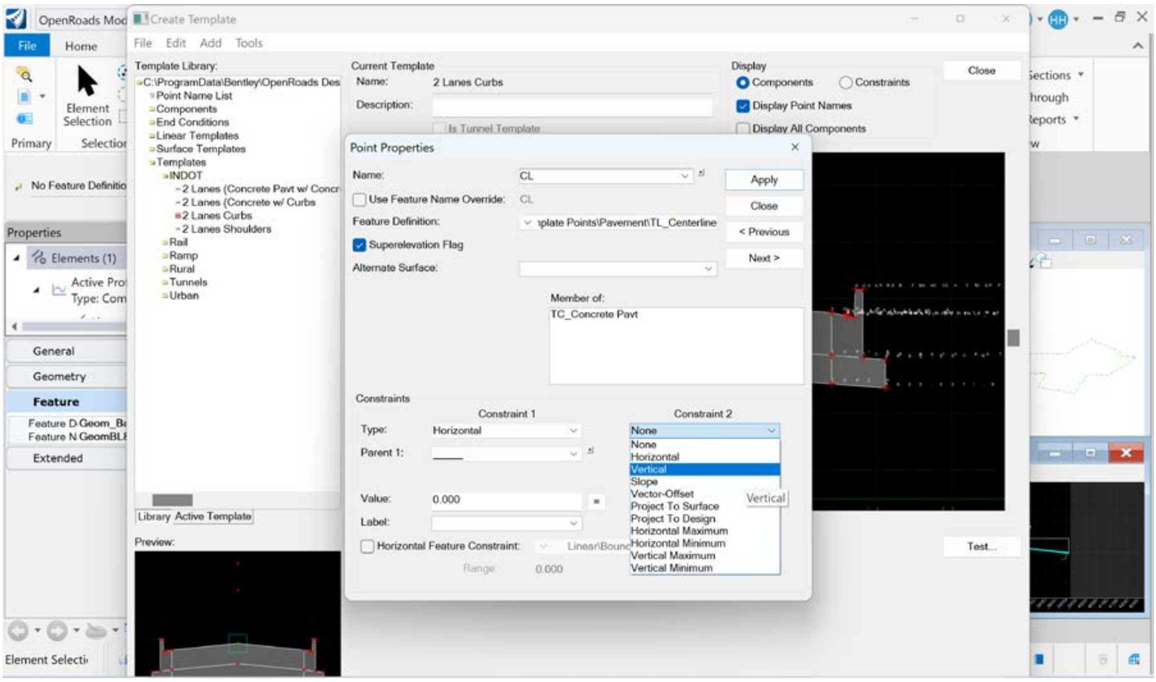


Figure B.138 Define the constraints for the point (constraints 2).

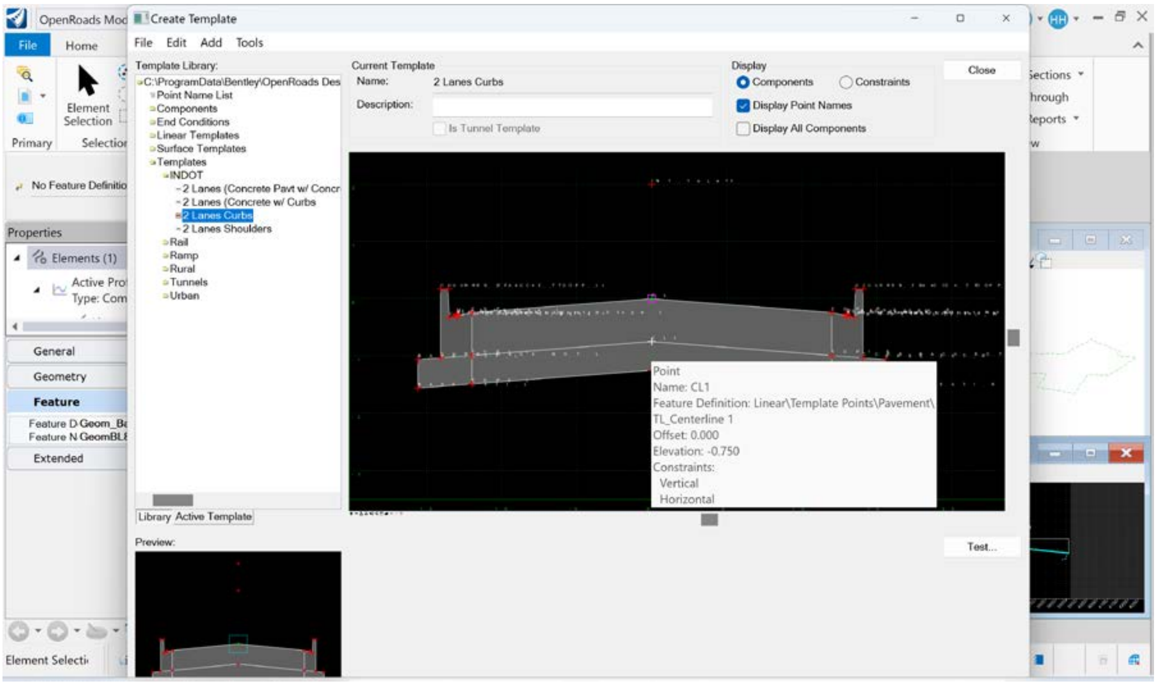


Figure B.139 Details for the point.

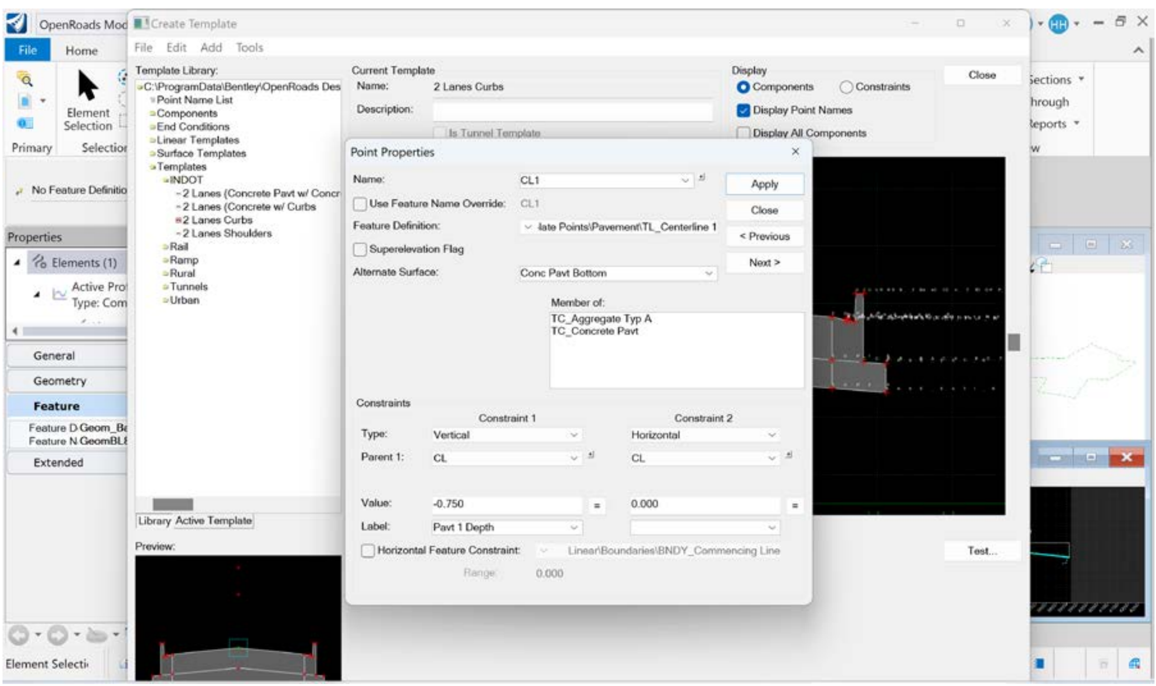


Figure B.140 Details for the second point between the concrete layer and aggregate layer.

Also, continue to check all points. Then double-click on the shape for the first layer.

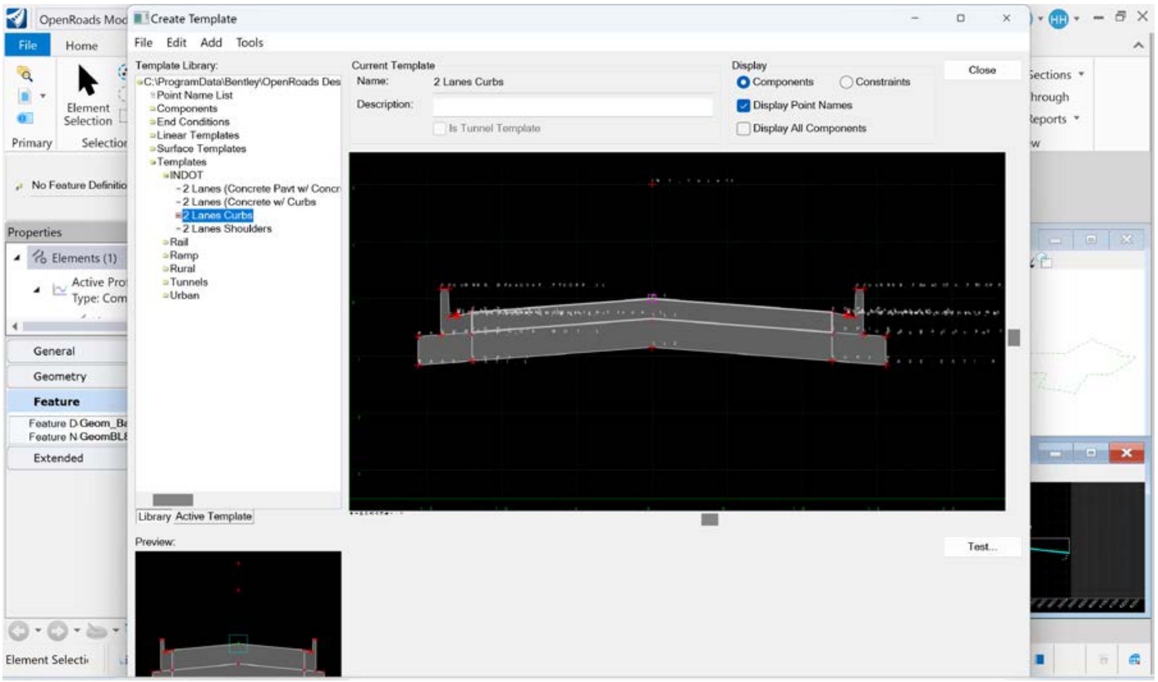


Figure B.141 Click on the edge of first layer to show the details of “component properties.”

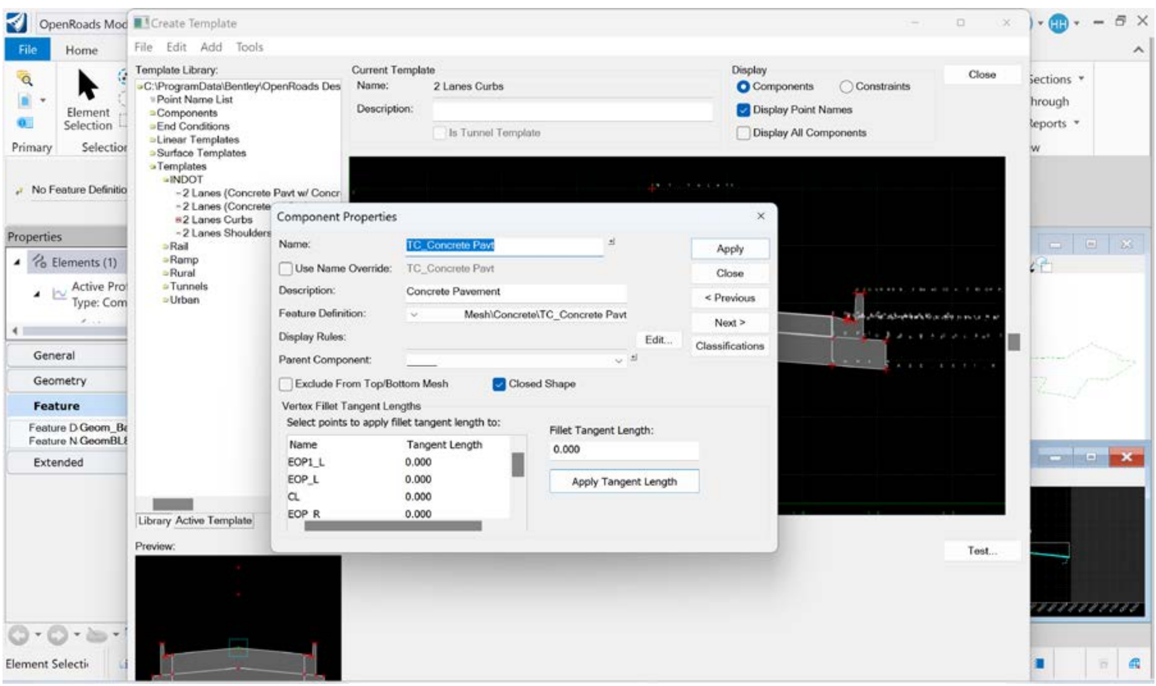


Figure B.142 Dialog for the “component properties”—aggregate layer details.

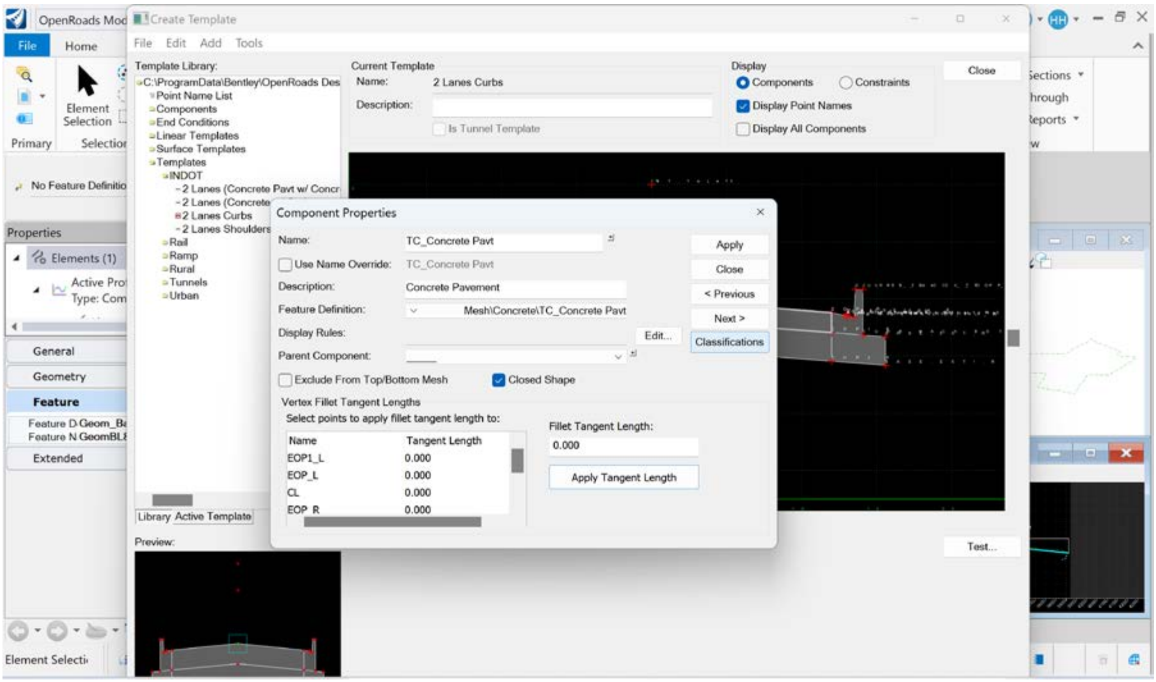


Figure B.143 Click on “classifications” to show “classification properties.”

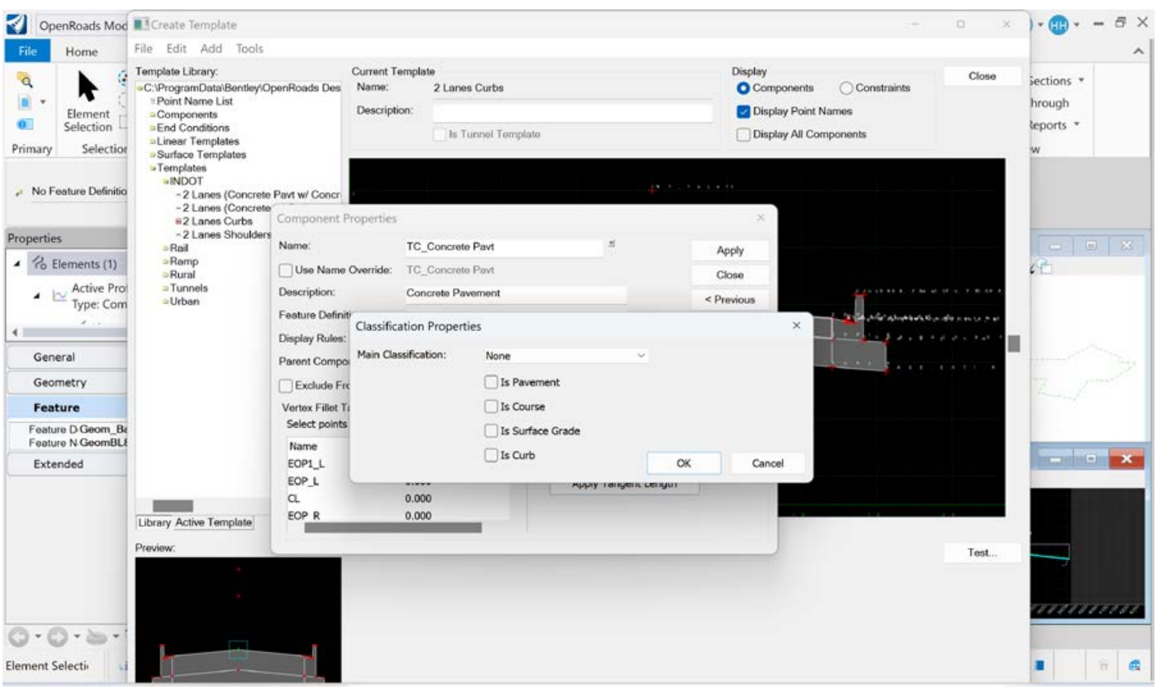


Figure B.144 Dialog for the “classification properties.”

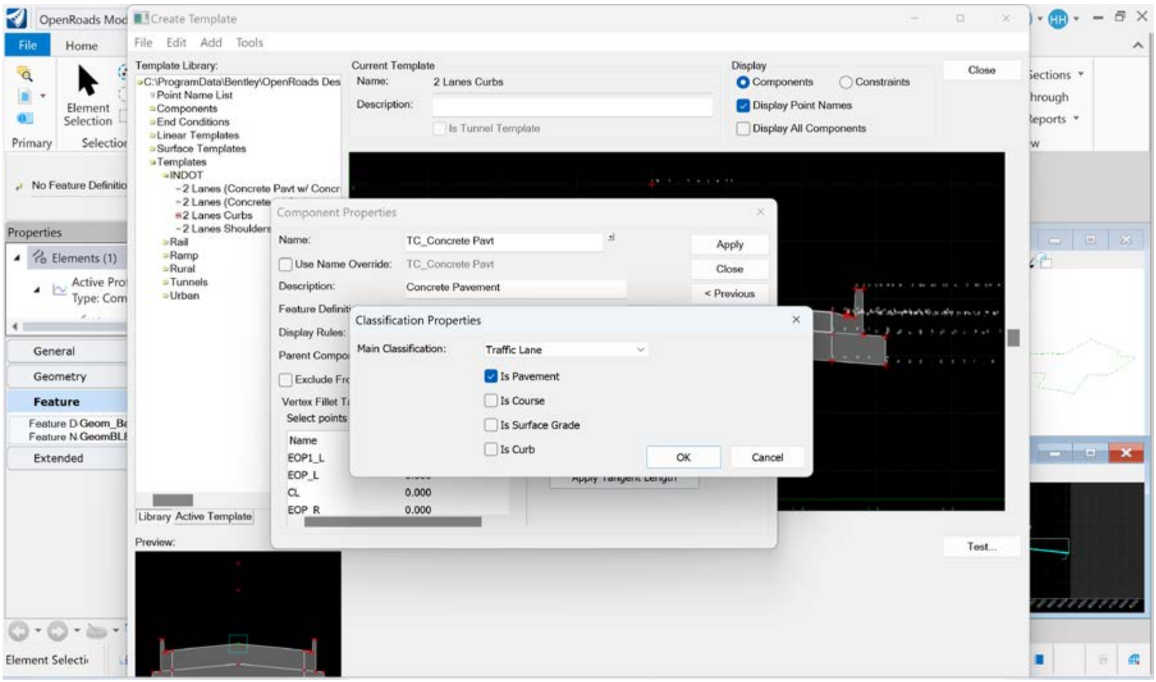


Figure B.145 Dialog for the “classification properties” and set the main classification as “is pavement.”

The second layer:

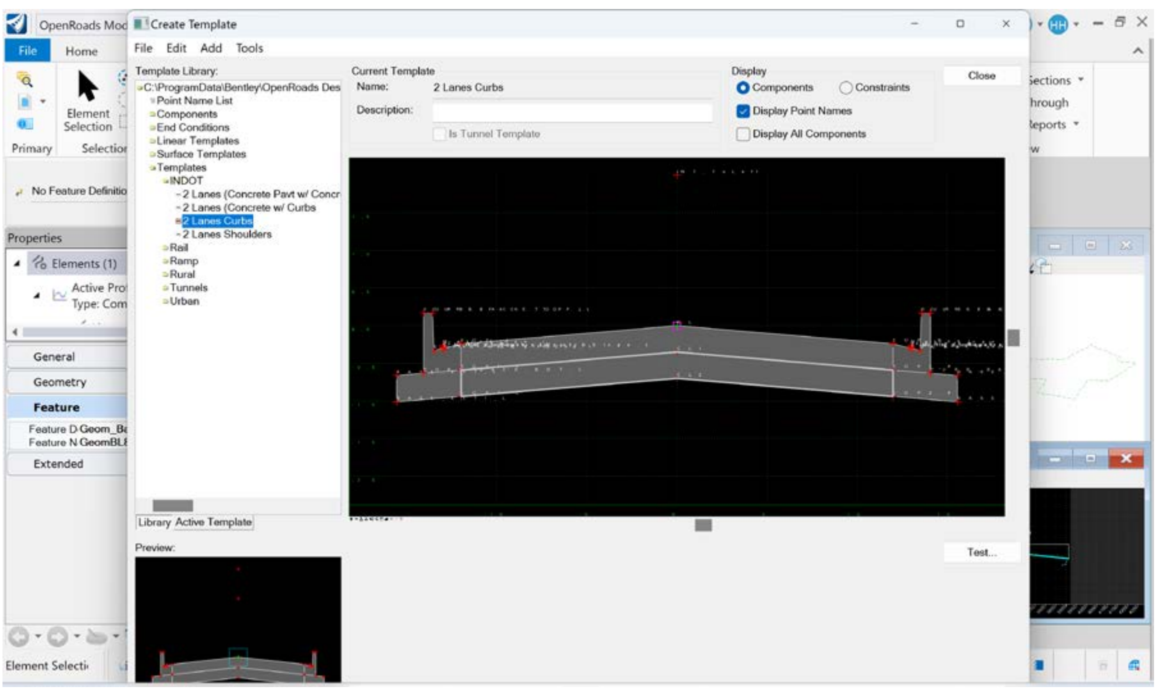


Figure B.146 Click on the second layer to show the details of “component properties.”

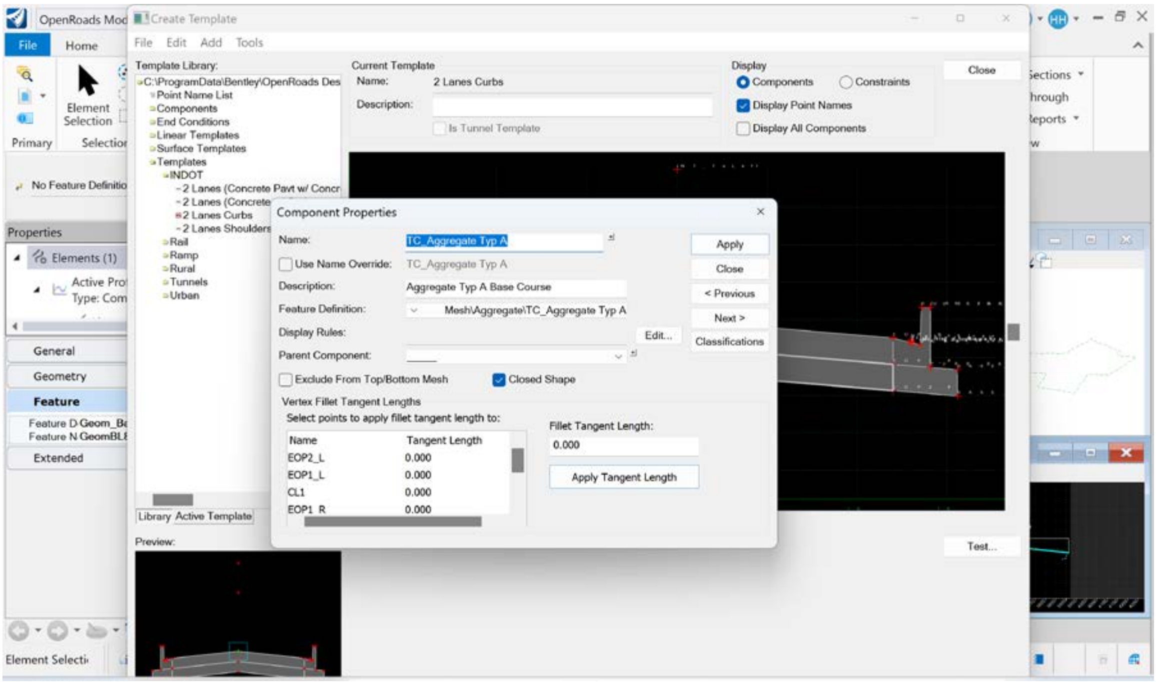


Figure B.147 Dialog for the “component properties”—aggregate layer details.

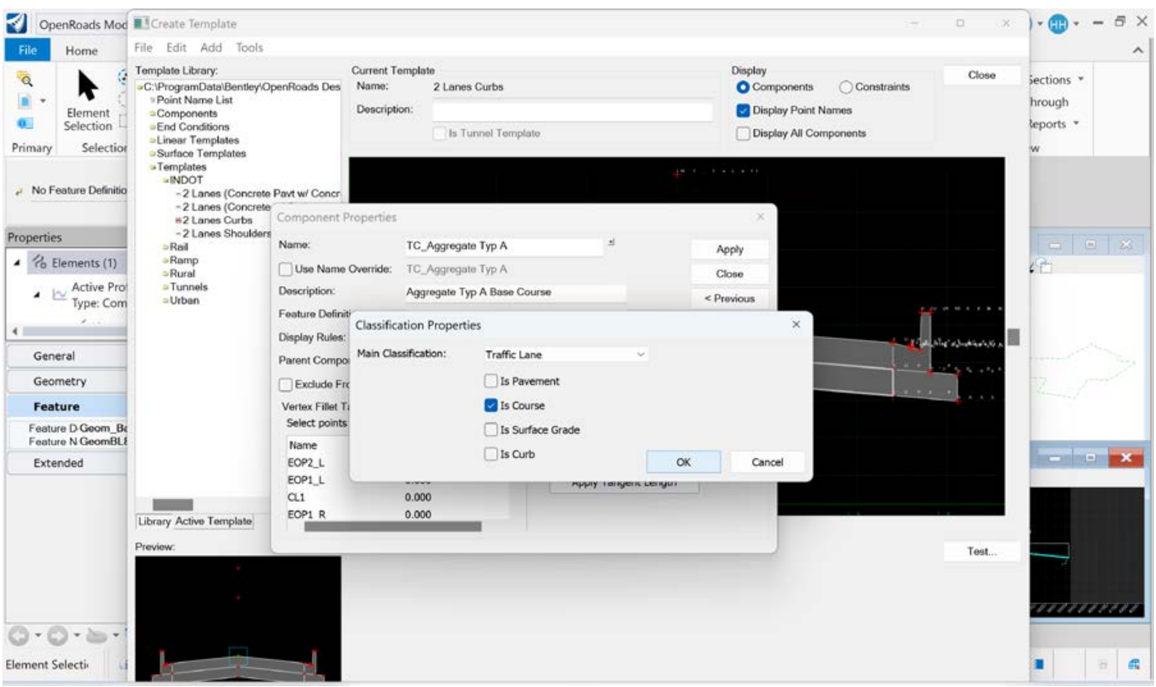


Figure B.148 Dialog for the “classification properties.”

For curbs:

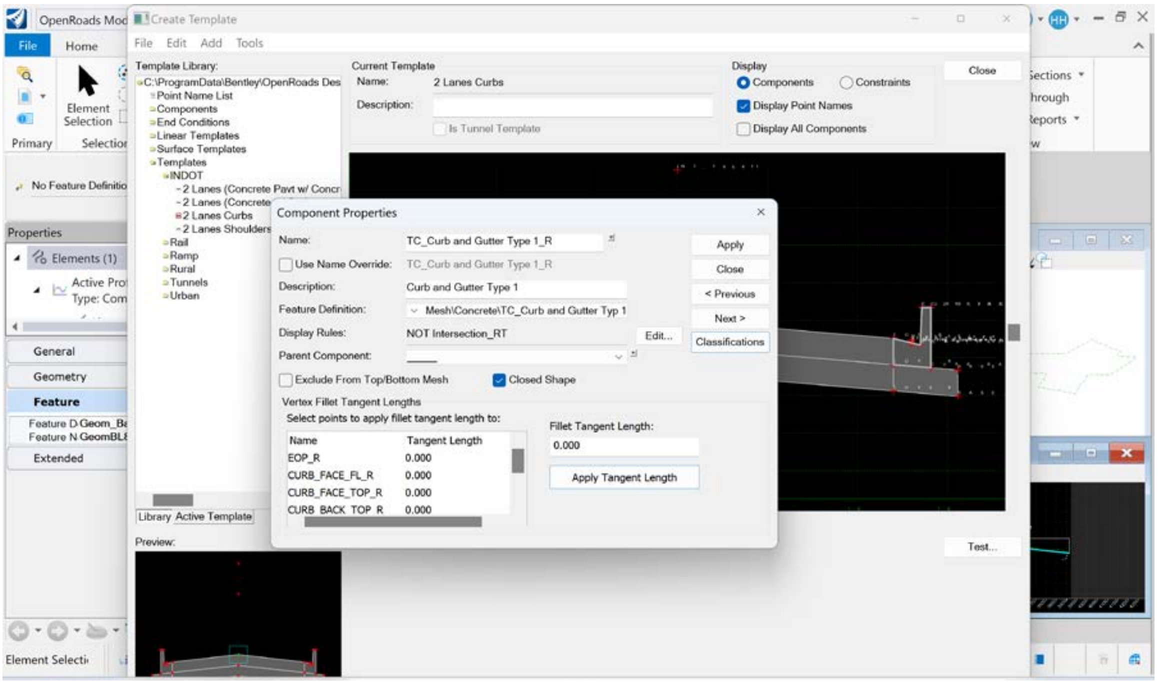


Figure B.149 Dialog for the curb details.

Then add the third layer.
Right Click> Add New Component>Simple

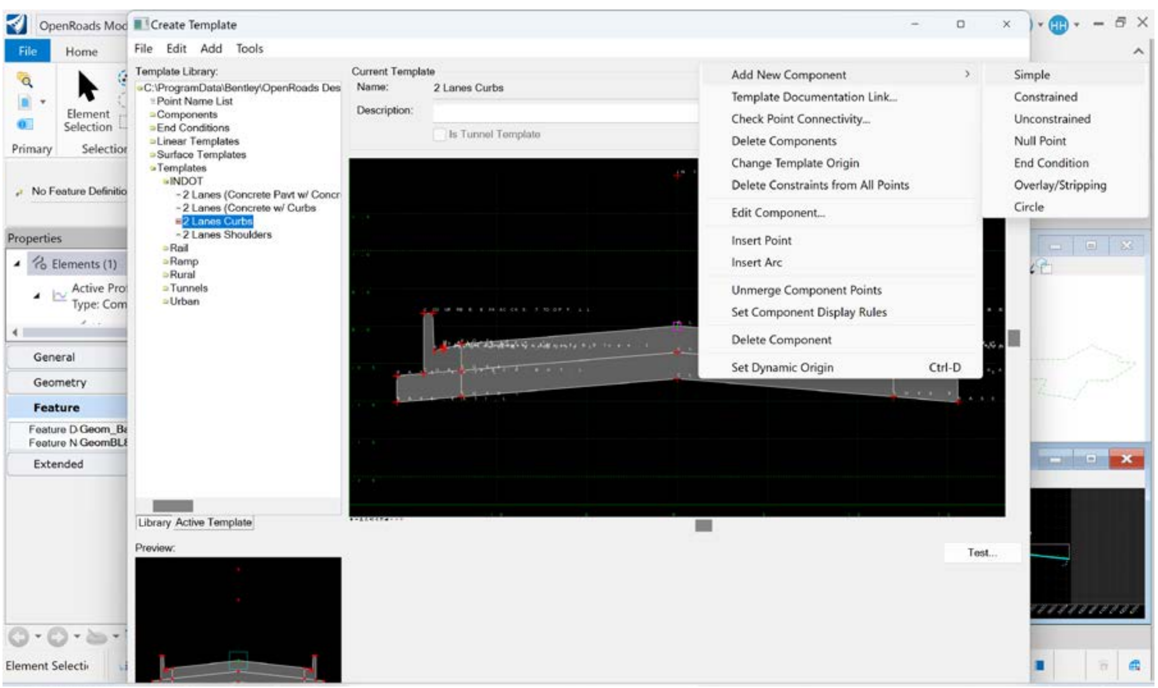


Figure B.150 Select "add new component."

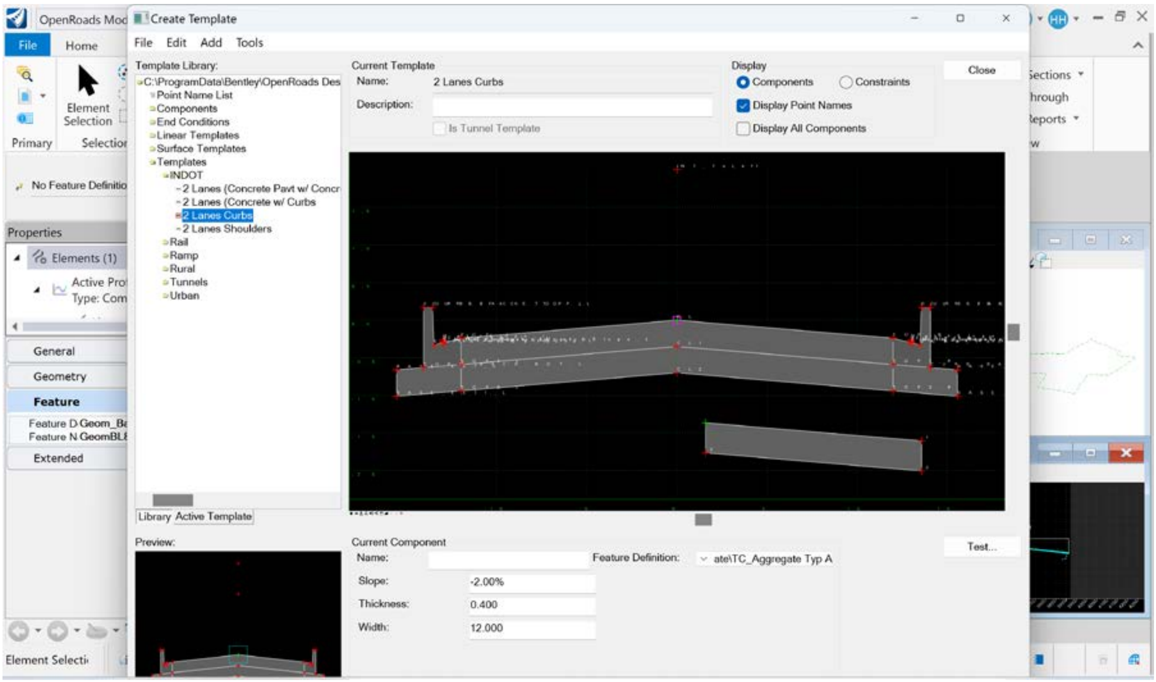


Figure B.151 Start to add layers.

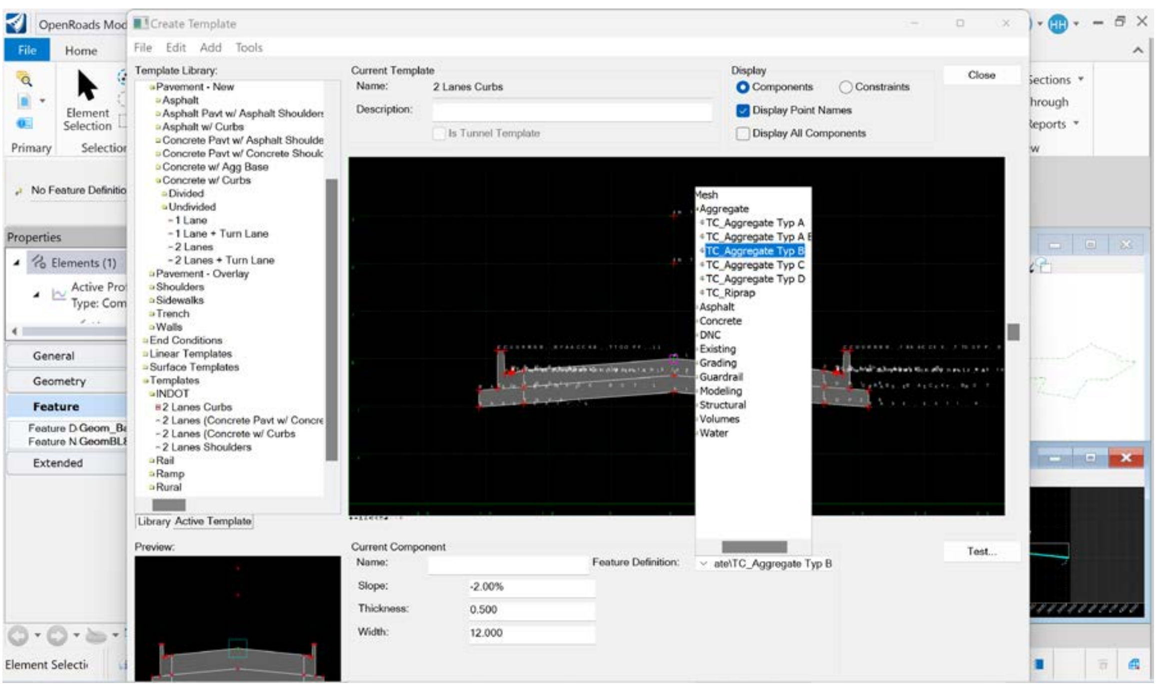


Figure B.152 Details for the new layer.

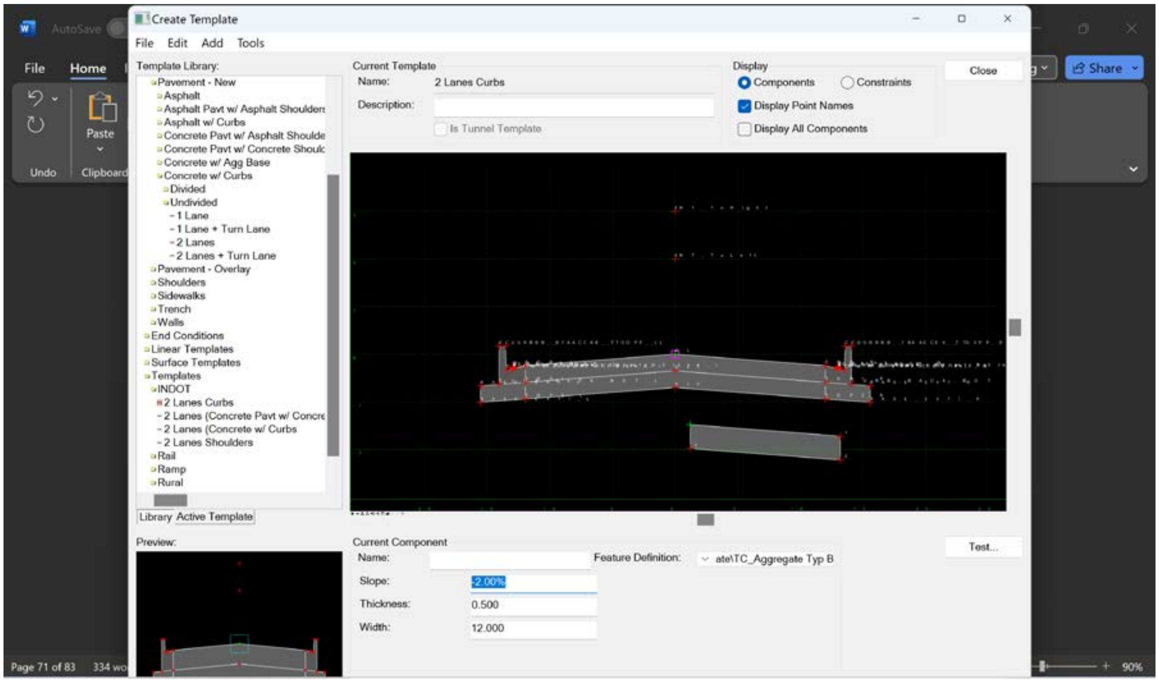


Figure B.153 Complete the process for adding the new layer.

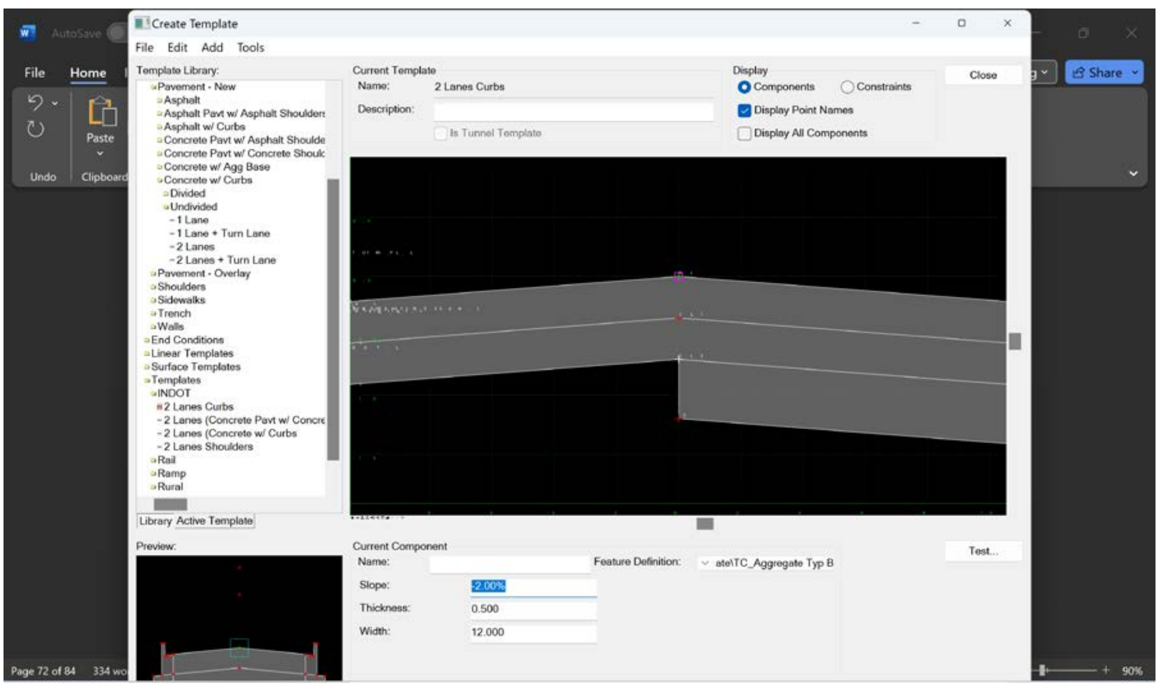


Figure B.154 Check the new layer.

Then complete by the same steps.

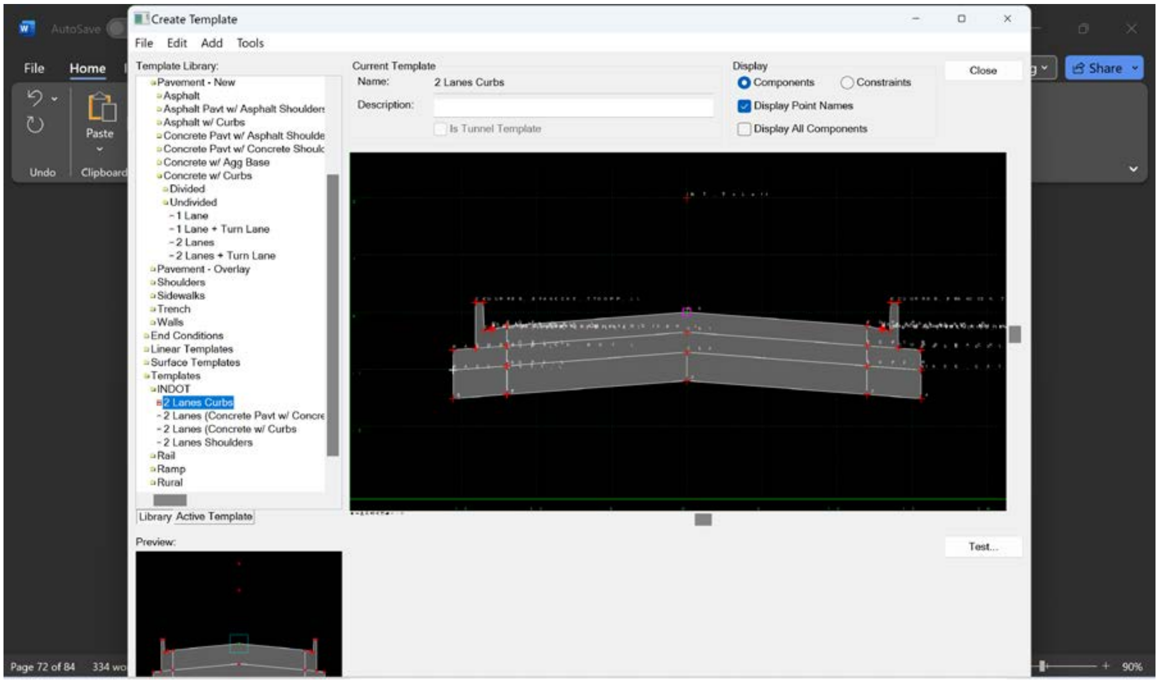


Figure B.155 Interface for the template “concrete pavement sections with concrete curb.”

Copy and paste to edit the cross section for 6 in.

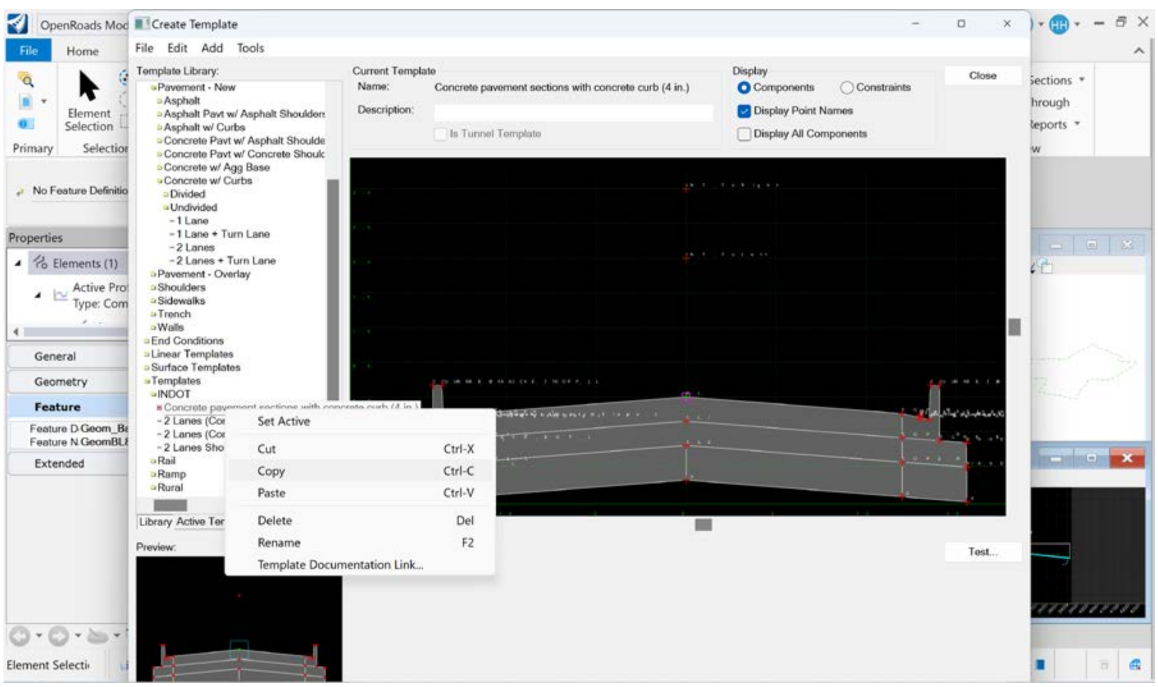


Figure B.156 Copy the new template.

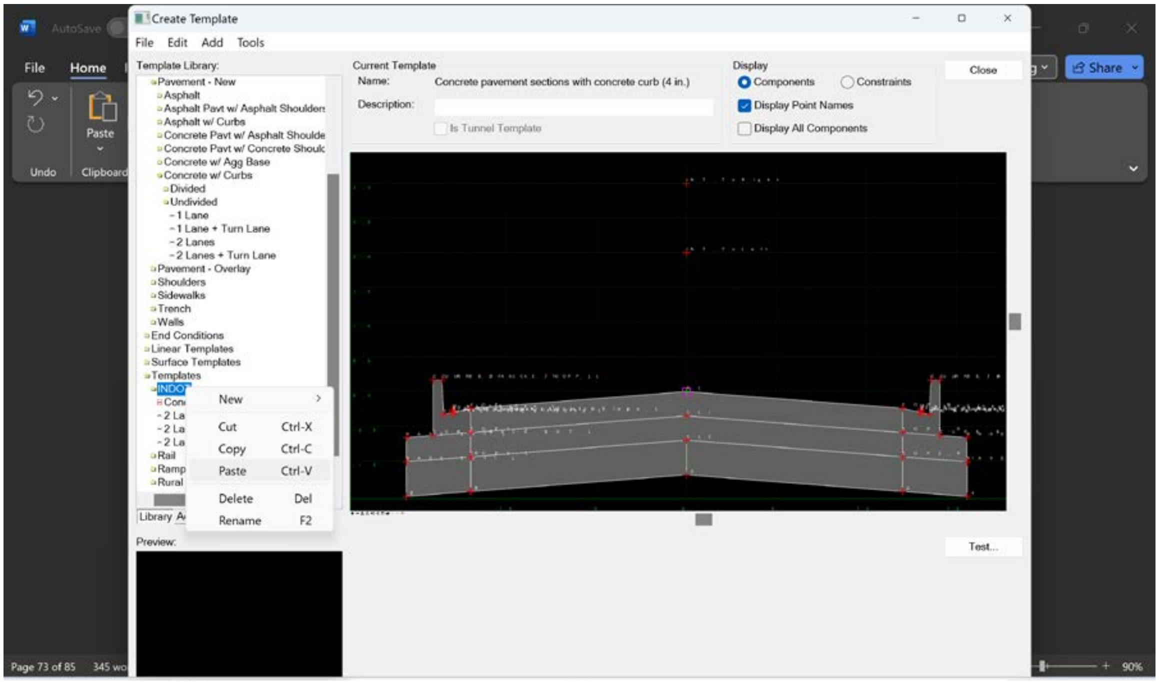


Figure B.157 Paste the template.

Apply the same steps with the cross-section of concrete/shoulders.

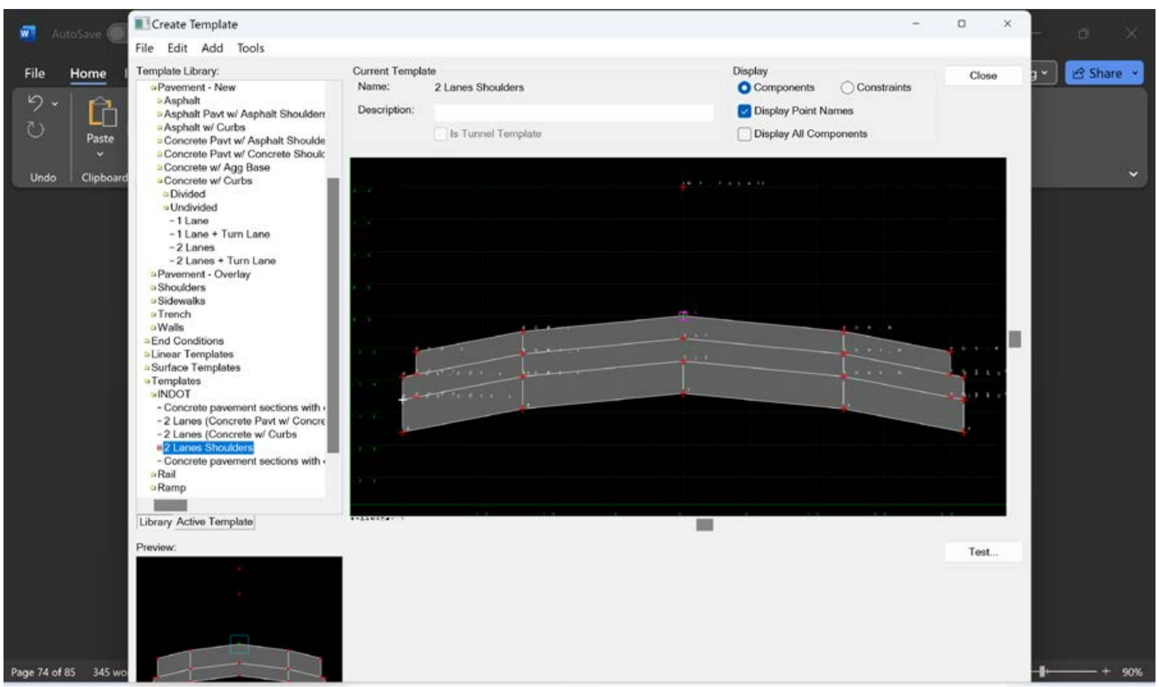


Figure B.158 Samples for the concrete with shoulder.

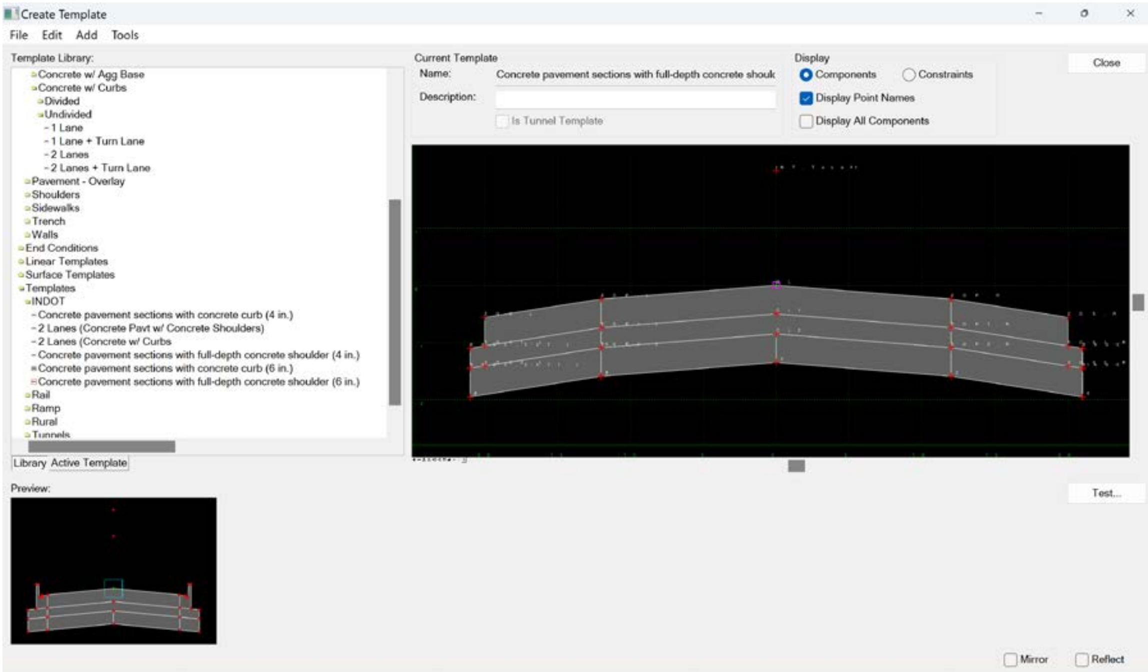
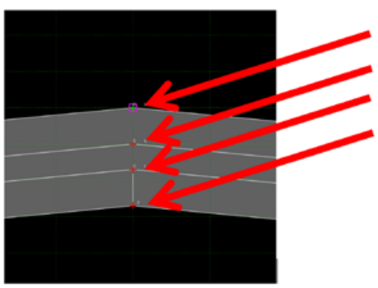


Figure B.159 Interface for the INDOT templates.

Notes: In this model, we set the thickness of the concrete pavement (4 in.) in 0.35 ft., the thickness of the concrete pavement (6 in.) in 0.5 ft., the 1st layer of aggregate is 0.35 ft., and the 2nd layer of aggregate is 0.5 ft, as shown in Figure B.128 to Figure B.133.



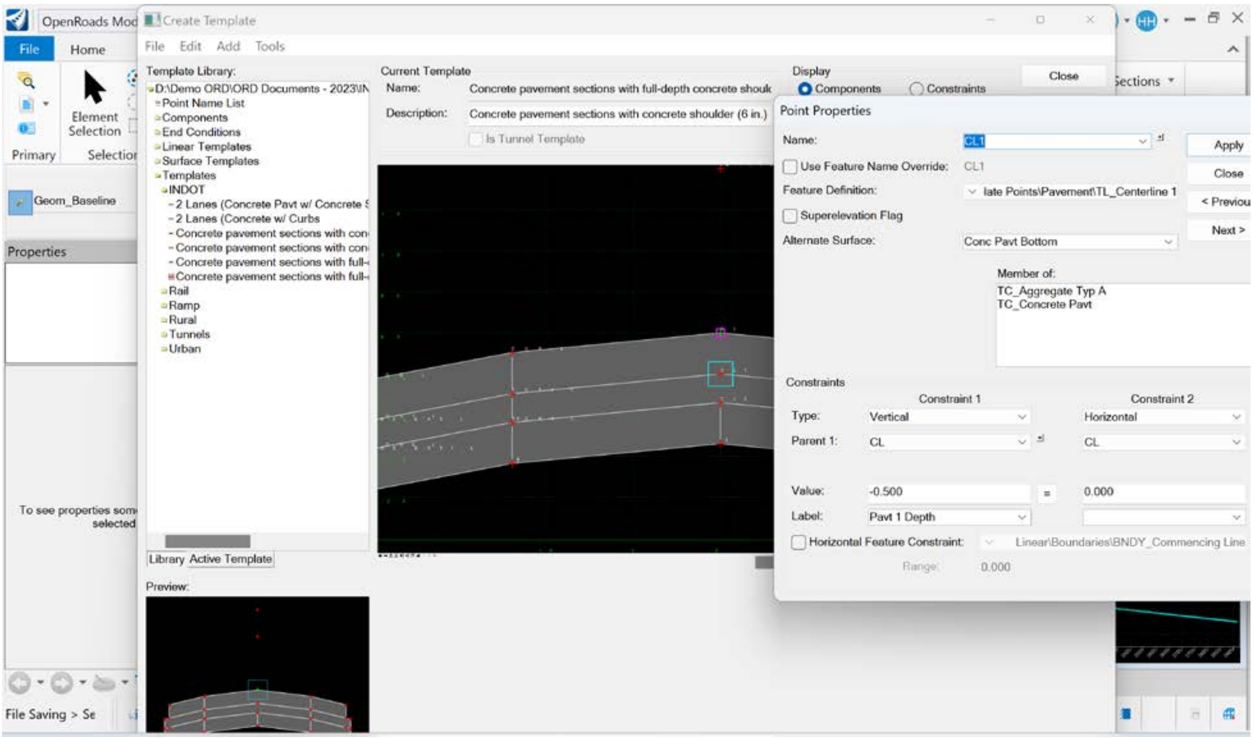


Figure B.160 2nd point (value 0.500) for (6 in.).

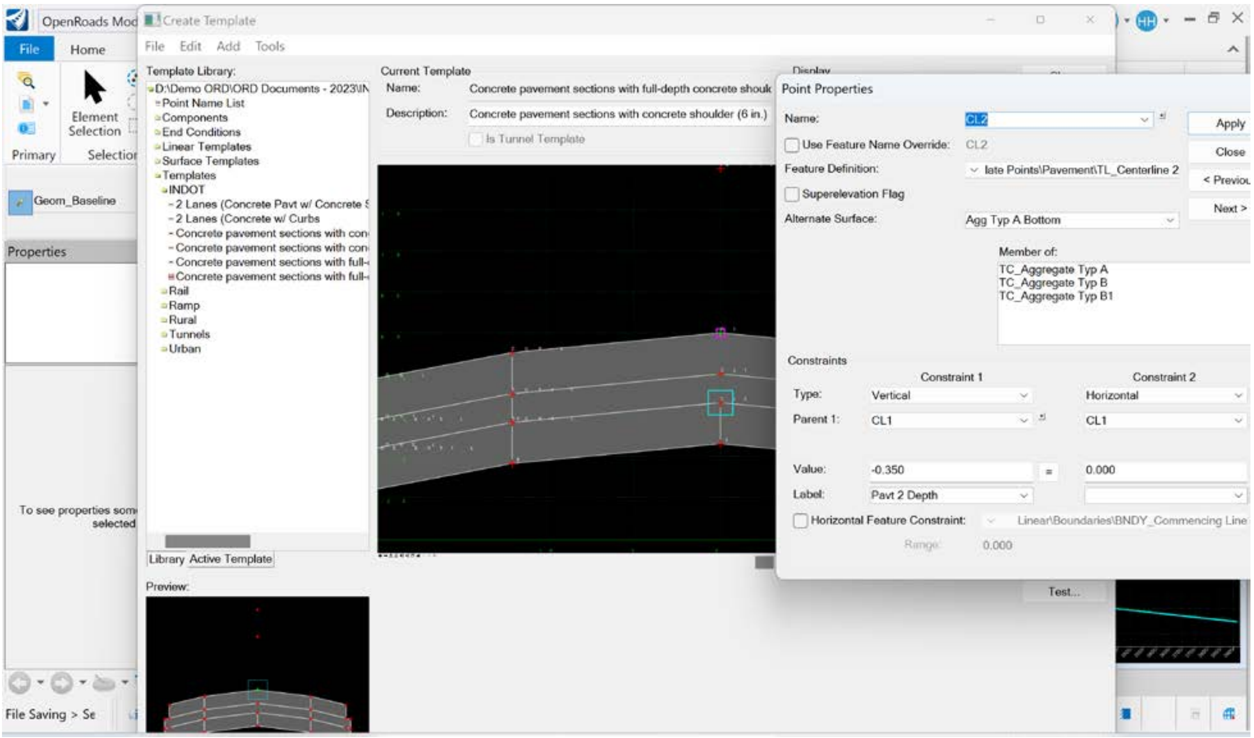


Figure B.161 3rd point (value 0.350) for (4 in.).

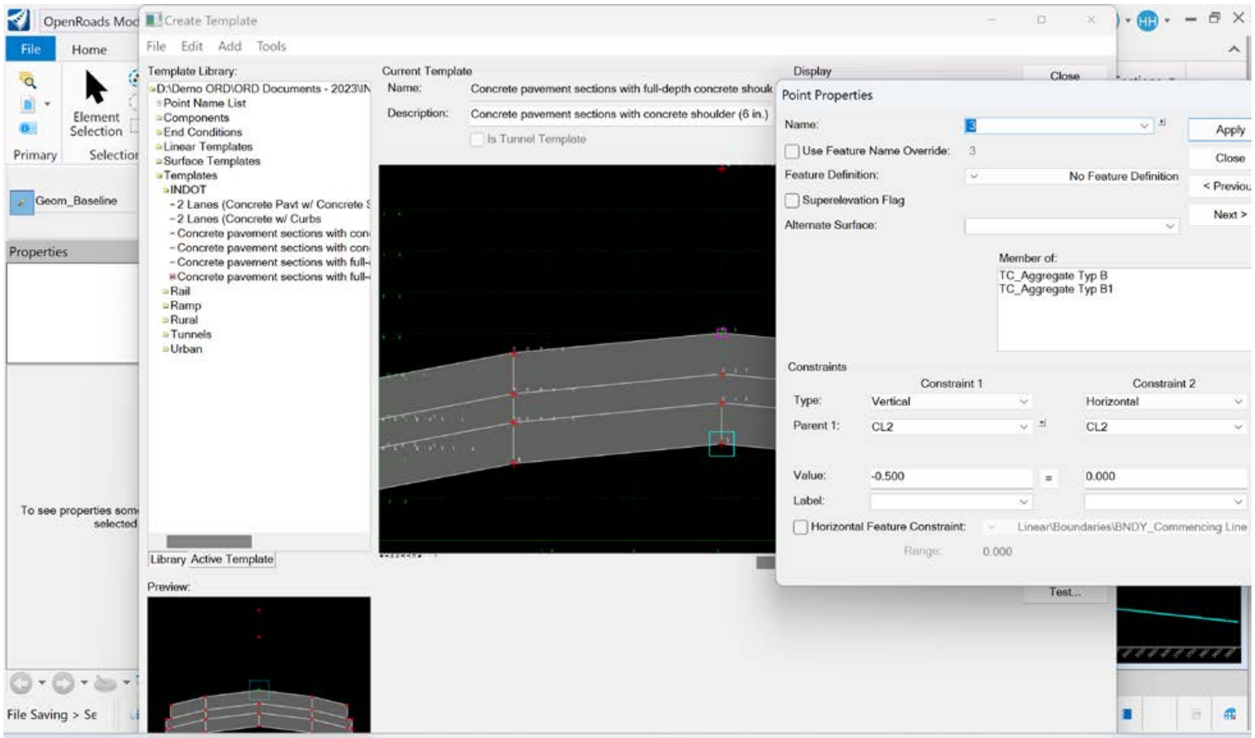


Figure B.162 4th point (value 0.500) for (6 in.).

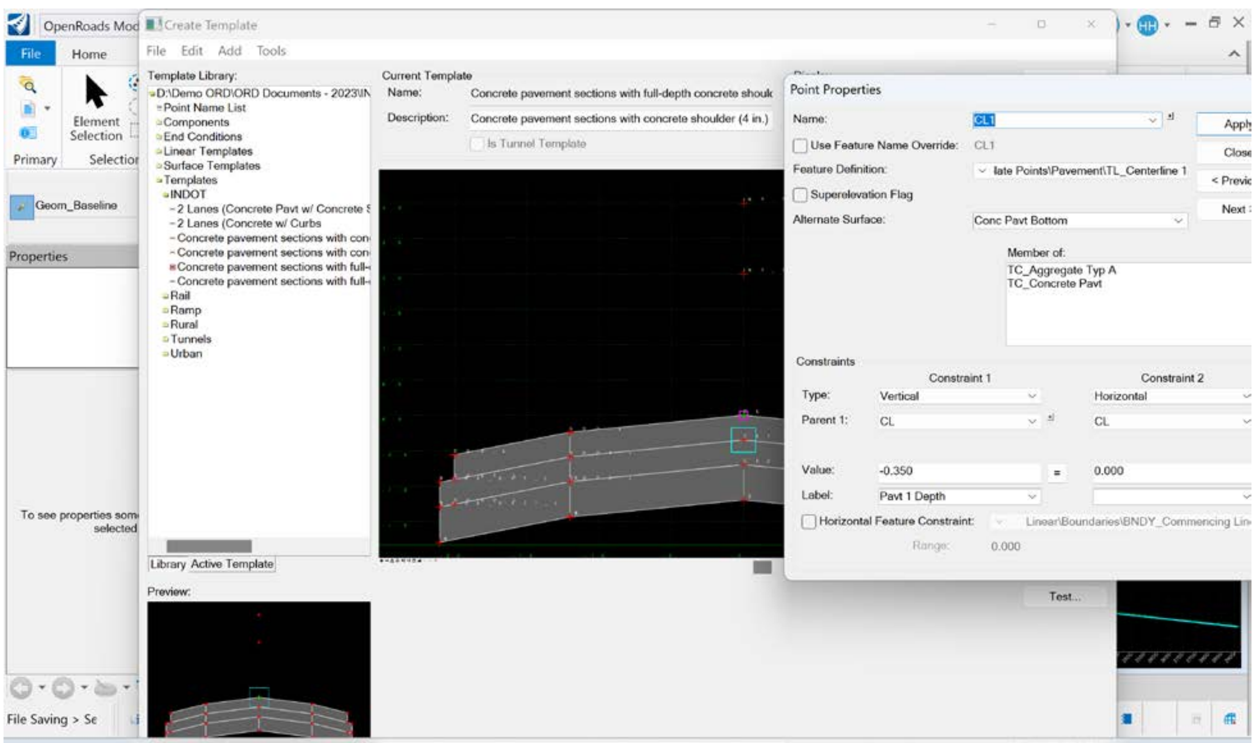


Figure B.163 2nd point (value 0.350) for (4 in.).

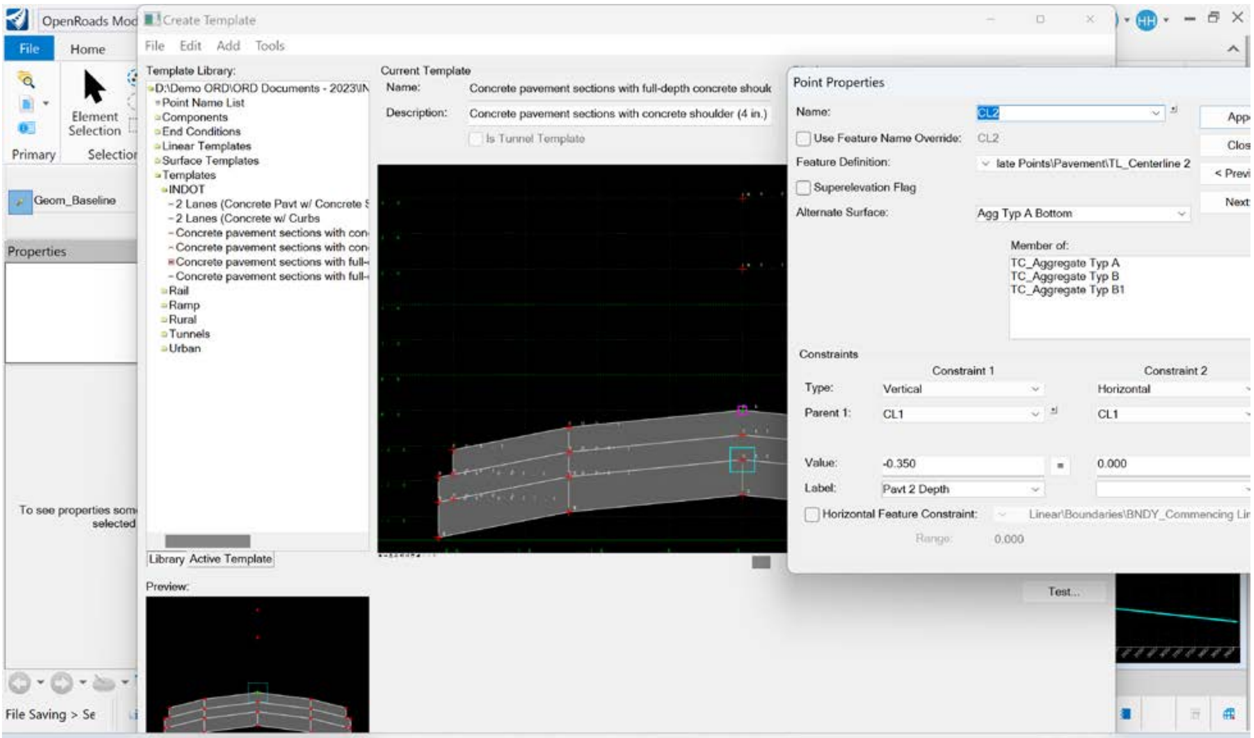


Figure B.164 3rd point (value 0.350) for (4 in.).

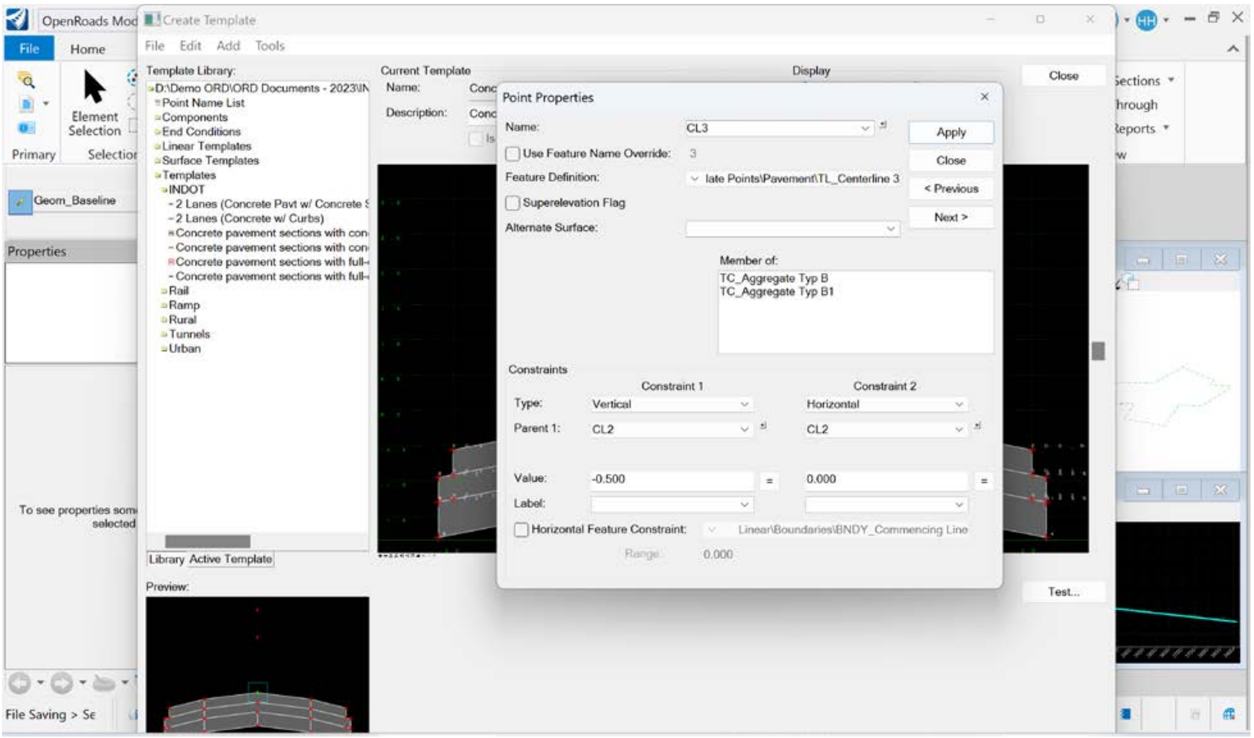


Figure B.165 4th point (Value 0.500) for (6 in.).

To make a copy of the template library (Use the template library organizer to manage templates across the library files).

Tools>Template Library Organizer

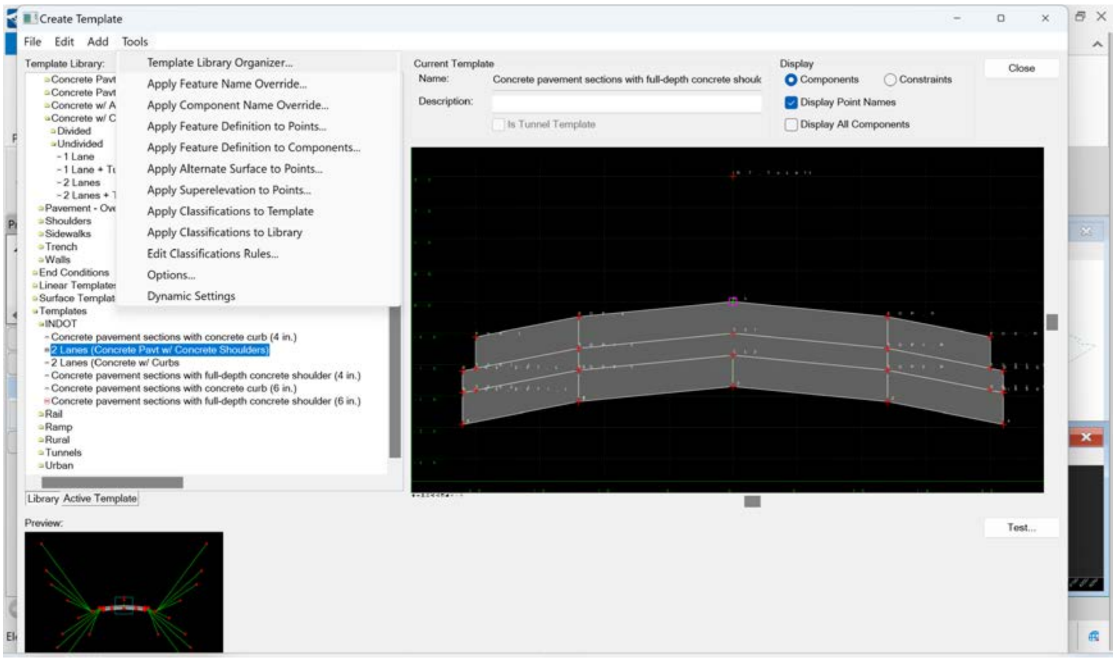


Figure B.166 Interface for the template “concrete pavement sections with full-depth concrete shoulder.”

Open another dialog:

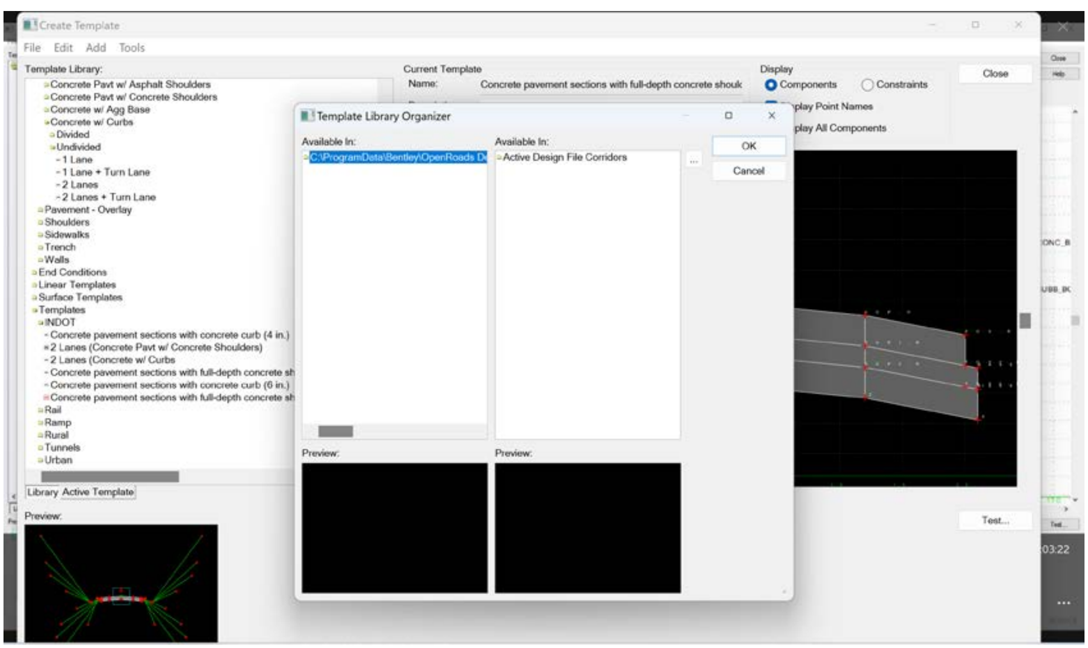


Figure B.167 Interface for the “template library organizer.”

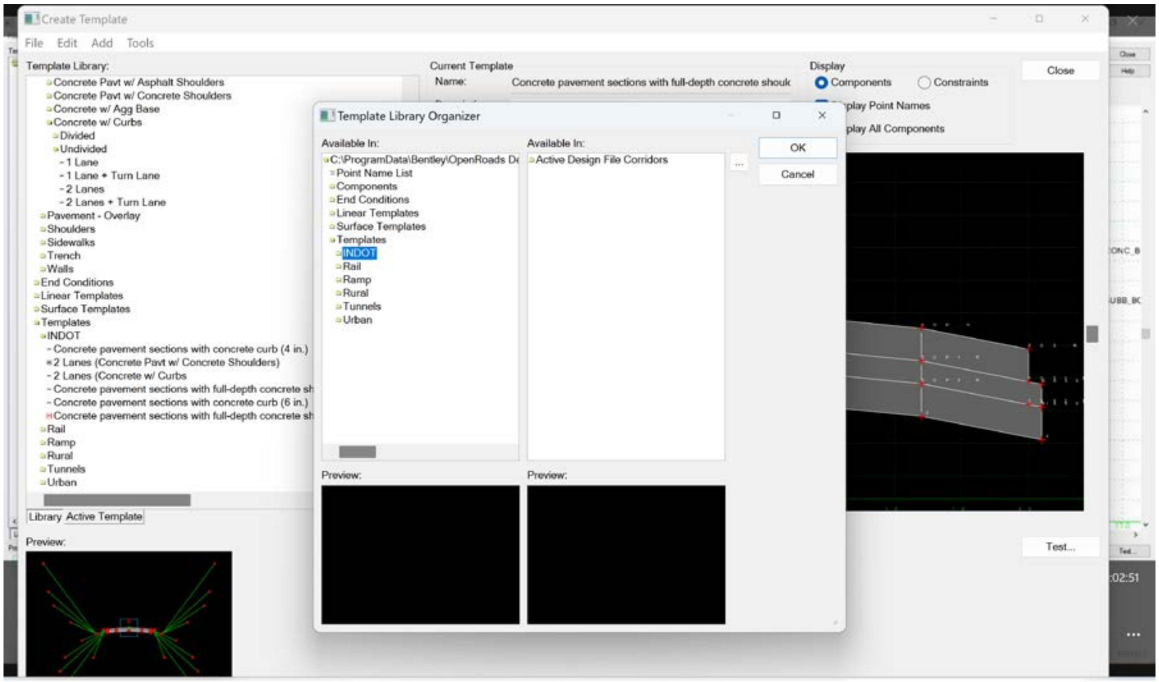


Figure B.168 Copy the new folder to insert INDOT file as "active design file corridors."

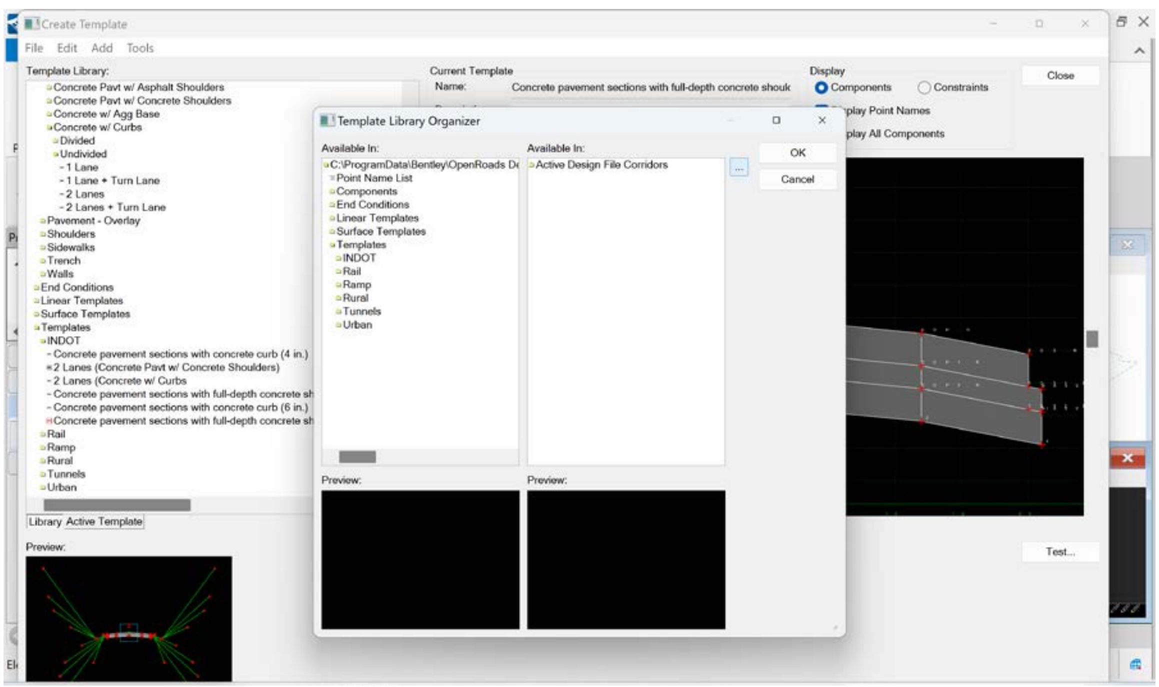


Figure B.169 Select the icon in the active folder to insert INDOT file as "available in: "active design file corridors."

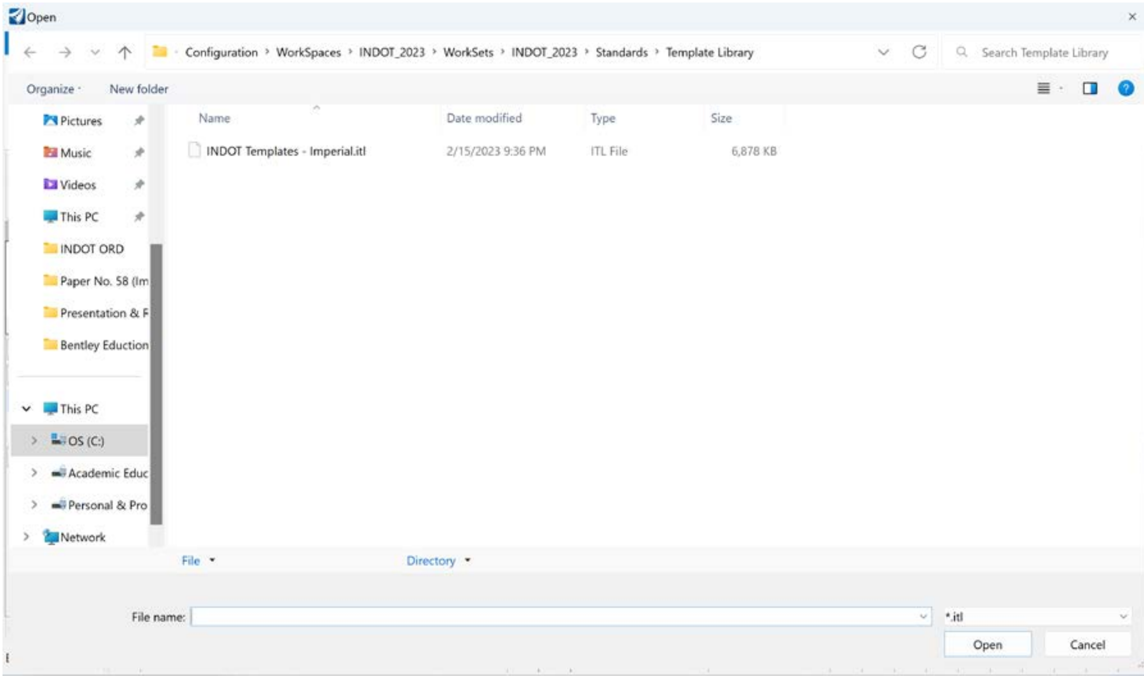


Figure B.170 Save the new template.

Sixth Step: Create Corridor 3D Model!

Notes: Check the Terrain and the profile "As Active" then "Create Corridor."

Corridors Tab>New Corridor>Feature Definition (Corridor/Road/Final)>select the profile>select the template.

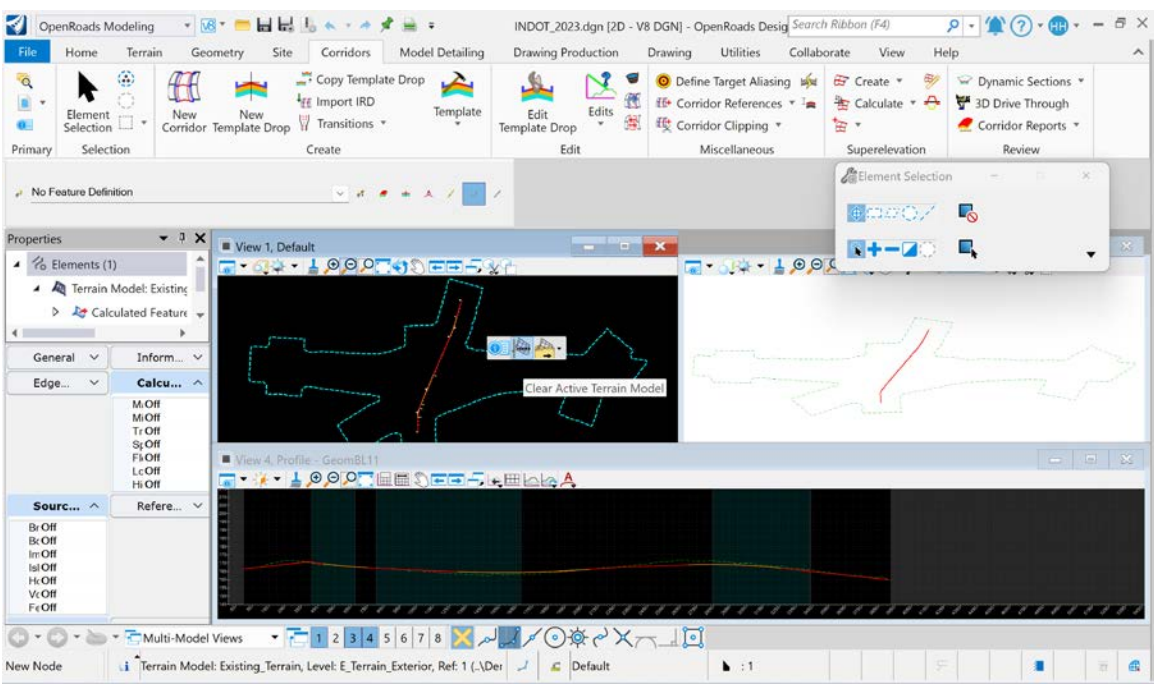


Figure B.171 Set the terrain as active.

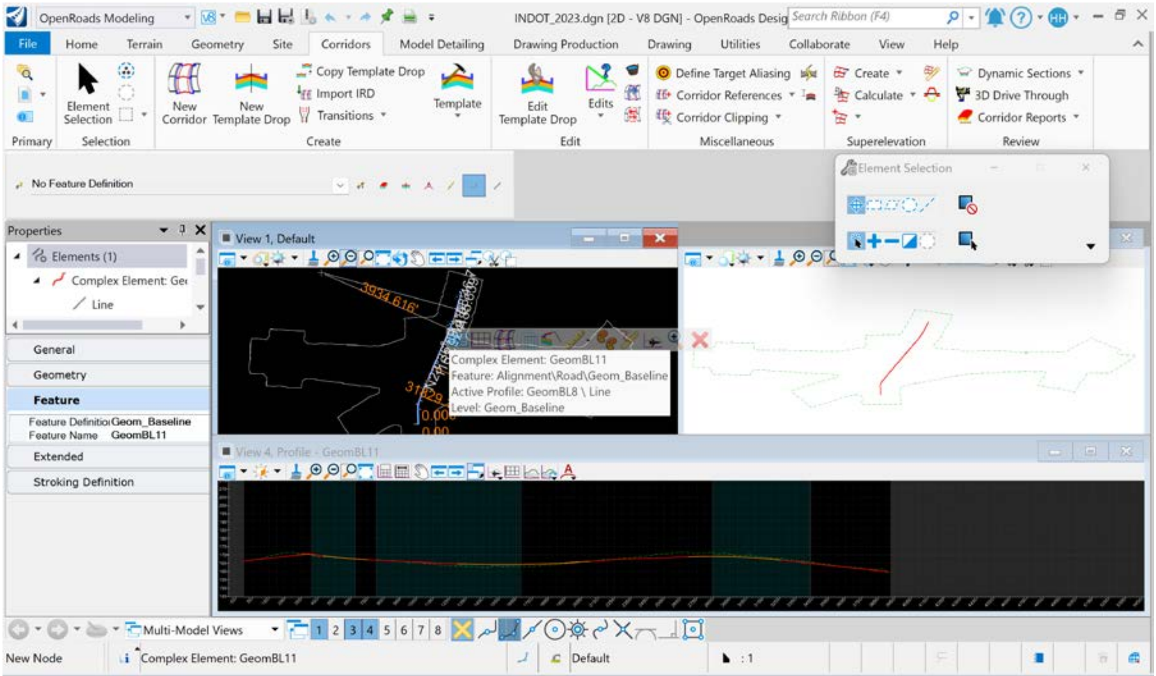


Figure B.172 Select the profile to check the details.

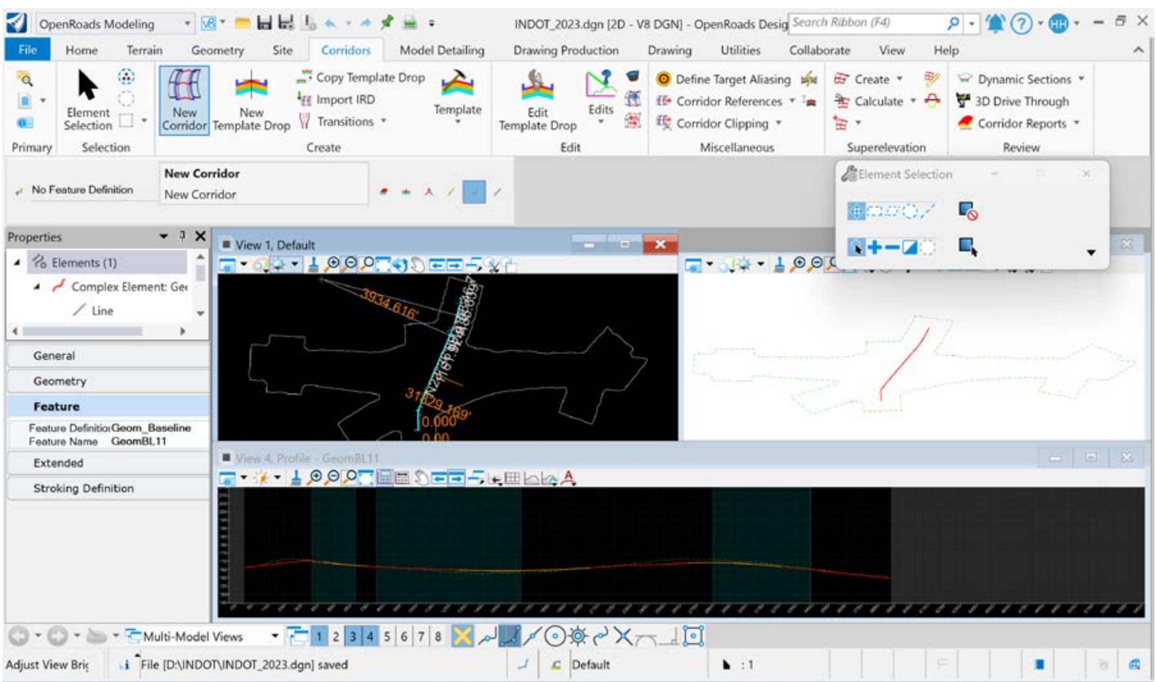


Figure B.173 Select "new corridor."

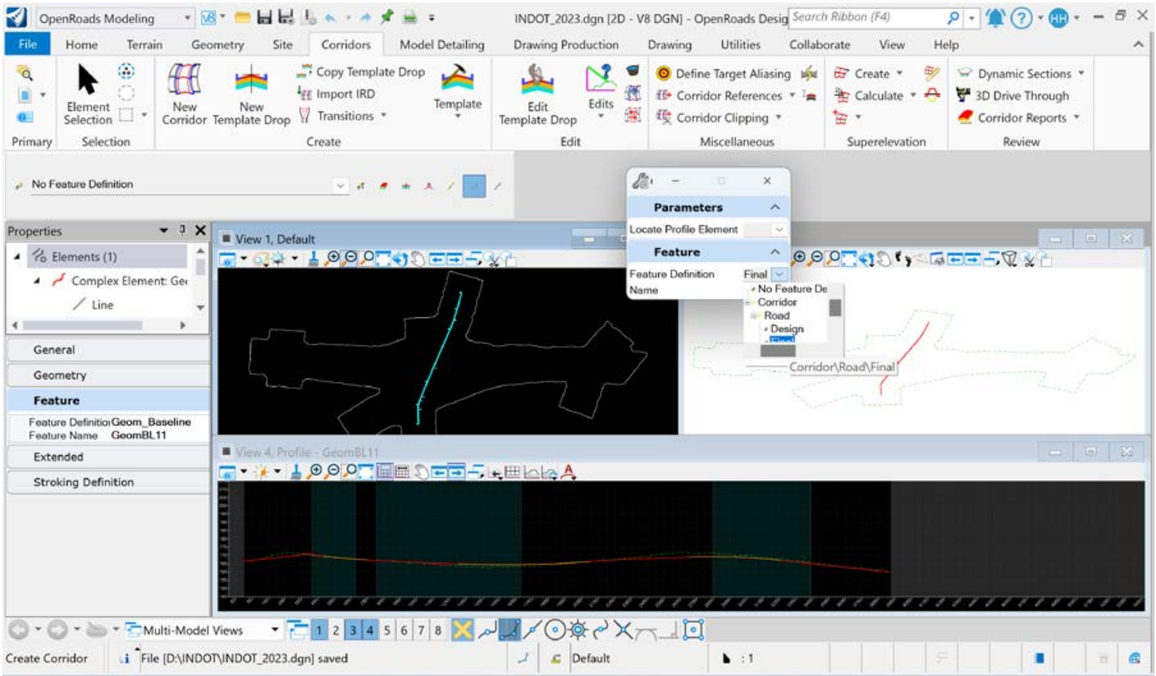


Figure B.174 Select the “feature definition” as “final.”

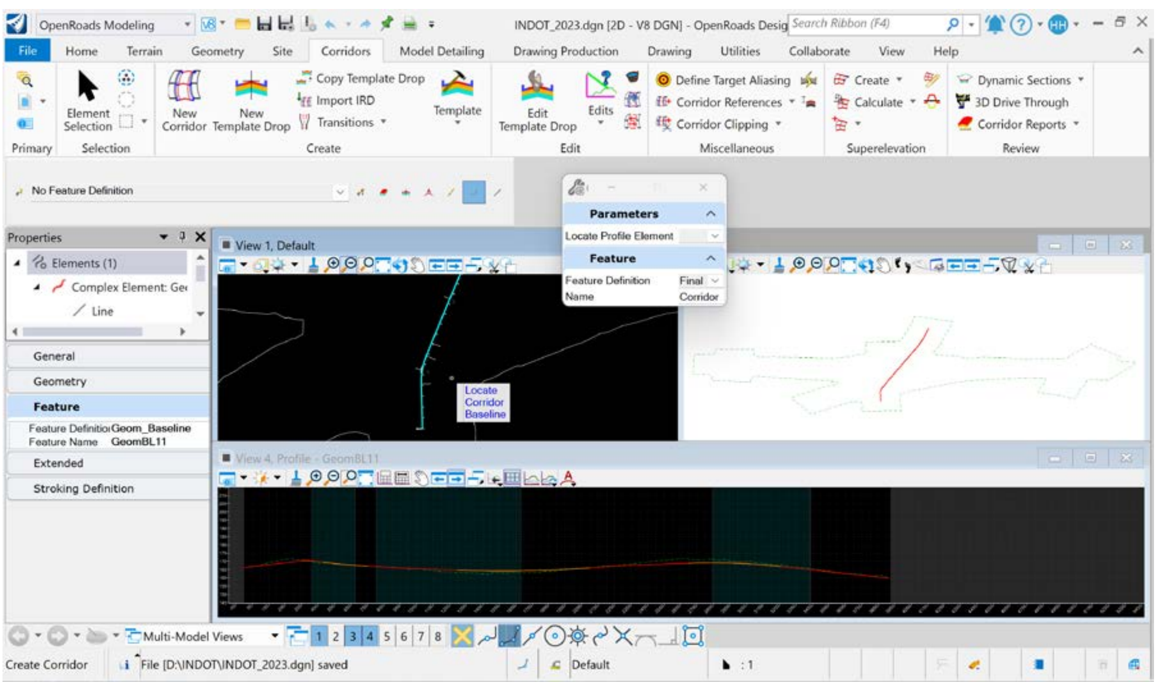


Figure B.175 “Locate corridor baseline.”

Click on the profile.

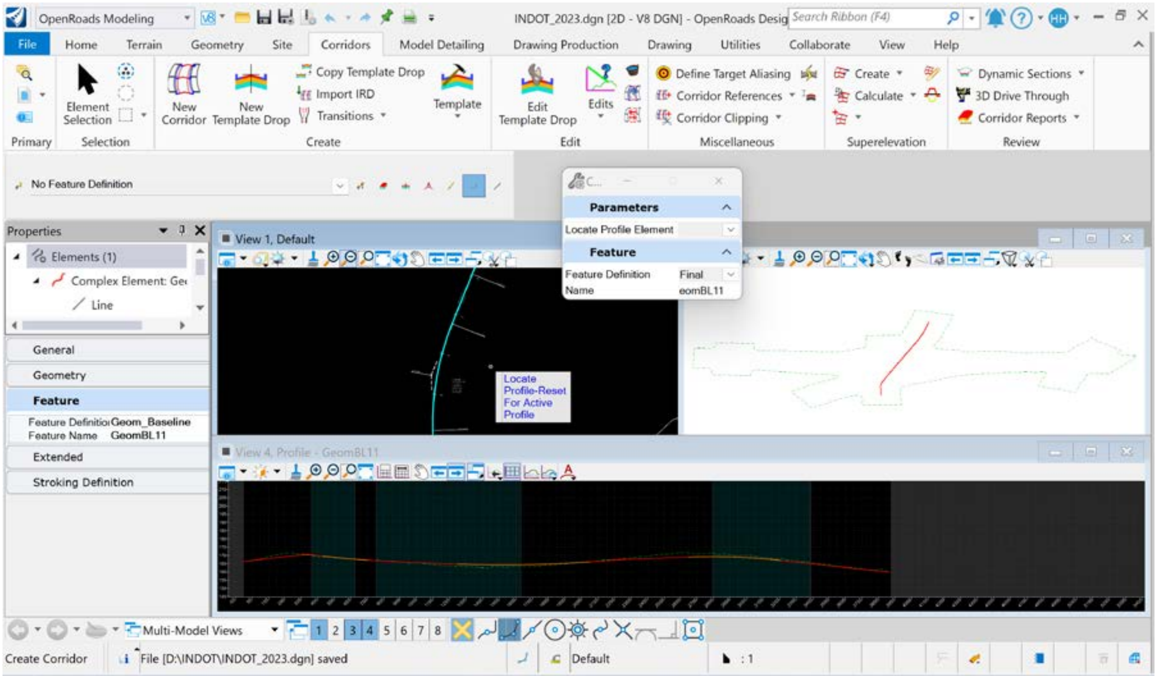


Figure B.176 Locate profile for the active profile.

Right click to accept that.

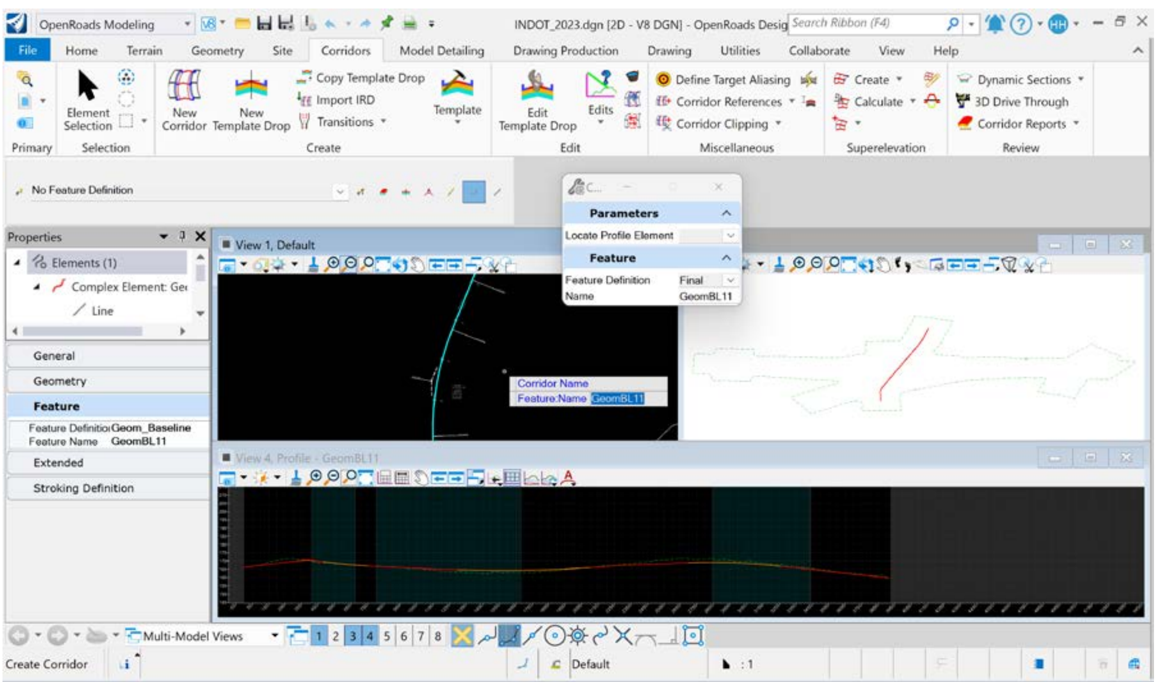


Figure B.177 Confirm for the feature name.

Left click to accept that.

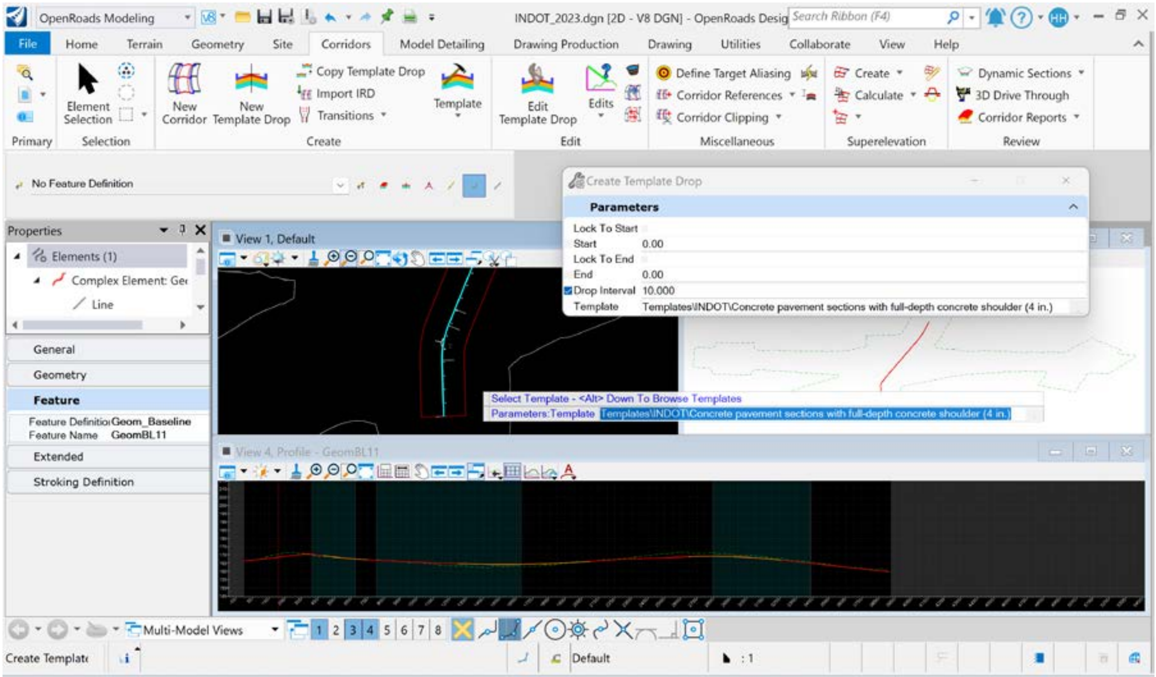


Figure B.178 To select the template, click on the icon of “template.”

Then, identify the Template.

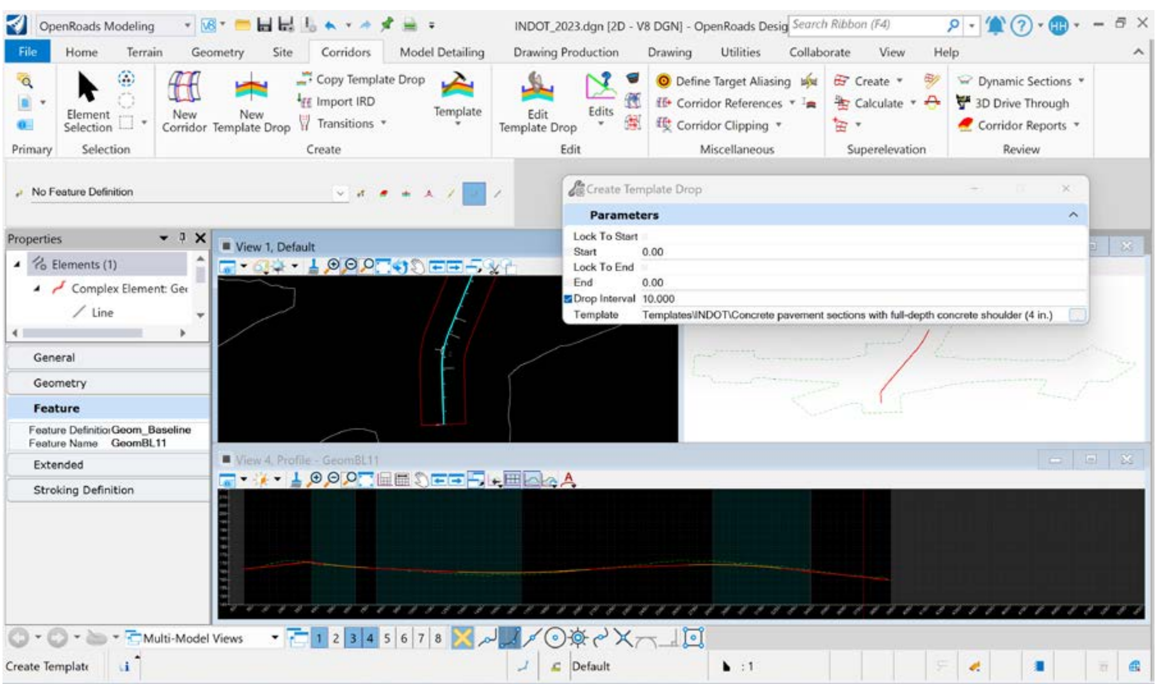


Figure B.179 Interface for the template that was selected.

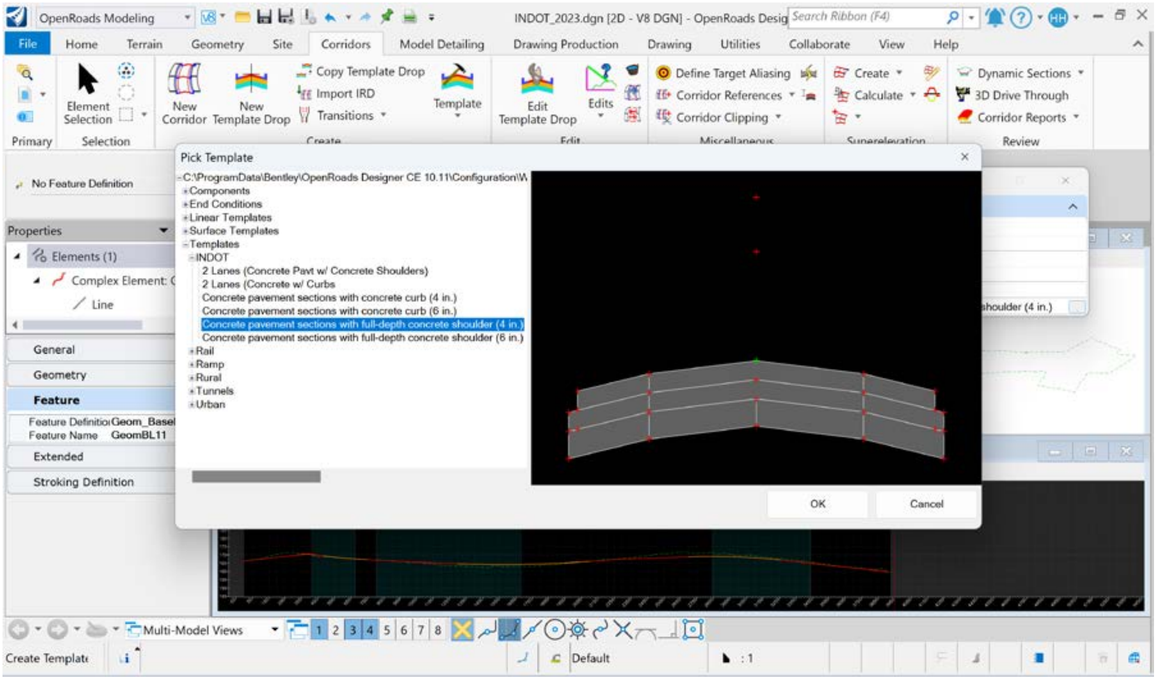


Figure B.180 Choose the suitable template.

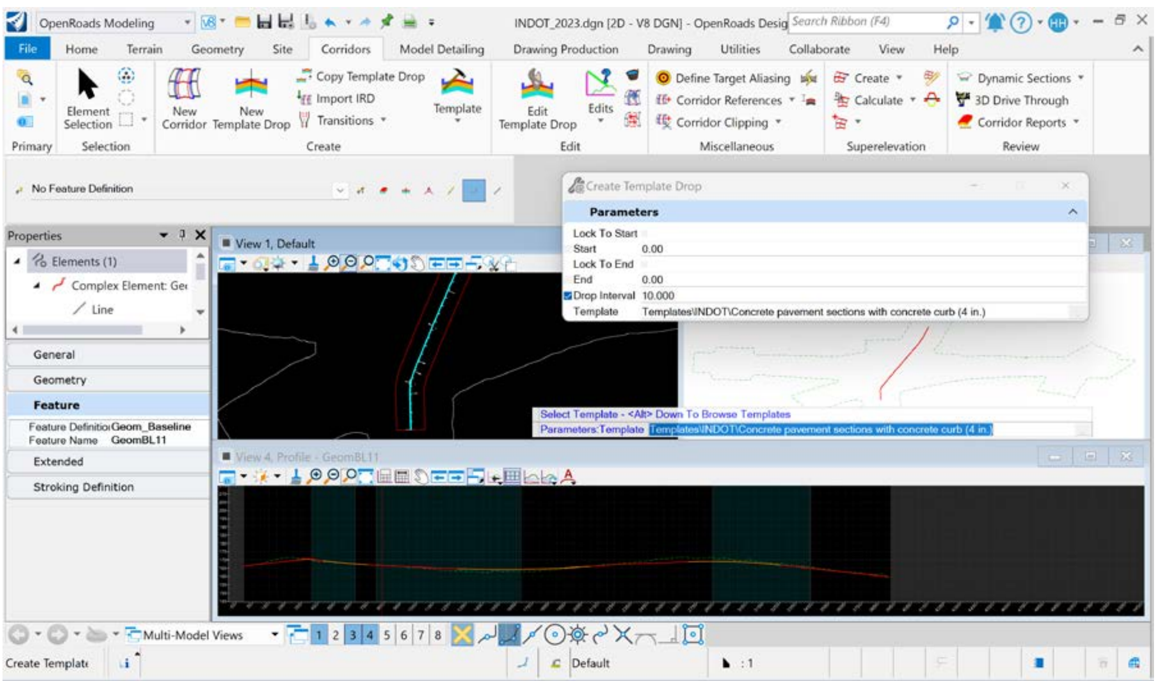


Figure B.181 Confirm the template that was selected.

Left click to accept that.

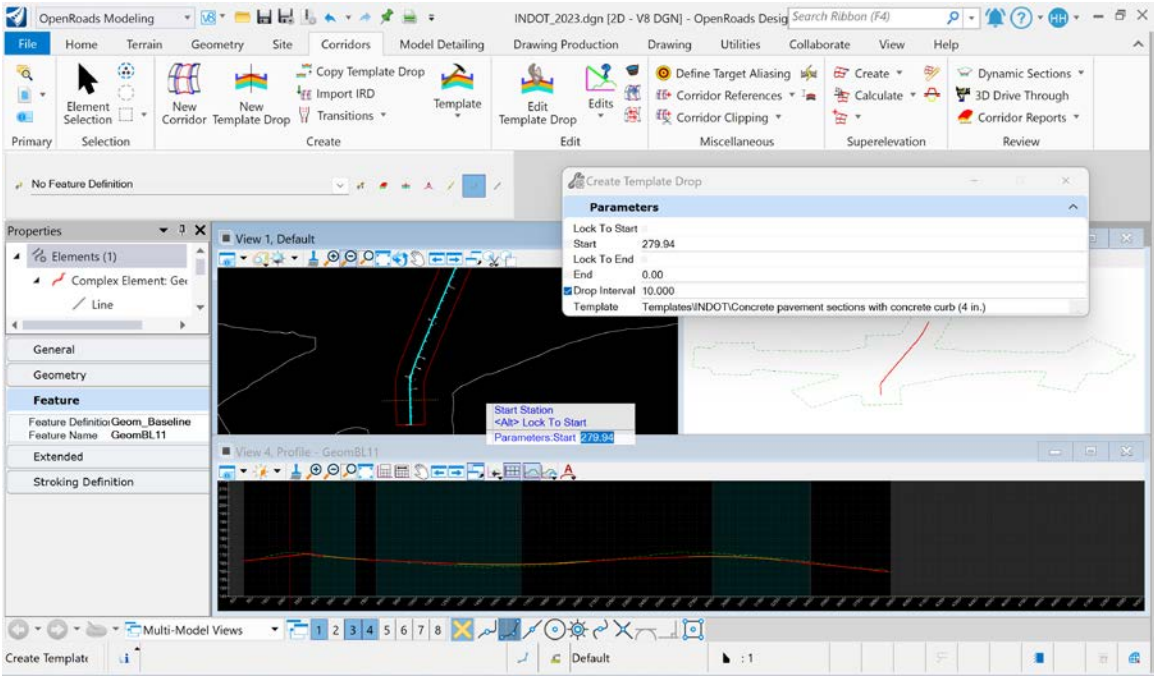


Figure B.182 Select the “start station.”

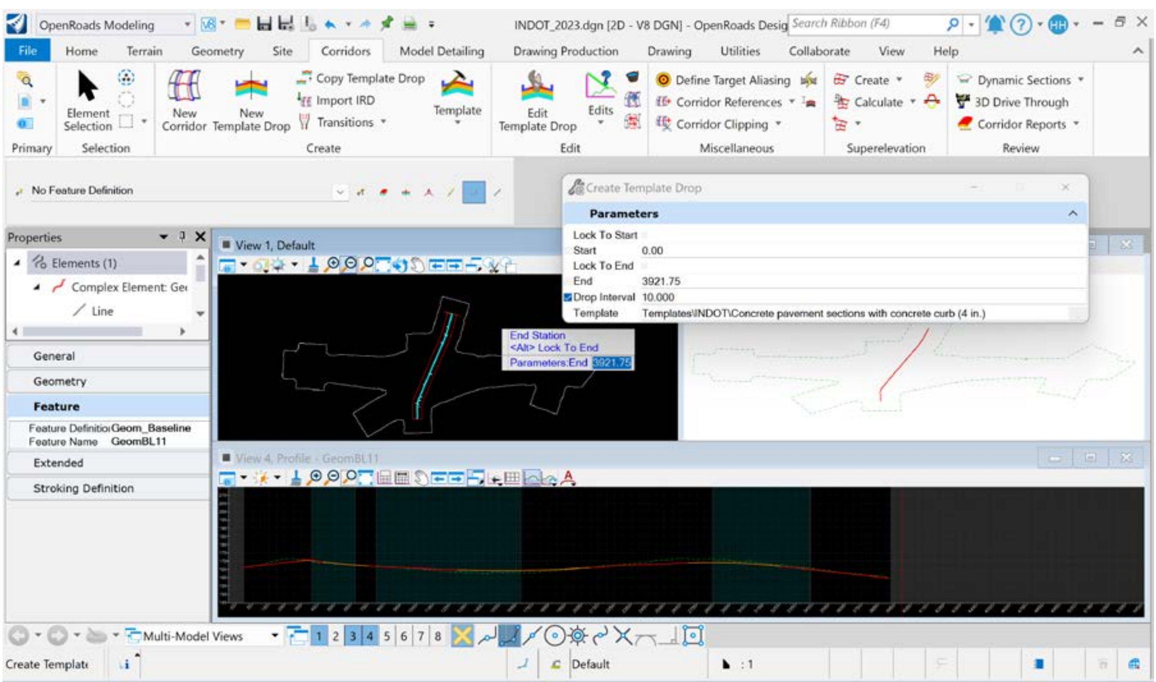


Figure B.183 Select the “end station.”

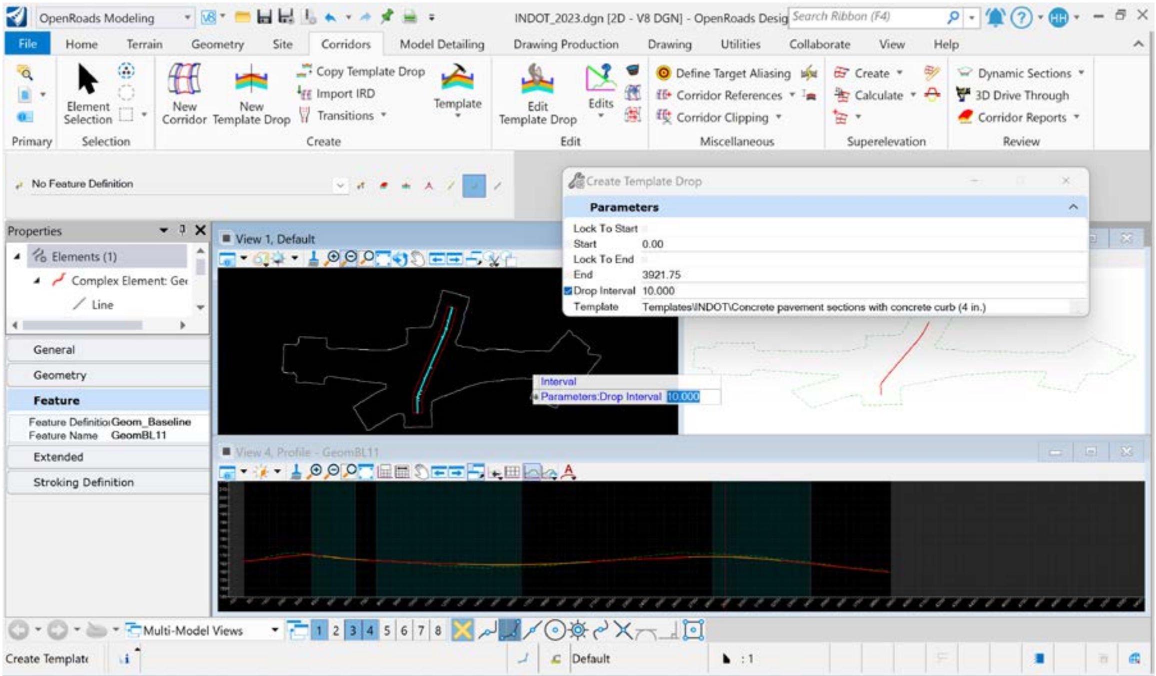


Figure B.184 Check “drop interval.”

Left click to accept that.

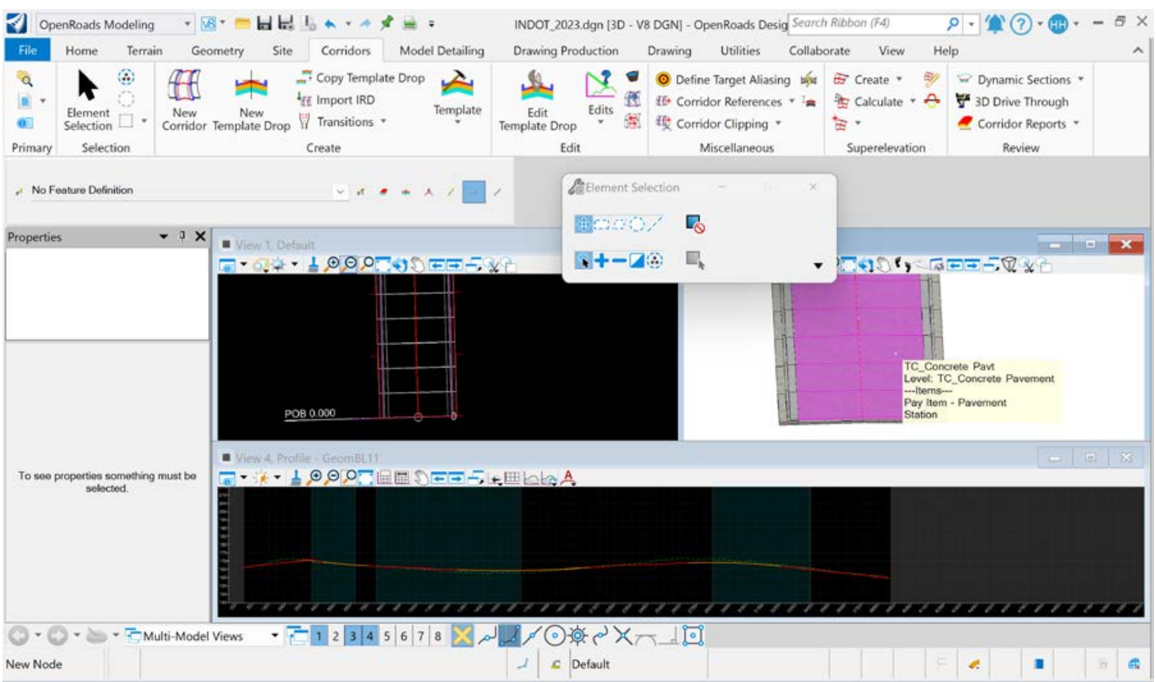


Figure B.185 Interface for the 2D and 3D model.

- Cross-Section View (*Corridors>Dynamic Sections>Open Cross Section View*)

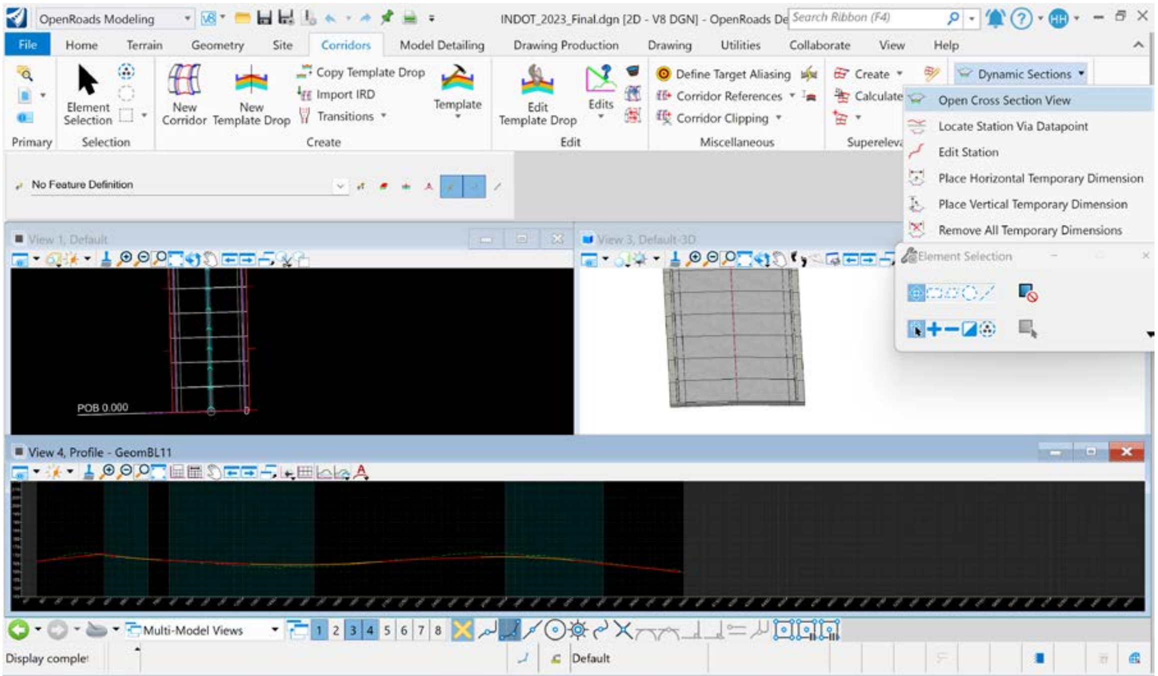


Figure B.186 Open cross-section view.

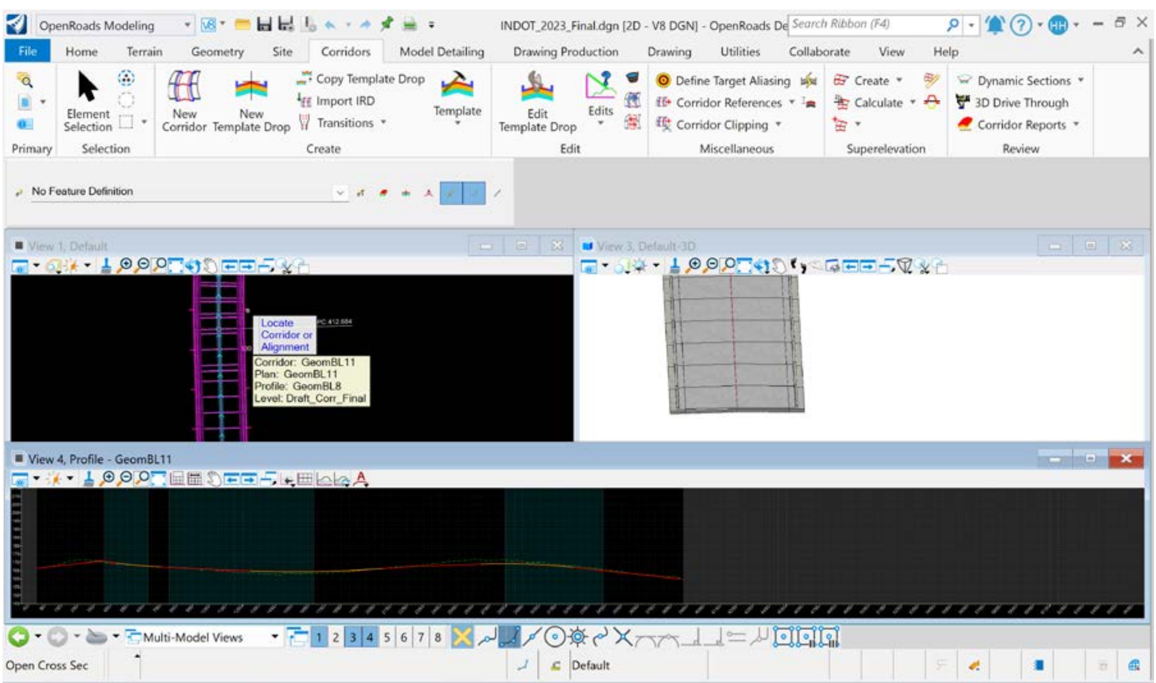


Figure B.187 Select the corridor.

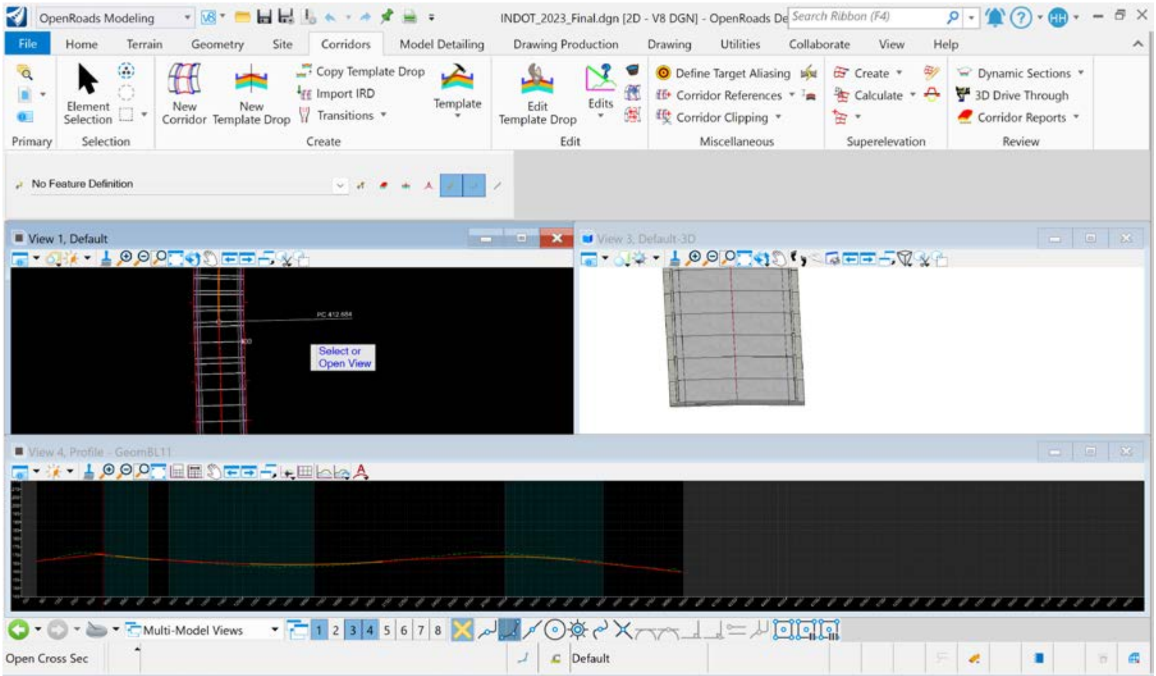


Figure B.188 Select “open view.”

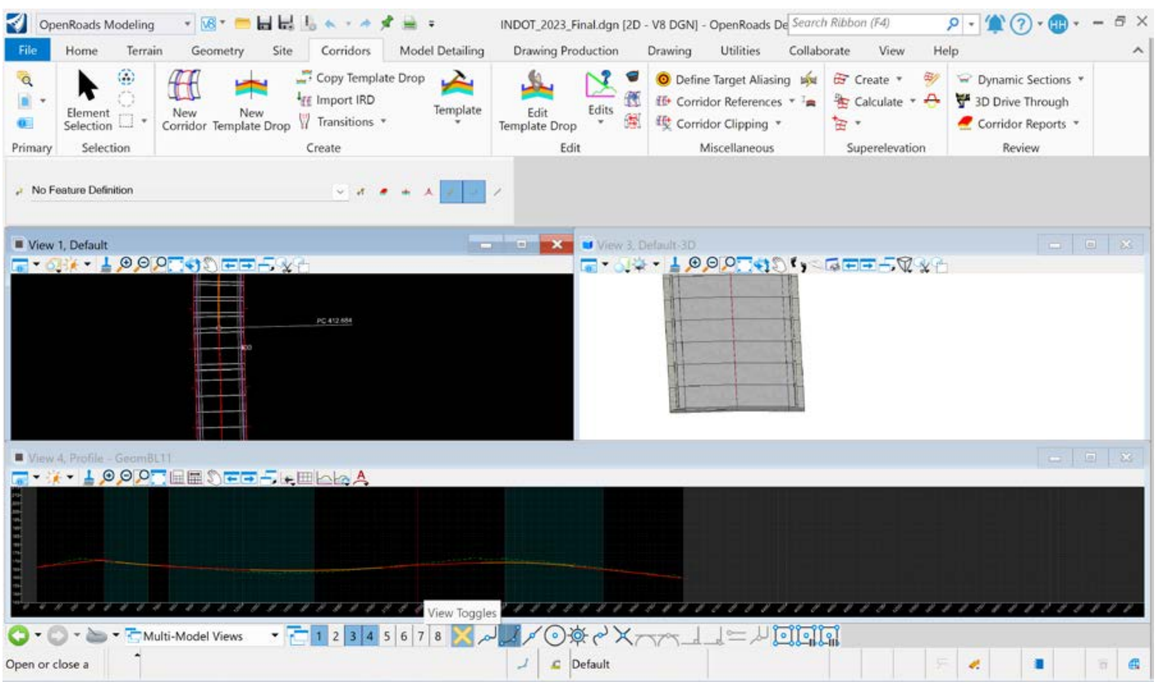


Figure B.189 Select “View toggles.”

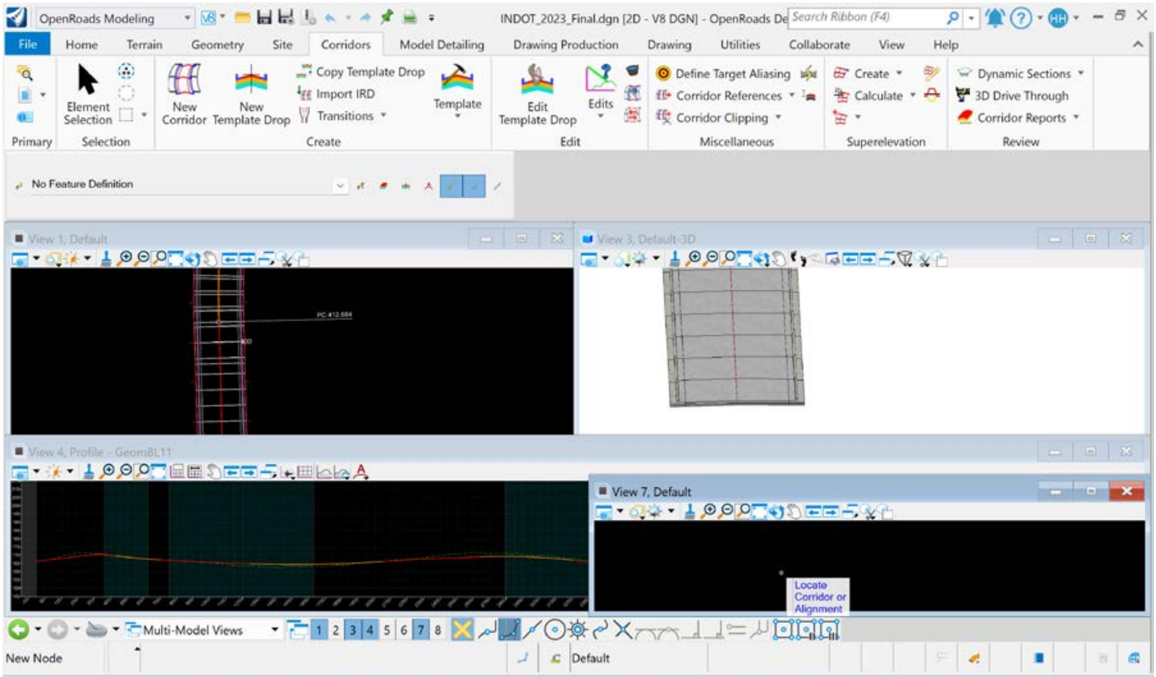


Figure B.190 Select the corridor from “view 1.”

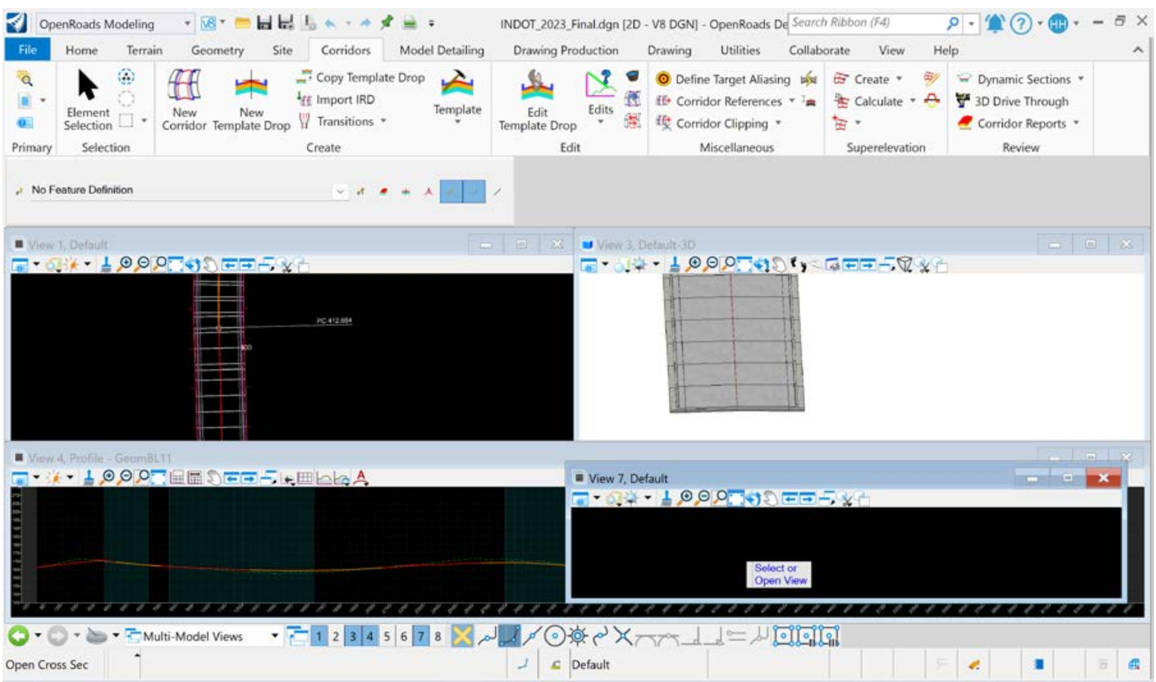


Figure B.191 Select the “open view” in “view 7.”

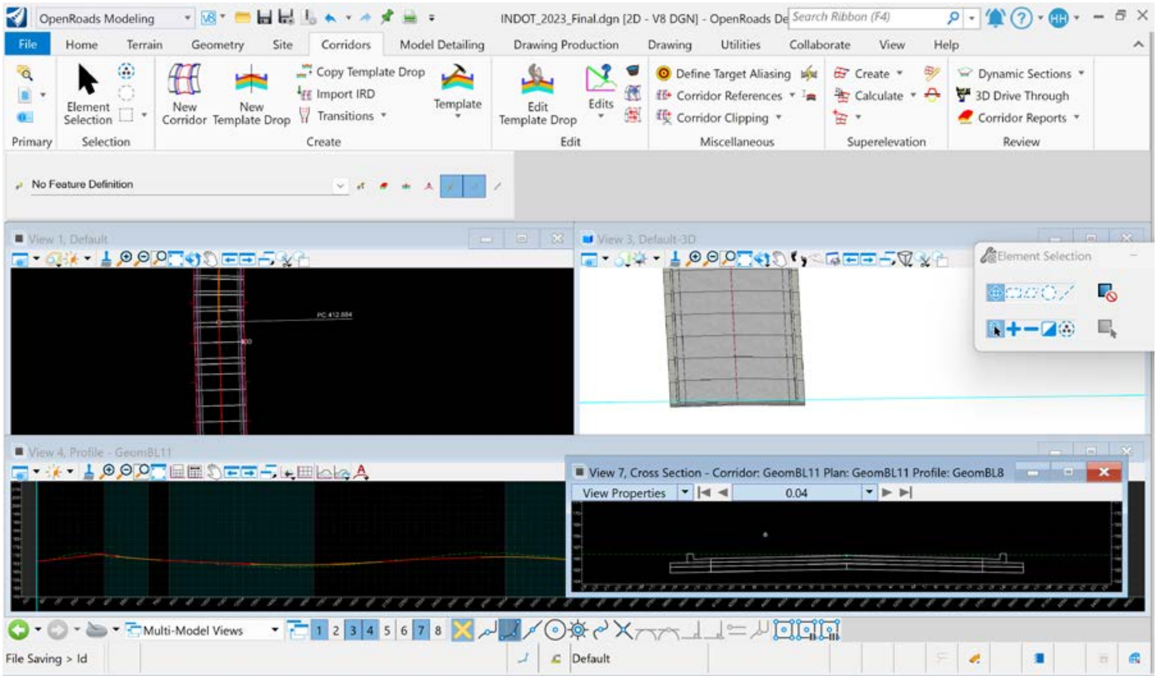


Figure B.192 Interface for the “cross section.”

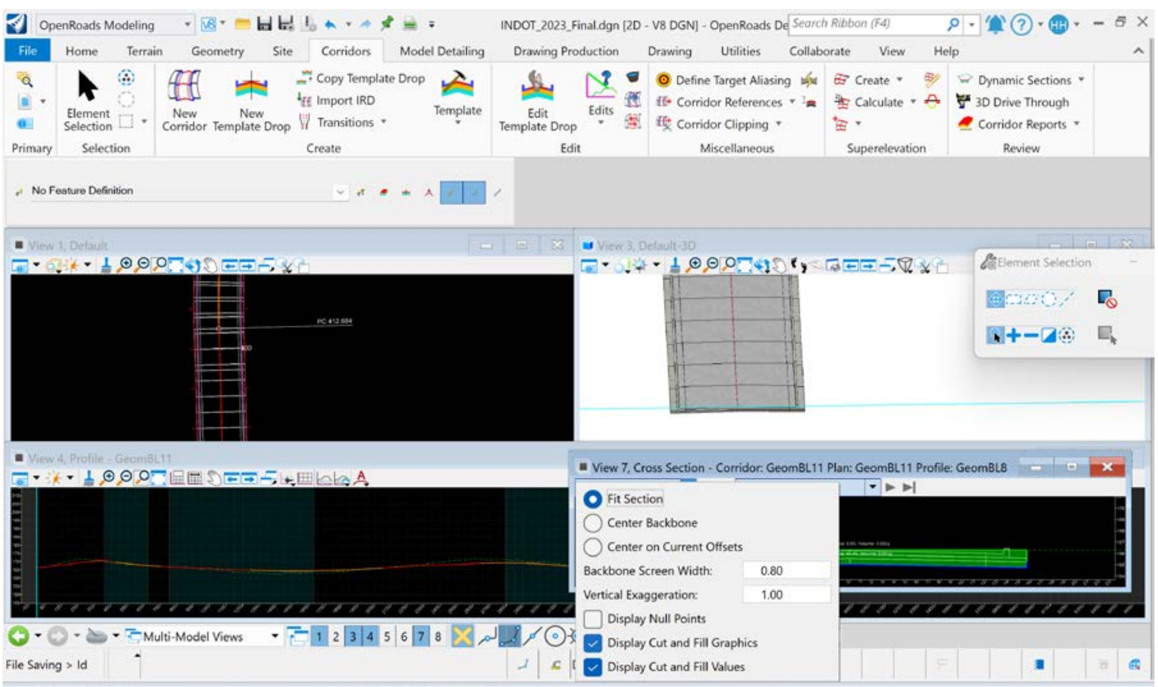


Figure B.193 Display the details from “view properties” in the “view 7” dialog.

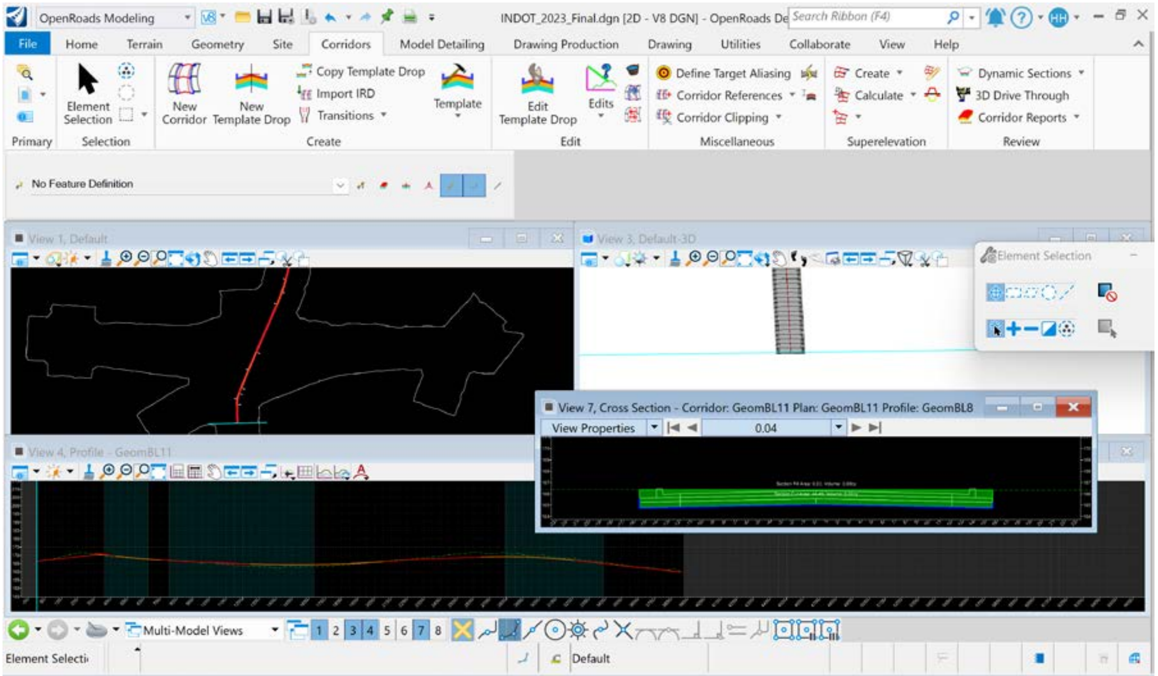


Figure B.194 Interface for the details of the cross section.

Quantities report: (*Home Tab>Corridor Reports>Component Quantities*)**.**

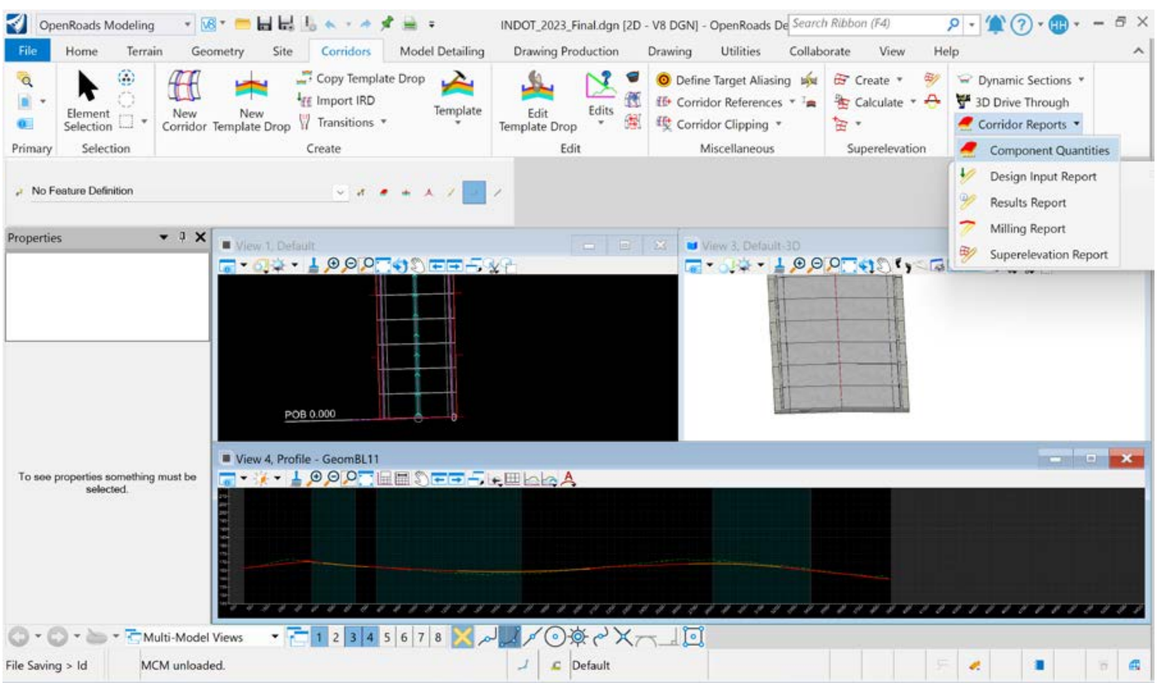


Figure B.195 Interface for selecting the “component quantities.”

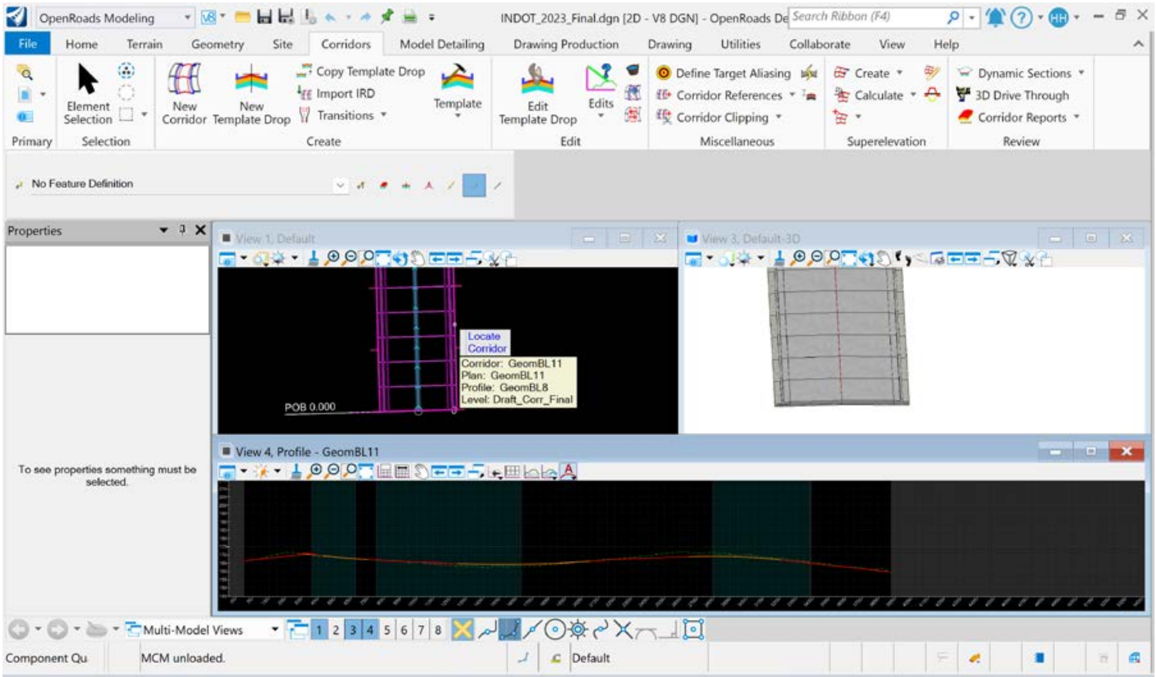


Figure B.196 “Locate Corridor.”

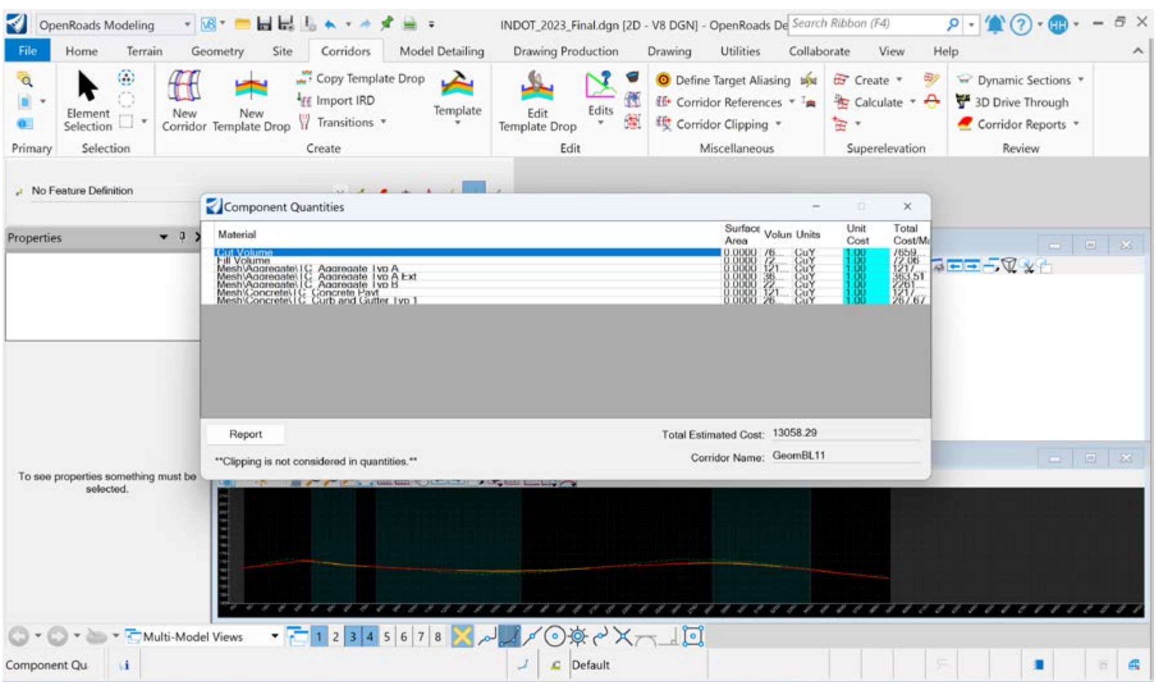


Figure B.197 Interface for the “component quantities report.”

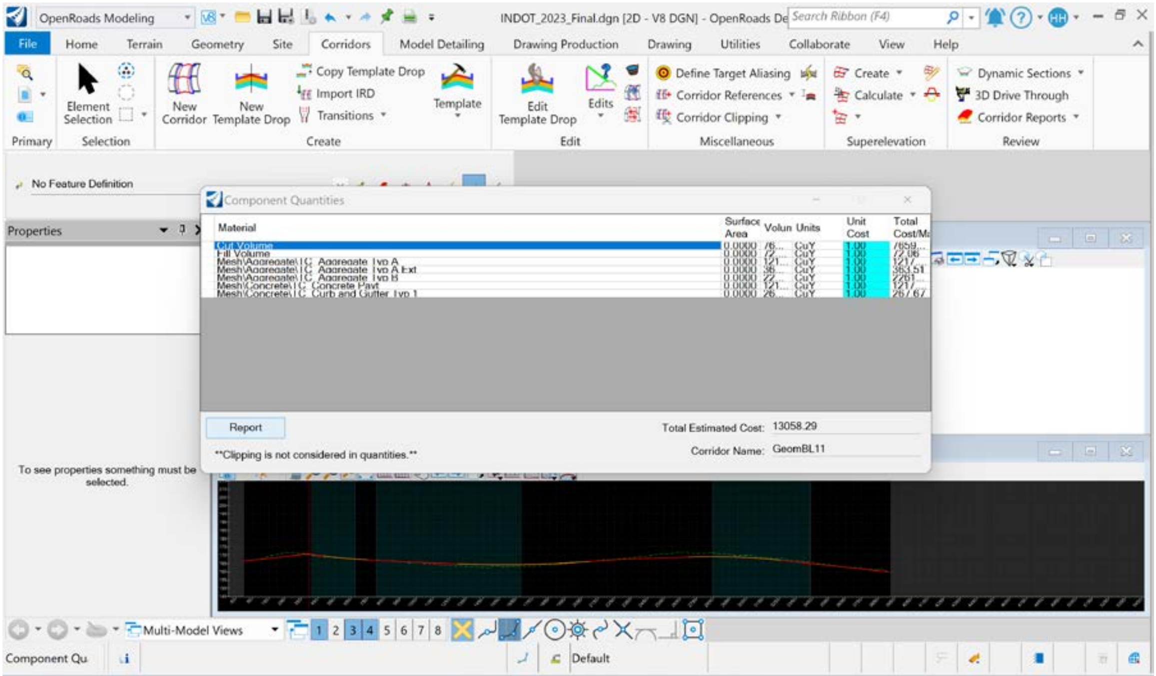


Figure B.198 Select the report to show.

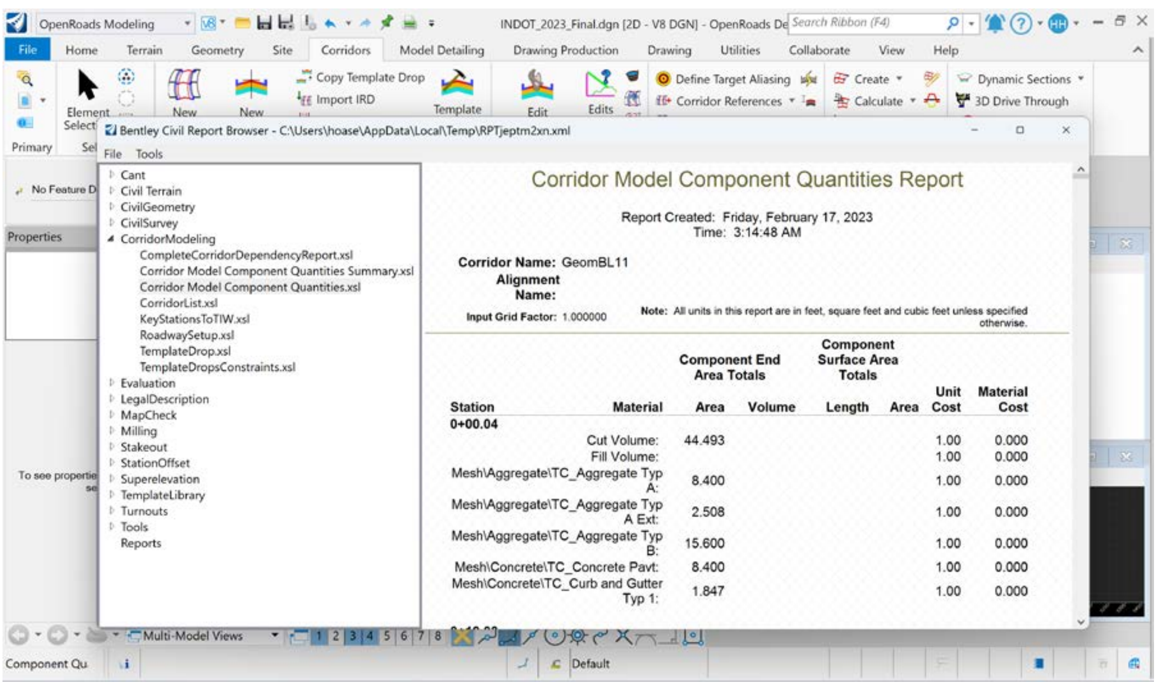
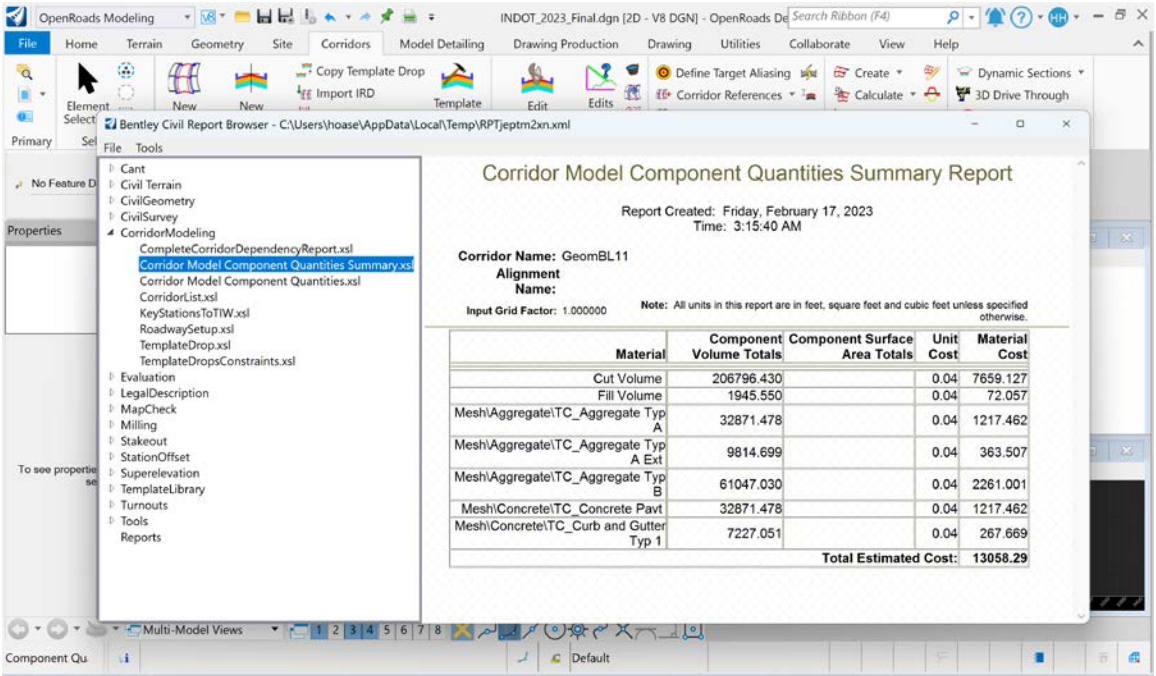


Figure B.199 Interface for “component quantities.”



Material	Component Volume Totals	Component Surface Area Totals	Unit Cost	Material Cost
Cut Volume	206796.430		0.04	7659.127
Fill Volume	1945.550		0.04	72.057
Mesh\Aggregate\TC_Aggregate Typ A	32871.478		0.04	1217.462
Mesh\Aggregate\TC_Aggregate Typ A Ext	9814.699		0.04	363.507
Mesh\Aggregate\TC_Aggregate Typ B	61047.030		0.04	2261.001
Mesh\Concrete\TC_Concrete Pavt	32871.478		0.04	1217.462
Mesh\Concrete\TC_Curb and Gutter Typ 1	7227.051		0.04	267.669
			Total Estimated Cost:	13058.29

Figure B.200 Interface for "component quantities summary report."

Exported IFC Format from OpenRoads Designer (ORD).

B.4.1 First Step: To export alignments from the ORD file to IFC format

Geometry Tab>General Tools>Import/Export>Export Geometry> ExportType> select IFCAlignment> Confirm IFCAlignment

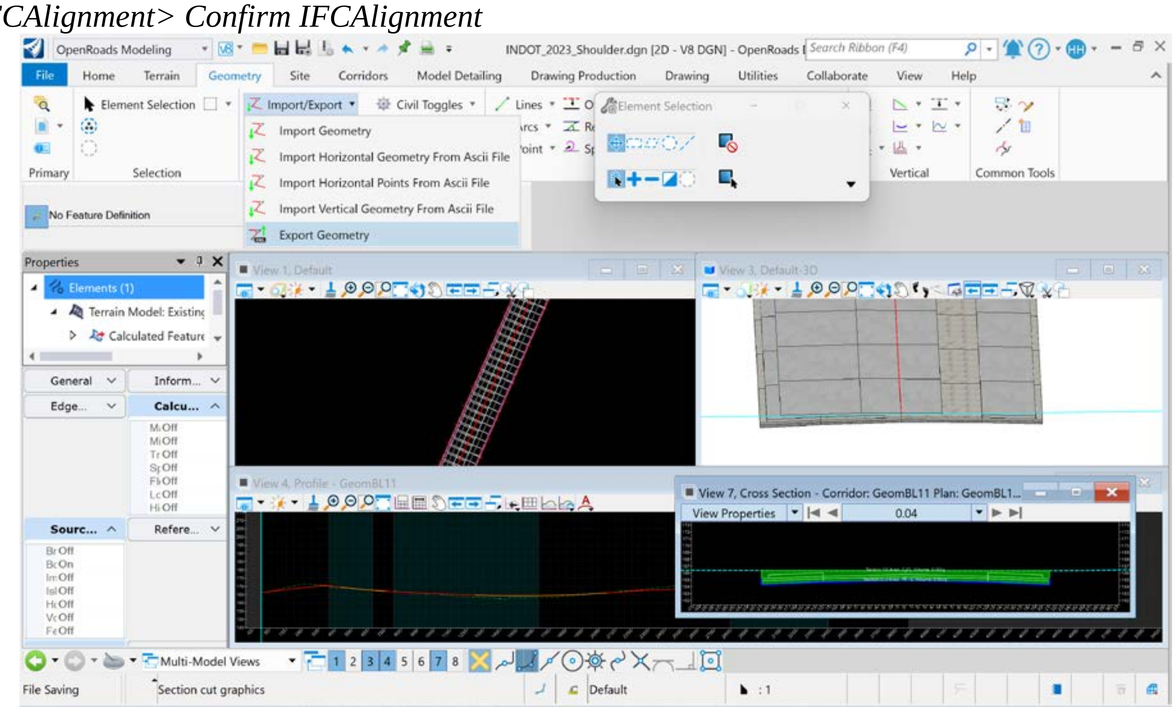


Figure B.201 Interface to export the geometry.

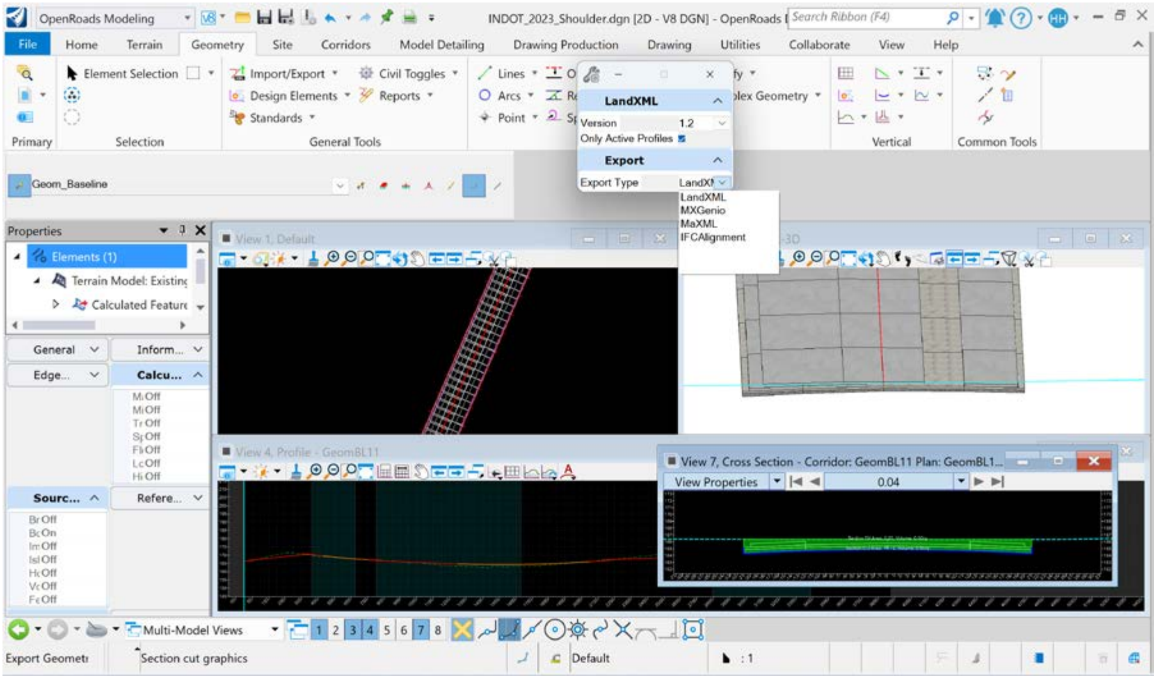


Figure B.202 Select the “Export Type” as “IFC Alignment.”

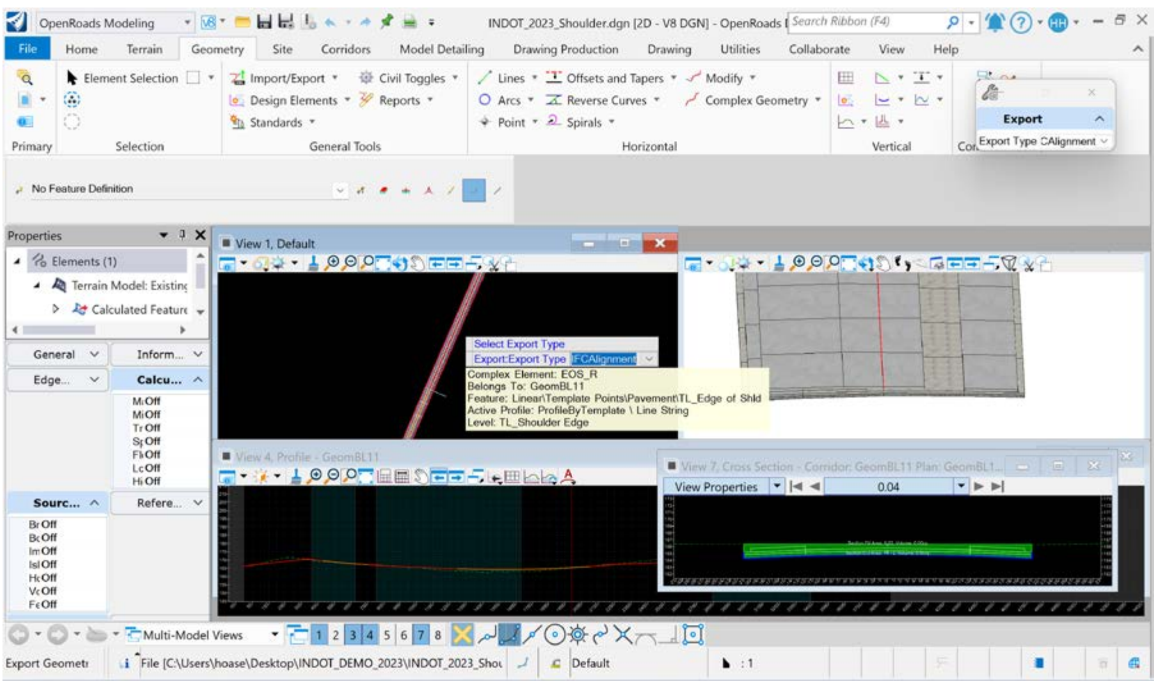


Figure B.203 Confirm the “Export Type” as “IFC Alignment.”

Left click.

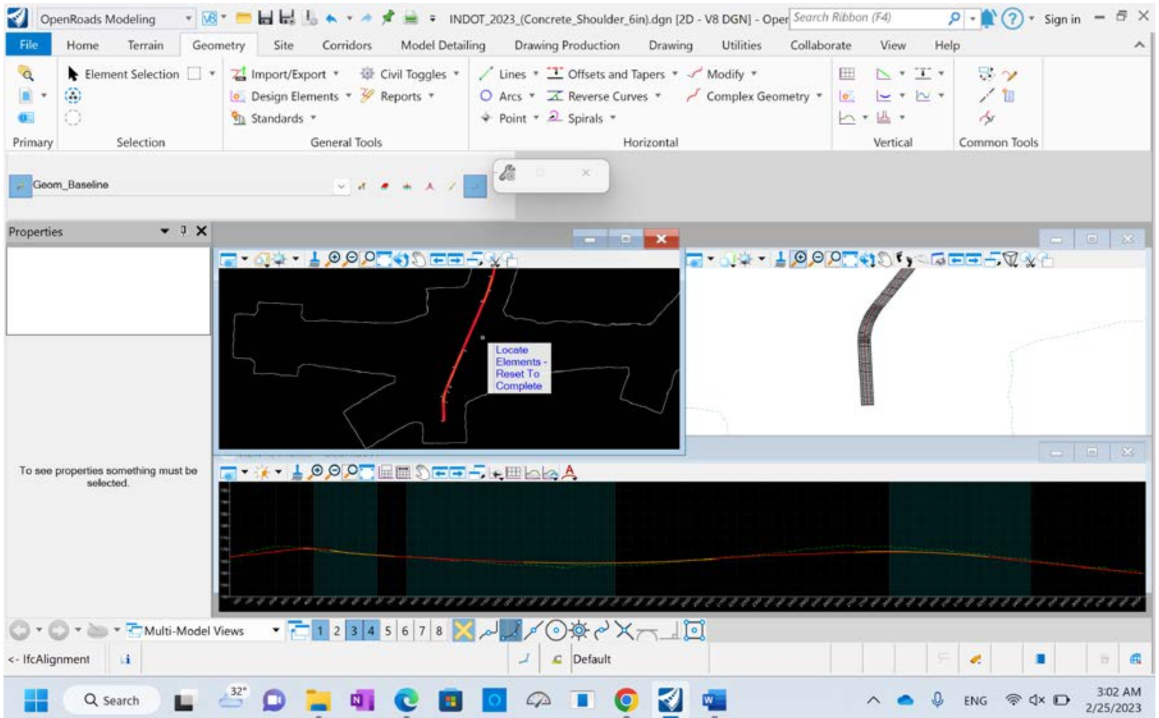


Figure B.204 Confirm for the “locate elements.”

Right click.

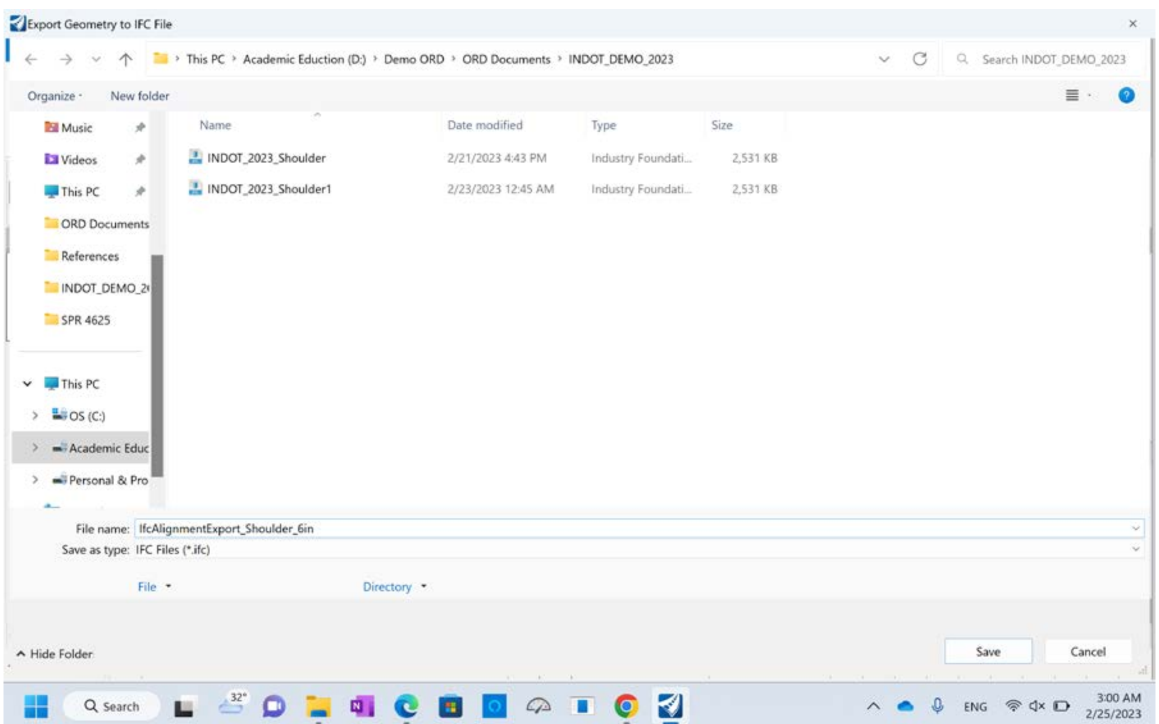


Figure B.205 Save the file.

Note: Repeat this step with the different templates.

B.4.2 Second Step: To export the design model from the ORD file to IFC format

Home Tab>Model Import/Export> Export to IFC>select IFC Version

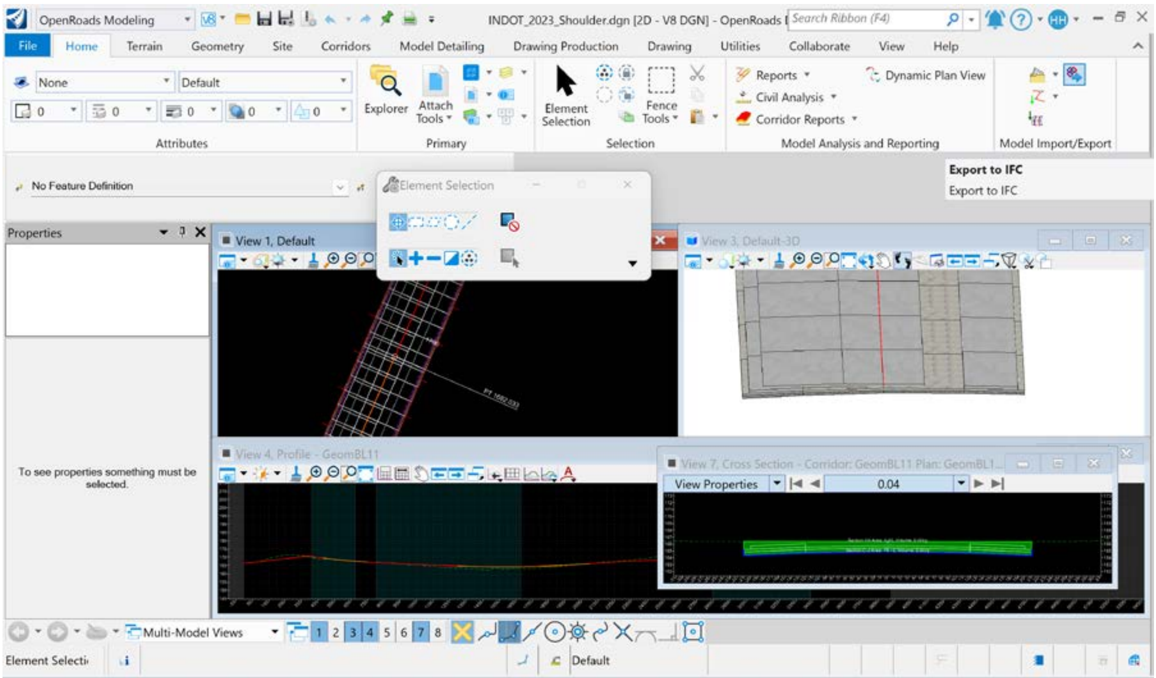


Figure B.206 Export to IFC.

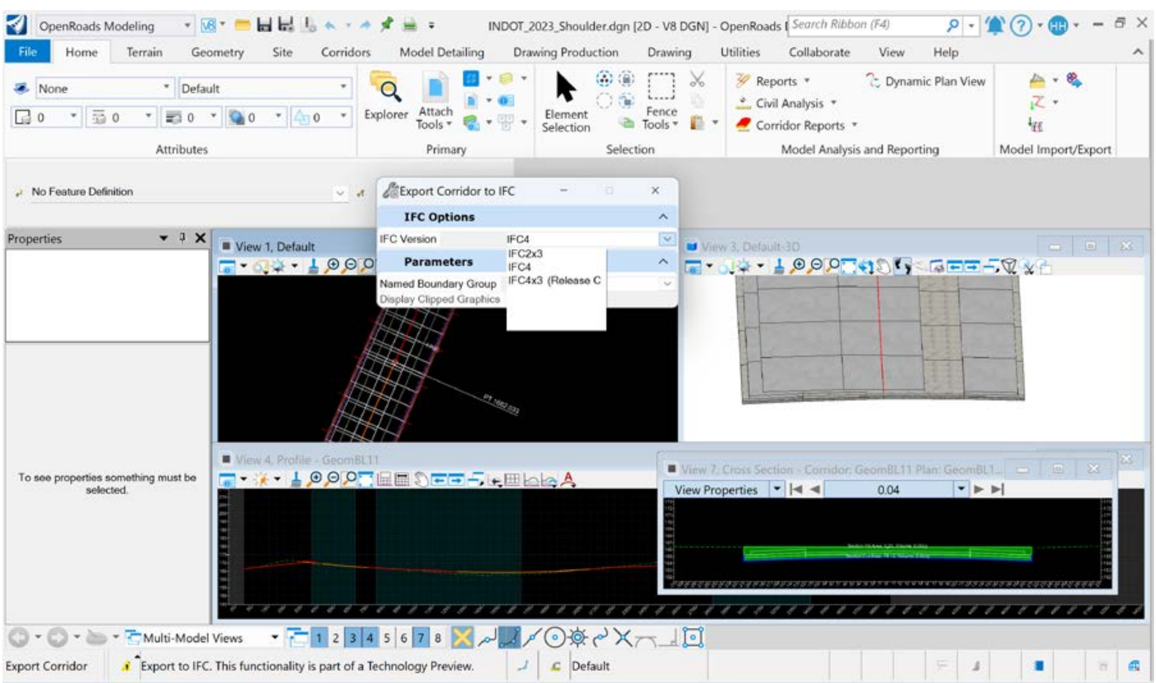


Figure B.207 Interface to select the “IFC Version.”

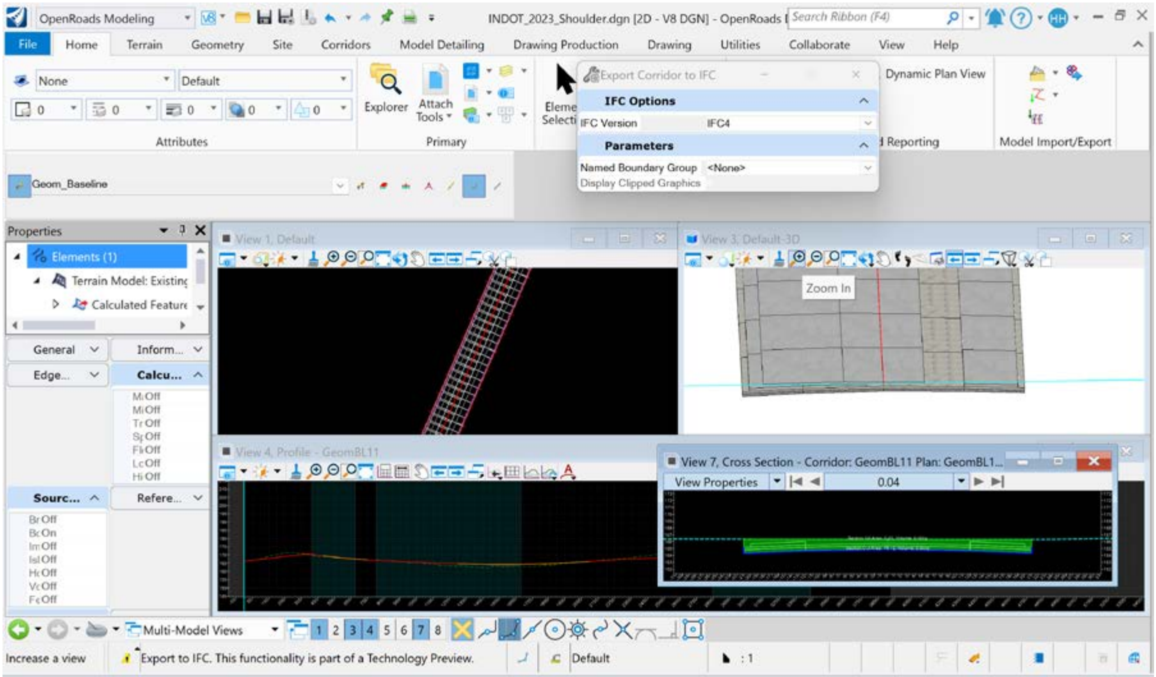


Figure B.208 Select IFC4 as the “IFC Version.”

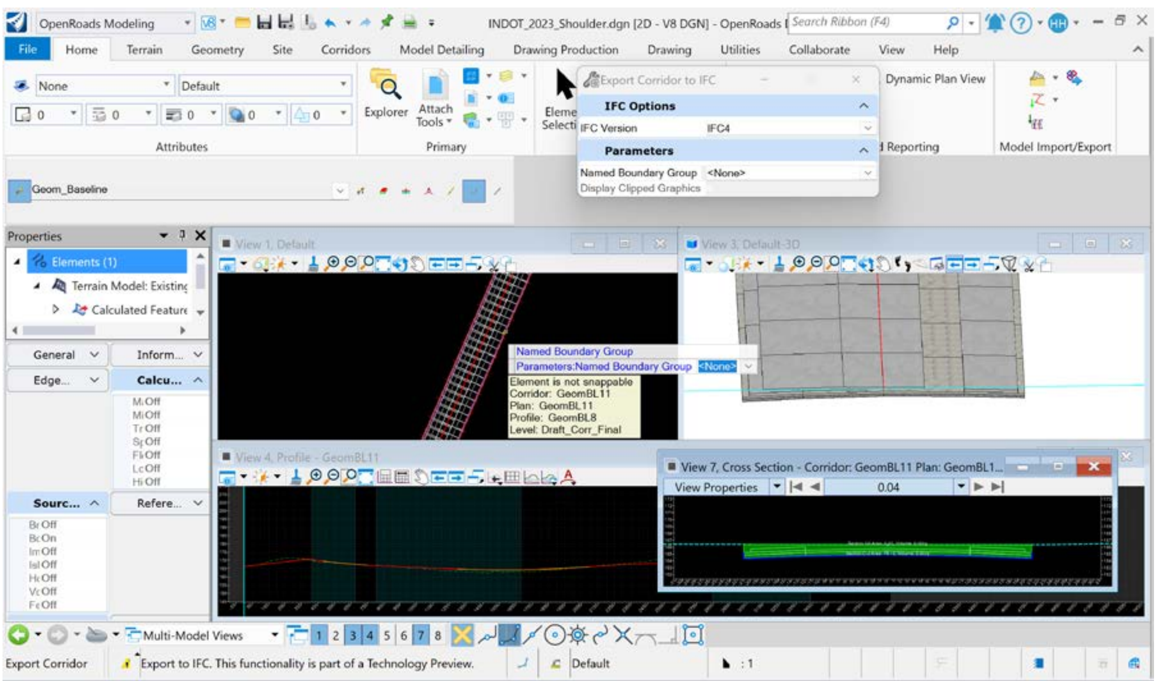


Figure B.209 Left-Click on the profile in “View 1.”

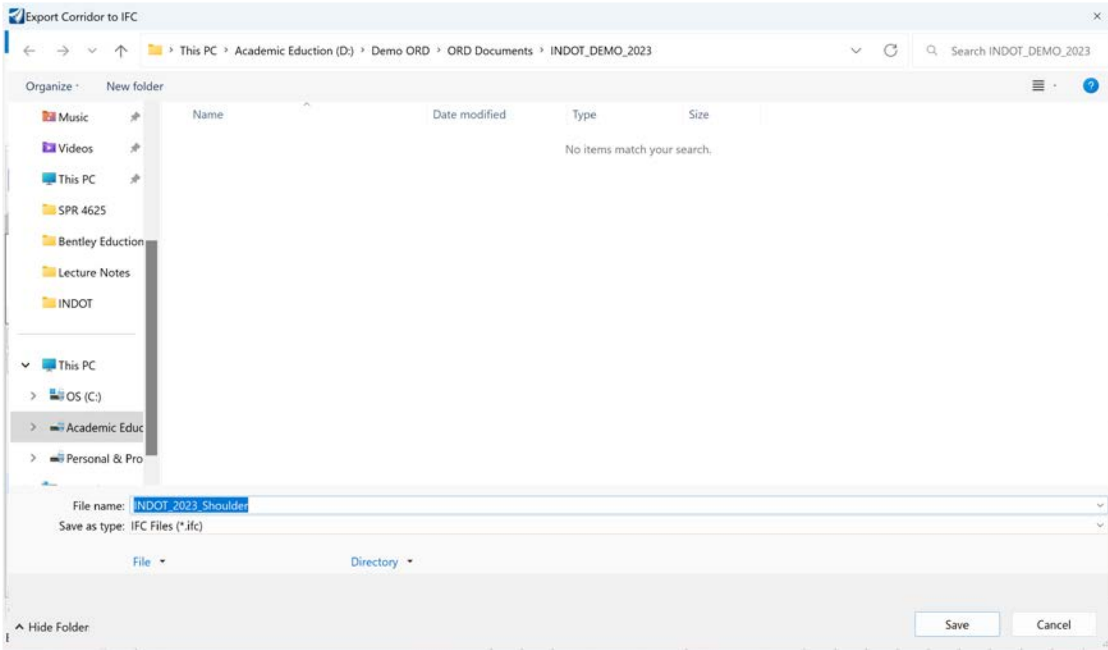


Figure B.210 Save the file.

Note: Repeat these steps with the other IFC Version and different templates.

B.4.3 Third Step: IFC Format

Notes: Using a BIM visualization tool (e.g., **BIMvision)** to open the file as "IFC", as shown below.

Right-Click>Open with> BIMvision – freeware IFC viewer

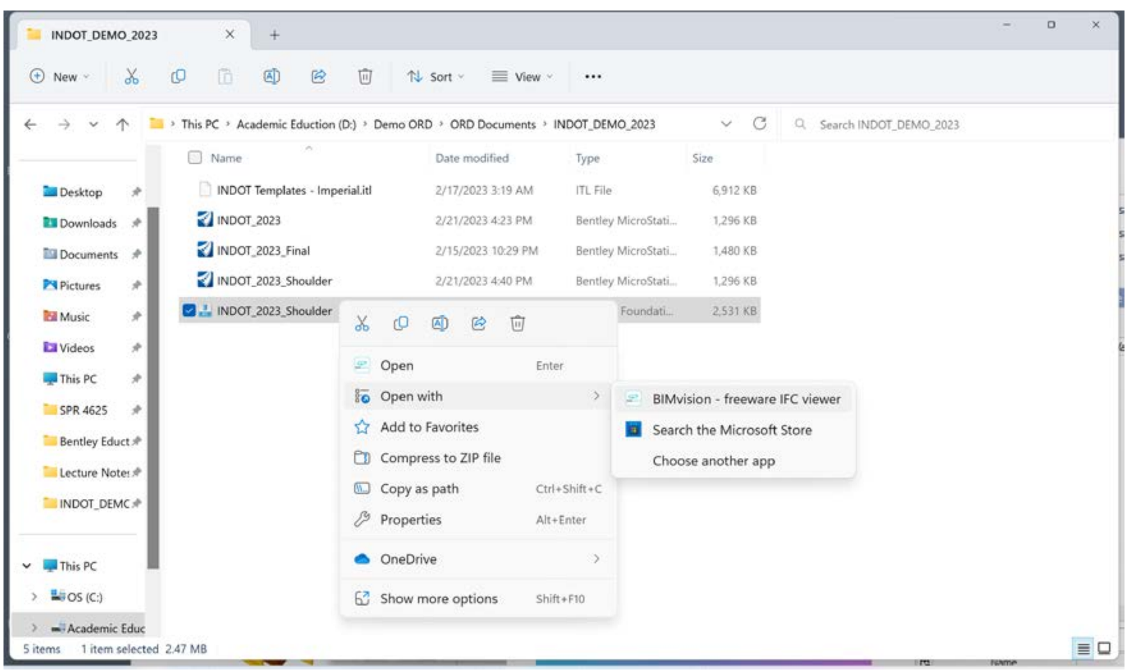


Figure B.211 Right-click on the icon.

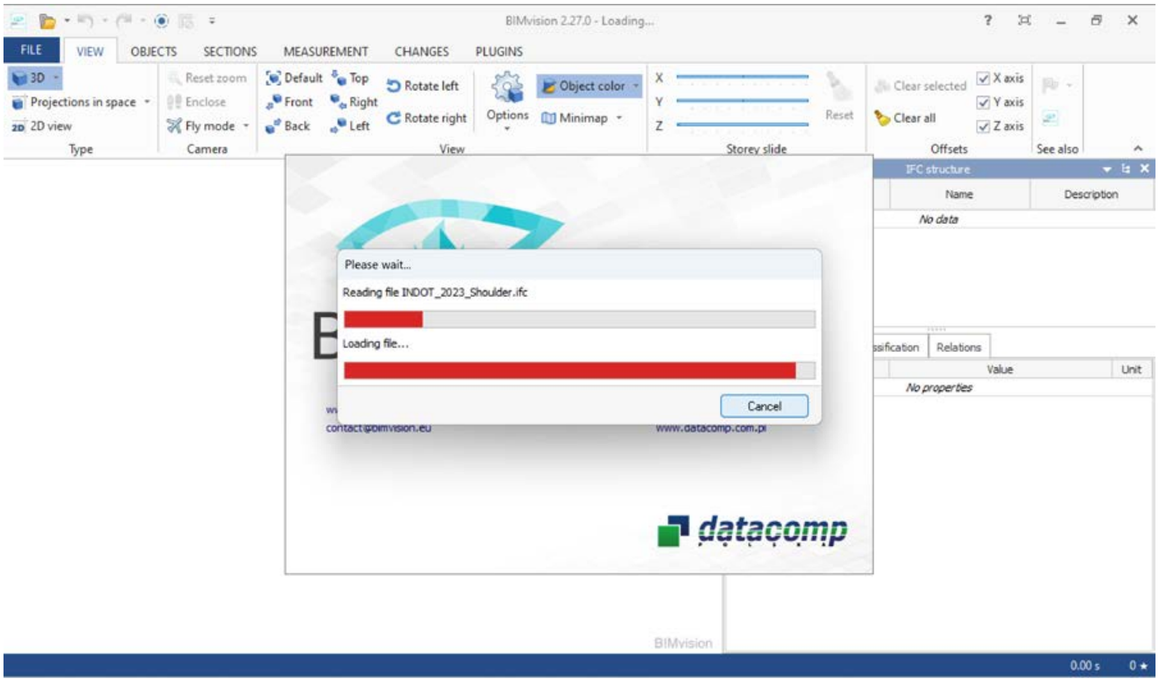


Figure B.212 Interface for reading and loading the file.

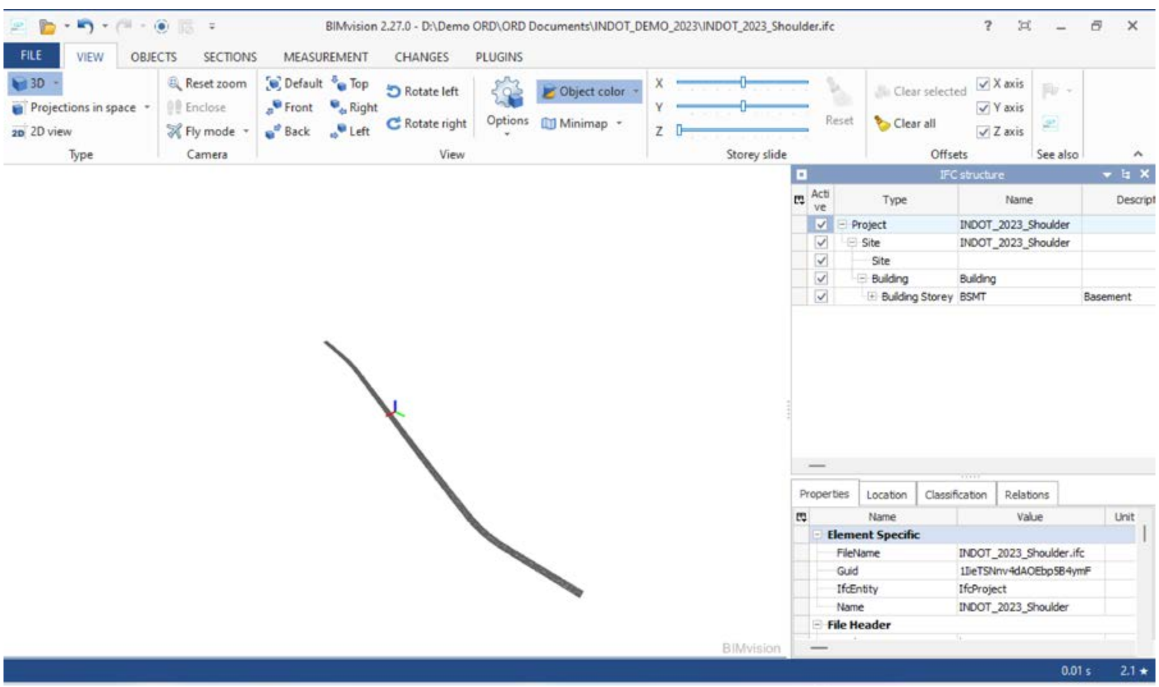


Figure B.213 Interface for the IFC view.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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