ADVANCED GEOMETRY MADE SIMPLE USING COMPUTATION DESIGN TECHNIQUES

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ABSTRACT

The demand for heightened precision in the development of intricate geometries associated with civil infrastructure necessitates a shift in the approach of civil engineers towards digital techniques. Digital modelling of linear road infrastructure has a long history, with 3D modelling tools like Autodesk Civil3D (and others) being in use for numerous years. This software solution is well-suited for designing string-based, linear infrastructure.

Additionally, software such as Autodesk Revit, has become established as valuable supplementary tools for creating bridge models and other elements of civil infrastructure. However, this software package needs more sophisticated modelling techniques to accommodate extreme geometry which does not conform to the normal road geometry design rules.

This paper showcases the application of computational design techniques in developing a reinforced concrete underpass tanking slab. The primary function of this tanking slab is to prevent groundwater from inundating a newly constructed railway underpass, part of a level crossing removal project. Micro piles, irregularly placed along the road alignment, are used to anchor the tanking slab, and prevent it from floating when the ground water levels rise.

The final geometry of the slab is heavily influenced by the complexity of the road design, the integration of concrete details, and the critical flood level considerations. This paper will illustrate how the Autodesk software suite coupled with visual programming can be leveraged to achieve highly intricate 3D geometries. Furthermore, the paper will shed light on the assumptions and limitations of the techniques used in developing the geometry of the reinforced concrete tanking slab.

1. INTRODUCTION

The Melbourne levelling crossing removal program is part of the multibillion commitment from the Victorian government to planning, building, running, and upgrading for this Australian State’s transport network (Victoria's Big Build, 2023).

The Robinson Road Upgrade, with the removal of the associated level crossing, is one of the approximately 110 of these projects across Melbourne, Australia. The road is classified as major north-south collector road. The road links Laverton and Calder Park and intersects with the Geelong/Ballarat Line (Victoria’s Big Build, n.d.).

Although a wider understanding of the project background will be provided for context, this paper showcases the application of computational design techniques in developing a reinforced concrete underpass tanking slab as part of the construction of a new underpass.

2. PROJECT DESCRIPTION

The level crossing on Robinsons Road was a 60km/h council road, intersecting with the Geelong/Ballarat rail line. It is located approximately 19km west of both the Melbourne central business district and the Deer Park Station. (Refer to Figure 1 for the location of the level crossing) The road was heavily trafficked and boom gates have been measured to be down 45% of the time during morning peak hours, where up to 37 trains traverse through the crossing. At the location of the original level crossing, the road crossed the Geelong/Ballarat railway line which comprise two broad-gauge tracks which are used by passenger, regional and freight services.

The Level Crossing Removal Project (LXRP) is being overseen by Victoria's Major Transport Infrastructure Authority (MTIA) and was delivered as part of various Alliance Programs. The Metropolitan Roads Program Alliance (MRPA), comprising the Level Crossing Removal Project, Fulton Hogan (Fulton Hogan, n.d.) and Metro Trains Melbourne, was responsible for the delivery of this project.

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 1: Robinsons Road Locality Plan

The removal of the Robinsons Road level crossing was achieved by means of a new grade separated solution including the construction of a new rail bridge to host the existing rail alignment and new Robinsons Road underpass (Figure 2 refers). The new structure will accommodate both road widening and additeional tracks for future development. A combination of piled retaining walls, soil nail and rock anchors were used to retain the existing ground levels on the approaches to the underpass.

A reinforced concrete tanking slab was constructed underneath the road surface to serve as a protective barrier against groundwater seepage in the underpass. Ground anchors, irregularly placed along the road alignment, are used to anchor the tanking slab, and prevent it from floating when the ground water levels rises.

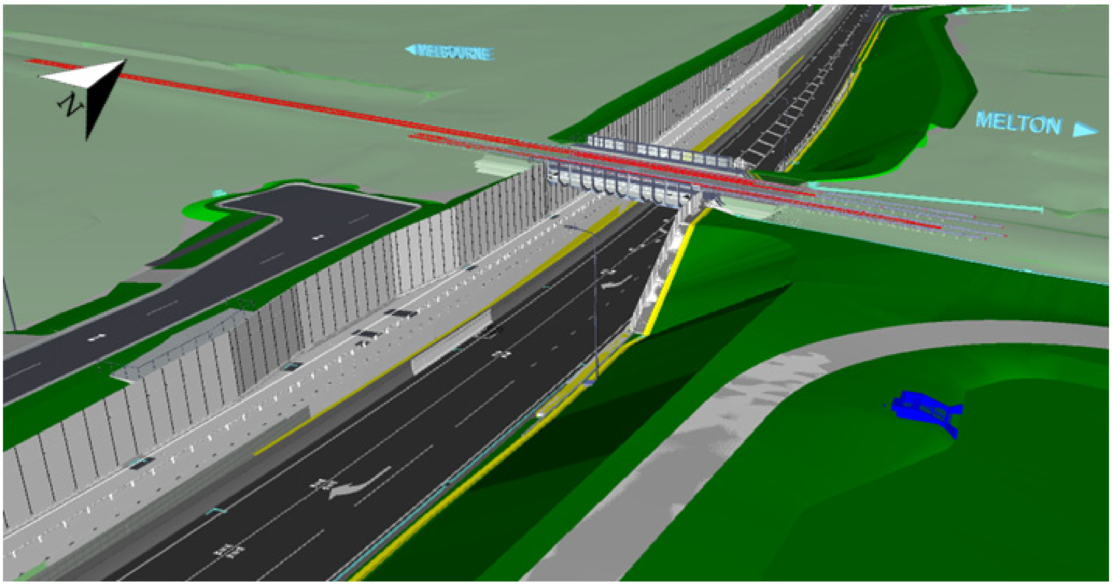


Figure 2: Autodesk Naviswork model of the new Robinsons Road layout

This paper showcases the application of computational design techniques in developing the complex geometry associated with the reinforced concrete underpass tanking slab. Although selective reference will be made to the hydrological and structural constraints, the design thereof will not be discussed.

Although it is not practical to give detail descriptions of the computational design code, the author wishes to convey sufficient information in this paper to highlight the possibilities for computational design in the Civil Engineering space. Computational design and automation allow us to manage complexity and drive innovation into our projects, digital processes and deliverables. Engineers, contractors and clients alike should utilise the technology and realise its associated opportunities for improved productivity and performance. Upskilling and reskilling of the transport industry in the digital design space is needed to ensure that industry keep up with world trends and effectively addresses future infrastructure challenges.

3. A BRIEF HISTORY OF COMPUTER AIDED DESIGN

Digital modelling of linear road infrastructure has a long and rich history, with 3D modelling and data driven design tools, being in use for numerous years. However, the necessity for increased accuracy and precision in crafting complex geometries for civil infrastructure calls for a transformation in the methodology that civil engineers and modellers adopt.

Autodesk Civil 3D, introduced by Autodesk in 2004, revolutionized the field of civil engineering and infrastructure design. It marked a watershed moment, integrating traditional Computer Aided Design (CAD) functionalities with specific tools tailored for civil engineering projects. Initially conceived as an addition for AutoCAD (Beesley, 2015), Civil 3D swiftly became a standalone software package owing to its comprehensive suite of features. This software geared towards streamlining the design and documentation of civil engineering projects, such as roads, highways, land development, and transportation systems. Intelligent objects and dynamic modelling capabilities enabled engineers and designers to create and simulate various scenarios, enhancing decision-making processes.

Autodesk Civil 3D's functionalities extended beyond basic drafting capabilities, instead incorporating Building Information Modelling (BIM) principles, facilitating the creation of data-rich and interconnected designs. This shift towards data-driven design greatly improved collaboration among various stakeholders involved in complex projects (Deutsch, 2015). The vendor's regular, periodic upgrades enhanced tools for grading, pipe design, corridor modelling, and visualization, solidifying its position as an industry leader. Autodesk Civil 3D remains a pivotal tool in civil engineering, empowering professionals to efficiently design, analyse, manage and realise innovative infrastructure projects with the prescribed precision.

Equally, Autodesk Revit was established in 2000 (LetsBuild, 2024) as a valuable supplementary tool for creating structural models and other elements associated with civil infrastructure. However, this software package, originally developed for the built environment (Gupta, 2022), is not designed to accommodate traditional road geometry design rules or linear infrastructure geometry on extreme scales and dimensions.

4. CONSTRAINTS, LIMITATIONS AND BOUNDARY CONDITIONS

4.1 General Description

The tanking slab serves as a protective barrier against groundwater seepage in the underpass, necessitating its placement above the designated water table level. This anticipated or designed water level accommodates prospective climatic variations and potential increases in water table levels. Additionally, while the structure comprises various elements or components, it is essential for the overall structure to maintain monolithic integrity. In instances where achieving complete monolithic unity is infeasible, waterproofing detailing becomes imperative to ensure the structural resilience and effectiveness in preventing water ingress.

The tanking slab is aligned along the north-south orientation of the road, adhering to the specific geographic alignment of the infrastructure (Figure 3 below). This strategic placement is beneficial for the optimized functionality of the tanking system in mitigating groundwater seepage along the designated route of the underpass. The reinforced concrete slab is approximately 180m long and 15m wide. A total of 382 ground anchors restrains the slab, preventing flotation.

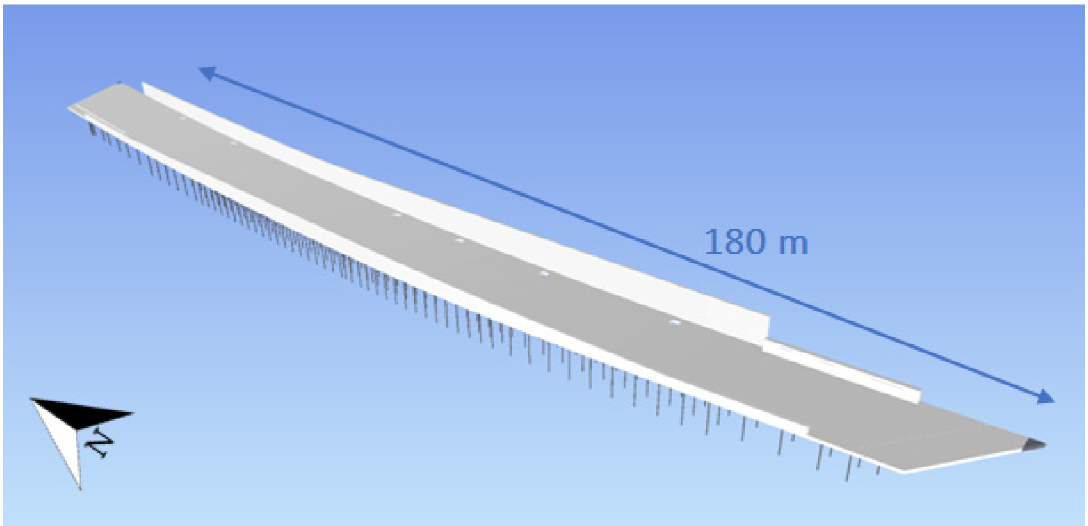


Figure 3: Autodesk Naviswork model of the tanking slab

At both terminations of the tanking slab, approach slabs have been incorporated to facilitate a seamless transition from the concrete/rigid structure to the conventional road pavement structure. The integration of approach slabs contribute to the structural integrity and durability of the interface between the tanking slab and the conventional road pavement structure. At each end of the slab, it terminates at skew angles. The intersection profile between the road design surface and the horizontal water surface resulted in a skew end slab, and a significant reduction in the volume of placed concrete. This design consideration reflects a deliberate optimisation of the structural geometry to optimize the use of materials.

4.2 Description of Cross-Section

The typical cross-section of the tanking slab (Figure 4) presented several constraints. In the first instance, the reinforced concrete slab had to adhere closely to the road pavement layer, ensuring a uniform thickness for the subsequent construction of an asphalt layer over the slab. Despite the road maintaining a single crossfall towards the east, this slope was not uniform over the length of the structure. Owing to specific road design specifications, the slope varied, necessitating careful consideration and adaptation to accommodate these dynamic changes in the structural configuration.

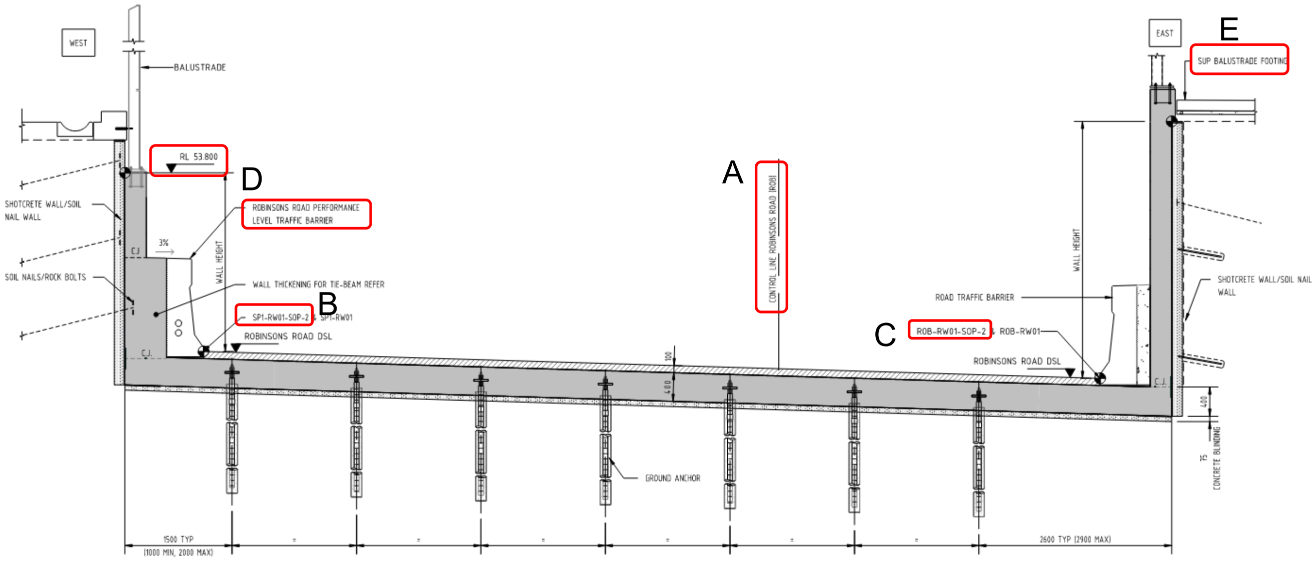


Figure 4: Typical annotated cross section of the tanking slab

On the eastern side of the underpass, a shared-use path (SUP) introduced a second constraint. The design of this SUP aimed to minimize unnecessary excavation beneath the underpass while ensuring sufficient clearance for its users. Consequently, the vertical alignment of the SUP was independent of the road alignment. For this reason, the eastern wall of the tanking slab was extended to function as a comprehensive retaining wall structure for the path. The top of this wall followed the vertical alignment of the SUP.

Towards the southern extent (Figure 5), the requirement for the eastern wall to serve as a retaining structure for the path diminishes and the wall transitions to a standard traffic barrier profile. This concrete element not only assumes the role of a traffic barrier and soil retaining structure, but also functions integrally within the tanking structure. This modification in the structural configuration marks a deliberate transition, addressing specific functional demands in alignment with the evolving requirements along the length of the underpass.

The western retaining wall height was constrained by the actual design groundwater level, set at 53.6 meters plus an additional 200 millimeters freeboard. To safeguard the structure from potential vehicle impacts, traffic barriers were installed directly in front of the wall. Consequently, the height of the western wall was further restricted by the elevation of these protective barriers. At the northern and southern extents of the the western wall where the road alignment is substantially higher, the top of the traffic barrier provides sufficient elevation and protection against egress of ground water.

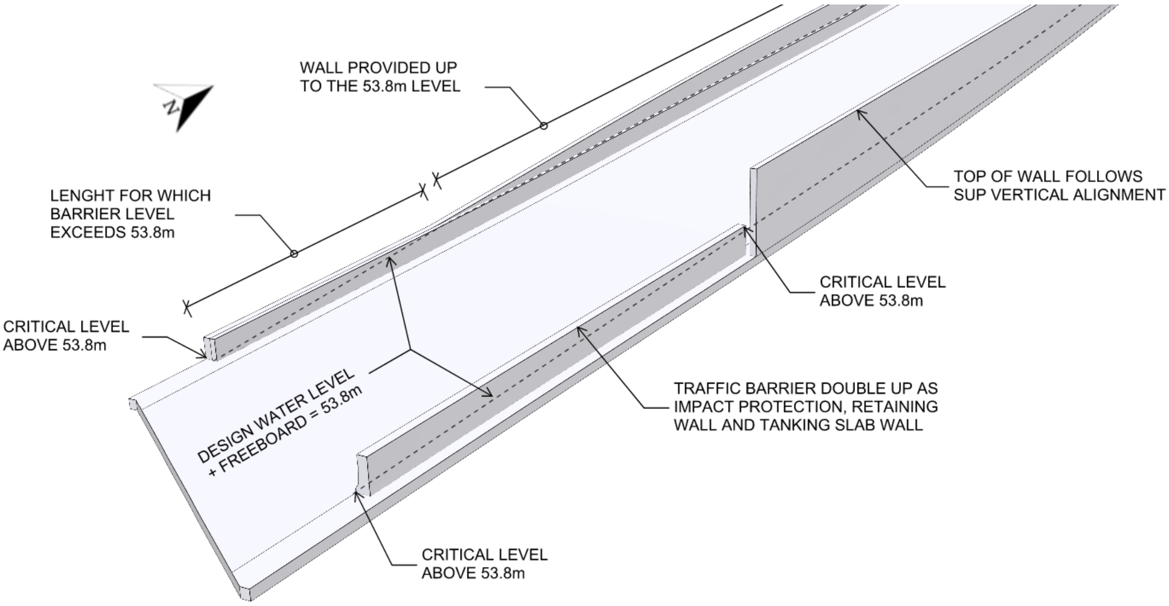


Figure 5: Cross section changes along the length (southern end)

4.3 Tanking Slab References

In linear infrastructure, conformity to a predetermined reference line or control string is imperative. Traditionally, these parameters align with the centerline of the road (denoted as A in Figure 4 above) and subsequent lane markings. The intricate nature of the road geometry associated with the tanking structure necessitated a more accurate representation of the road width. Therefore, two strings at the base of the traffic barriers, were defined as primary setting out lines for the tanking slab (denoted as B and C in Figure 4 above). Reference point A to C would provide the geographical primary easting, northing and reduced level for the tanking slab.

The western wall adhered to the lowest reduce level, determined by either the design water level or the upper edge of the traffic barrier (denoted as D in Figure 4 above). A secondary string, linked to the SUP vertical alignment, would furnish supplementary elevation details pertaining to the top of the wall (denoted as E in Figure 4 above). It is important to highlight that none of the aforementioned reference strings were synchronized in the longitudinal direction. In other words, the chainage along these lines did not align.

5. COMPUTATIONAL DESIGN METHODOLOGY

In civil engineering, computational design can transform the design by integrating advanced digital technologies for efficient modelling, data processing and optimization. This accelerates project timelines (particularly toward the delivery phase), identifies a range of optimal solutions, and ensures resilient designs. The precision of computational tools minimizes human-induced errors and could reduce costs through data-driven decisions.

Computational design techniques developed from as early as the 1960s with the algorithm-based system to optimize spatial location patterns for manufacturing plants (Armour & Buffa, 1963).

Key components of computational design include parametric modeling and algorithmic design which are well understood in the architectural industry. Caetano states that the definitions of the termonology associated with computational design has developed over numurous years (Caetano et al., 2020). Fundametally, parametric modeling allows engineers to create designs that are defined by parameters, facilitating easy exploration of design and form variations. Algorithmic design involves the use of algorithms or logic statements to generate and manipulate design elements, providing a systematic, data-driven approach to the design process.

The unique geometry associated with the tanking slab at Robenson Street Underpass did not suit the use of parametric elements or modelling techniques. A more sophisticated modelling technique was required for the development of the digital model. This entailed four discrete computational design steps (Figure 6), each of which is explored in more detail.

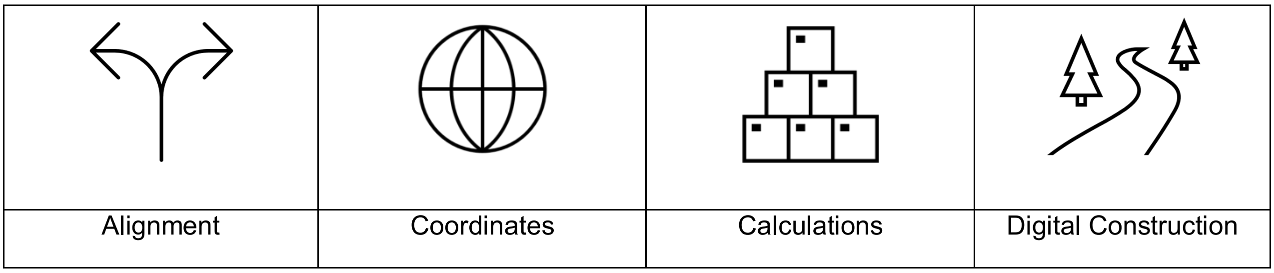


Figure 6: Computational design steps for the development of the tanking slab model

The evolution of Building Information Modeling (BIM) reflects a dynamic synergy between technological innovation and industry demands. Autodesk recognized the need for collaborative, data-driven design processes, and the need for BIM. Dynamo, an open-source, low-code/no-code visual programming platform, evolved as a catalyst for enhancing BIM workflows and advanced geometry (Shishina & Sergeev, 2019). Its integration within Autodesk products (Revit and Civil3D) empowered users with limited to no knowledge nor experiece of traditional programming with reusable scripting highly automated workflows. The platform allows users to utilize the power of algorithmic or computation design especially for highly repetitive processes and complex geometry.

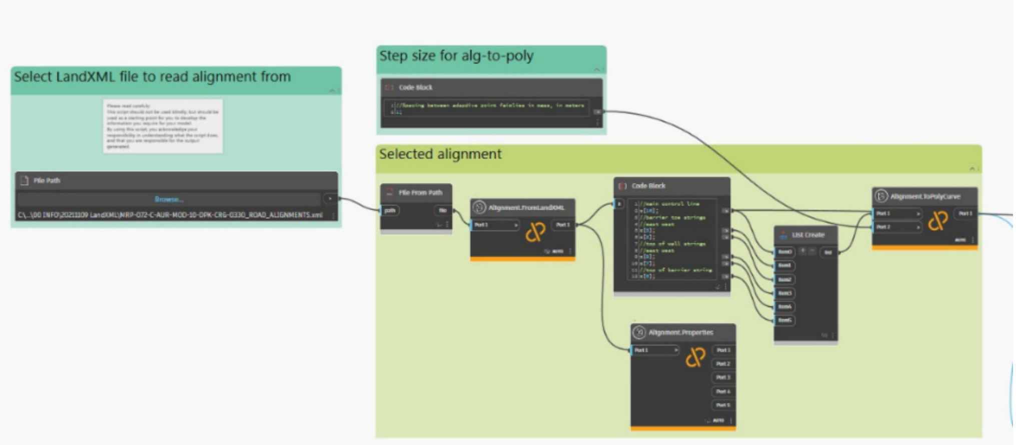


Figure 7: Extract from Dynamo script

5.1 Alignment to Memory

Employing the most recent alignment information is pivotal for the success and expeditious delivery of the model following alterations or updates in the alignment. In this project, extensible markup lanuage file format (*.xml) exports from the civil design software were utilised as the human-readable exchange format between the civil and structural design. In-house developed Dynamo nodes were employed to read, digest, and process the alignment reference and retain this information as digital memory (Figure 8).

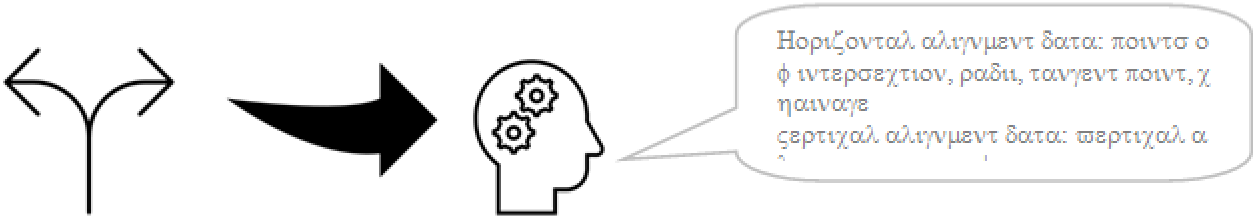


Figure 8: Alignment to memory

Having the alignment data in non-volatile memory allows for downstream calculations to utilize native geometrical data in the purest format. This facilitates not only rapid change implementation but also enhances the overall accuracy of the modeling output.

5.2 Global to Local

Generally, the Revit families intended for placement are averse to large number representation, such as those associated with world coordinates, as the origin of the family is too far from the actual components (AutoDesk, 2022; Autodesk Support, 2023). Consequently, the coordinates derived from the alignment necessitated transformation into a local coordinate frame (Figure 9). A comprehensive understanding of this transformation process was imperative to guarantee the accurate generation and placement of the model.

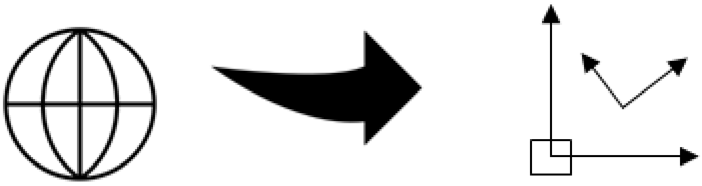


Figure 9: Global to local

5.3 Geometrical and Topological Calculations

This phase was where the majority of the mathematics and engineering magic came from. The computation involved determining the wall dimensions based on the geometry extracted from the control strings and the cross-sectional definition of the base slab and walls (Figure 10). It is noteworthy that the iterative refinement of the cross-sectional definition was an ongoing process, evolving in parallel with discussions on the engineering design/analysis and the construction preferences of the contractor.

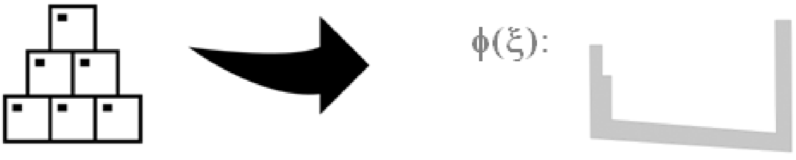
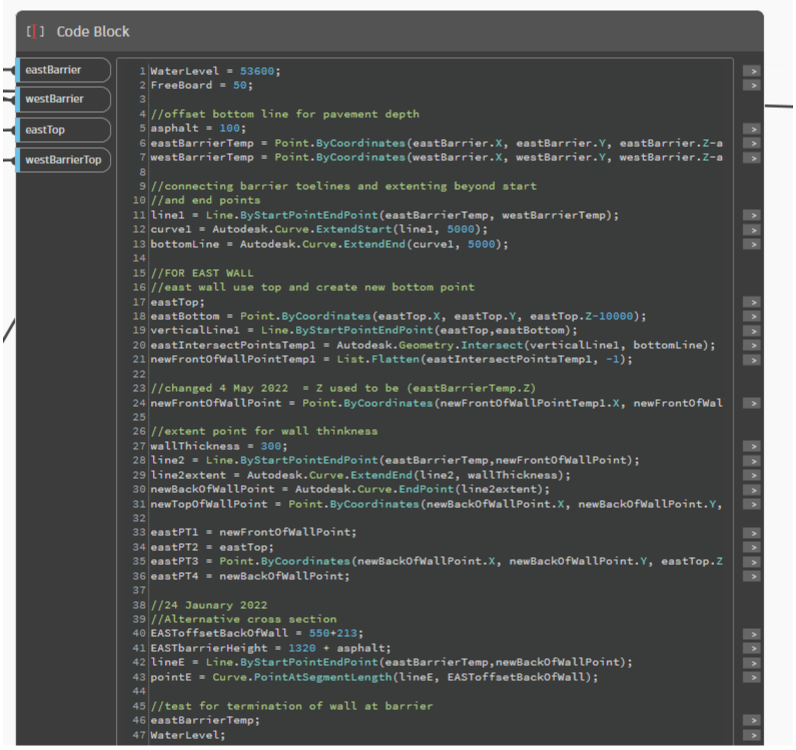


Figure 10: Geometrical and topological calculations

Dimensions, including wall thickness, wall offset, and wall and barrier terminations, were all treated as variable parameters. By defining these elements as variables in the coding implementation, rapid updates and changes were realised. The only limitation to the flexibility of the Dynamo code (Figure 11) was the topological definition of the structure itself. Provided that the design stayed within the boundaries of the topological definition, component geometries were scaled and flexed in accordance with the engineering design requirements.



```
WaterLevel = 53600;
FreeBoard = 50;

//offset bottom line for pavement depth
asphalt = 100;
eastBarrierTemp = Point.ByCoordinates(eastBarrier.X, eastBarrier.Y, eastBarrier.Z-a
westBarrierTemp = Point.ByCoordinates(westBarrier.X, westBarrier.Y, westBarrier.Z-a

//connecting barrier toelines and extenting beyond start
//and end points
line1 = Line.ByStartPointEndPoint(eastBarrierTemp, westBarrierTemp);
curve1 = Autodesk.Curve.ExtendStart(line1, 5000);
bottomLine = Autodesk.Curve.ExtendEnd(curve1, 5000);

//FOR EAST WALL
//east wall use top and create new bottom point
eastTop;
eastBottom = Point.ByCoordinates(eastTop.X, eastTop.Y, eastTop.Z-10000);
verticalLine1 = Line.ByStartPointEndPoint(eastTop,eastBottom);
eastIntersectPointsTemp1 = Autodesk.Geometry.Intersect(verticalLine1, bottomLine);
newFrontOfWallPointTemp1 = List.Flatten(eastIntersectPointsTemp1, -1);

//changed 4 May 2022  = Z used to be (eastBarrierTemp.Z)
newFrontOfWallPoint = Point.ByCoordinates(newFrontOfWallPointTemp1.X, newFrontOfWal

//extent point for wall thinkness
wallThickness = 300;
line2 = Line.ByStartPointEndPoint(eastBarrierTemp,newFrontOfWallPoint);
line2extent = Autodesk.Curve.ExtendEnd(line2, wallThickness);
newBackOfWallPoint = Autodesk.Curve.EndPoint(line2extent);
newTopOfWallPoint = Point.ByCoordinates(newBackOfWallPoint.X, newBackOfWallPoint.Y,

eastPT1 = newFrontOfWallPoint;
eastPT2 = eastTop;
eastPT3 = Point.ByCoordinates(newBackOfWallPoint.X, newBackOfWallPoint.Y, eastTop.Z
eastPT4 = newBackOfWallPoint;

//24 Jaunary 2022
//Alternative cross section
EASToffsetBackOfWall = 550+213;
EASTbarrierHeight = 1320 + asphalt;
lineE = Line.ByStartPointEndPoint(eastBarrierTemp,newBackOfWallPoint);
pointE = Curve.PointAtSegmentLength(lineE, EASToffsetBackOfWall);

//test for termination of wall at barrier
eastBarrierTemp;
WaterLevel;
```

Figure 11: Dynamo extract of a script – topological calculations

At the heart of the calculation was a single code block containing the mathematical definitions that defines the tanking slab geometry. The geometry of the structure was derived from various positional offsets, absolute and reletive height, and structured to ahear to the contraints described earlier in this paper.

Although the standard Dynamo script comprised numerous nodes and wired connections, reverting to a single script of code improved the readability for the experienced computational designer. The output of this Code Block contained the global and local geographical information that was required to create and place the Revit elements into the project world.

5.4 Digital Construction

Using the data generated from the alignment and the topological calcuations, the final phase entailed the placement of Revit components or families – the digital construction of the infrastructure (Figure 12). While many Revit users are adept at placing standard structural framing, floors, foundations, and other conventional building elements, their familiarity and proficiency might be limited to the creation of model in-place families. It is essential to note that the geometry associated with the tanking slab surpassed the scope and capacity of these conventional traditional elements.

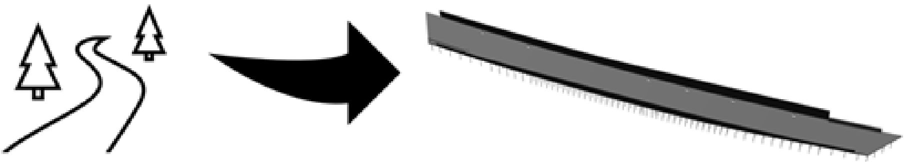


Figure 12: Digital construction

Adopting a more sophisticated family definition in the form of Mass and Adaptive Profiles Families (Figure 13), allowed for the modelling of more complex geometry that are ordinarily assocaited with building facades and extreme shapes in the architecrual domain.

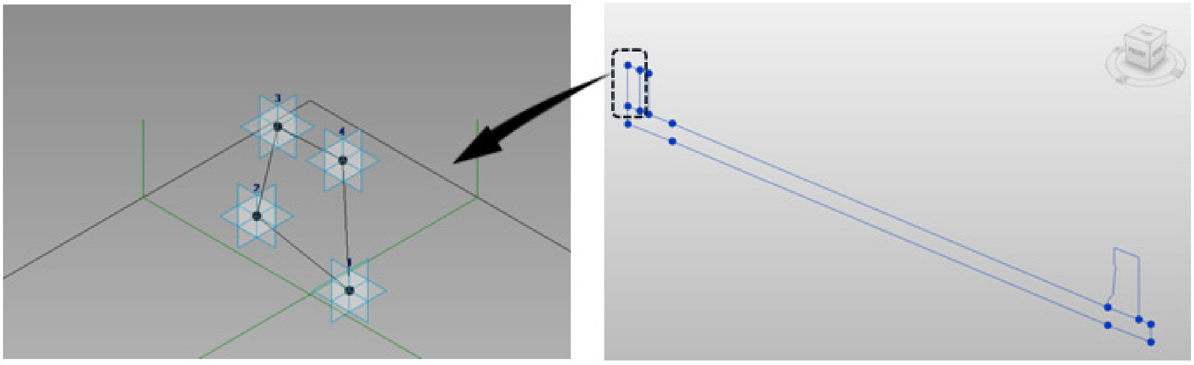


Figure 13: Integration of multi point Adaptive Profiles into a Mass Family

The Generic Model Adaptive Family serves as the 'amoeba' of forms in the REVIT space. Profiles defined in this space are constructed using any number of reference points and can thus be transformed into nearly any two or three dimensional shape . For the purpose of this project, a combination of 4 and 8-point adaptive profiles were used to compile the cross-sectional definition. Compiling the profile from discretised polygons, allowed for cross sectional variation along the length of the tanking slab. At specific locations along the alignment, the visibility of elements could be selectively toggled.

After placing all the cross sections in space in accordance with the cross-sectional definitions, and selecting the start and end locations of the respective profiles, Revit generated a form from the geometry (Figure 14 below). A solid form (enclosed volume) was extruded between adjacent profiles, seamlessly translating the geometric specifications into a tangible, three dimensional representation within the digital space.

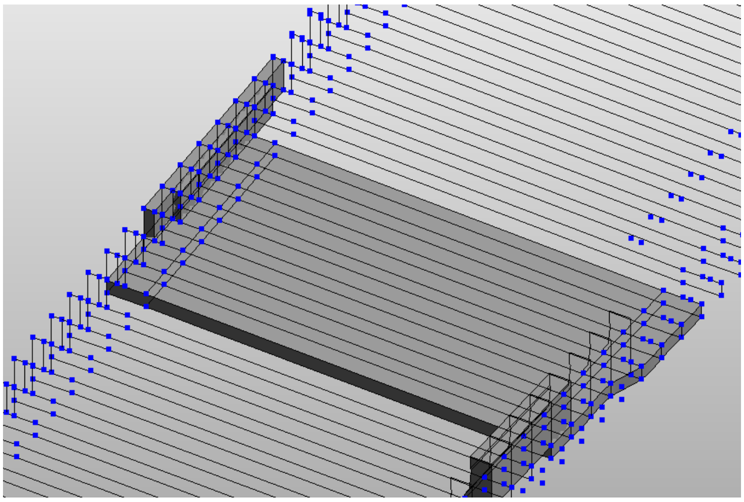


Figure 14: Form creation illustration

The formed mass automatically responded and adjusted geometry to suit as the reference or adaptive points moved in space. In addition, each of the profiles embeded specific metadata to ensure quality control was adhered to alongside accurate synthesis of the model geometry. For example, each cross section contained the chainage and master control line reduced levels – each of the cross section's paramaters was uniquely identifiable and verifiable at any point in time. Finally, the compiled Mass Family was loaded back into the main Revit project for documenation and futher detailing.

6. CONCLUSION

The aforementioned methodology provided a concise overview of the utilization of standard Autodesk products for the generation of intricate and integrated topologies associated with the Robinson Road Tanking Slab. Mass and Adaptive Families presented an excellent solution for modelling intricate topologies. Futhermore, the placement of these families necessitated the utilization of computational design thinking. Employing a process of computational design, and utilizing road geometry as input, crucial reference points was mathematically defined to ensure the utmost accuracy and precision. Computational design further guaranteed repeatability and expeditious responsiveness to design modifications.

Consultants, contractors and clients are all essential contributors to the digital era and should appreciate the pivotal role of data-driven design and the potential of computational design. Computational design will significantly increase the effective execution of civil engineering designs of the future. Computational design is one important element to ensure the upskilling and reskilling of the transport industry in the digital design space. Developing new tools and methods to create great designs are essential to ensure that the industry keeps up with world trends and effectively addresses future infrastracture challenges.

Figure 15 illustrates the complexicty of the completed federated Robenson Road Underpass digital model.

Figure 15: Rendition from the Federated Model

7. ACKNOWLEDGEMENTS

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