

Powering Pile Design through Parametrics

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ABSTRACT

Parametric design skills are increasingly in demand within the engineering consulting industry due to ever-pressing time and budget constraints on medium- to large-scale infrastructure projects. The structural engineering team at Arup examined obstacles and manual processes encountered by the team during the design of a piled noise wall and endeavoured to automate, or at-least streamline, many of them. This resulted in a 94% saving in pile cross-sectional analysis computation time compared to manually inputting pile cross-section and design actions into analysis software and designing the pile using spreadsheets. The team's skills in parametric design in Grasshopper, a parametric modelling tool, and basic scripting were leveraged and developed throughout the process, providing an essential way of designing. The pile design process was selected to demonstrate the benefits of the parametric design due to it being a common design task on major infrastructure projects, such as pile wall design. The tool was developed with the intent of it being modular, employing a plug-and-play approach that connected the key stages of the design process with outputs, such as embodied carbon calculations and engineering drawings. McNeel Rhino, a 3D visualisation software, and Grasshopper were chosen for the tool development as they provided a user-friendly, visual programming interface and many plug-ins to existing automation workflows. Thus, enabling the engineer to interrogate the output of each stage of the design process both visually and numerically. The modular approach also enabled engineers to substitute ALP in place of Brom's calculation, as the design progresses.

Keywords: parametric design, parametric, geotechnical, pile, structural, automation

1 INTRODUCTION

The rationale supporting parametric design methodology has strengthened over time with growth in its adoption, further elucidating the time savings and efficiencies to be gained. Furthermore, as the design process is often iterative due to the dynamic nature of working with multiple stakeholders and collaborating with various engineering teams, the ability to quickly run a design from start to finish with updated inputs is highly beneficial.

This workflow was based on improving an existing workflow used in the design of a noise wall for a highway project in Victoria.

2 METHODOLOGY

2.1 Modularity

To enable flexibility in the use of this parametric tool across different design stages, it was important to identify the primary inputs to enable the tool to perform at each level. Naturally, this led to a modular design approach focussing on the inputs required for both high-level reference design and comprehensive detailed design. As a consequence of having different inputs for each stage, additional flexibility was required in the calculation components performing the engineering design process, hence reaffirming why modularity was so critical.

2.2 Inputs

To design the piles, the design actions at the top of the piles were needed, and this was subject to the ground conditions. The primary inputs required irrespective of the design stage were the wall alignment, topography, geotechnical design parameters, design loads, and initial structural properties and geometry of the piles and noise wall, as shown in Figure 1. For detailed design, additional inputs were required, such as additional and refined geotechnical parameters, inputs for wind loading and fatigue assessments.

2.3 Geotechnical pile design

The loading at the top of each pile was determined using the geometry of the piled wall itself and the specified wind pressure acting on the noise wall. A cantilever was idealised to simplify the problem with the intention being to emphasise the power of automation and allow subsequent users to further develop the tool. Subsequently, the design axial force, shear force, and bending moment under both ultimate limit state (ULS) and serviceability limit state (SLS) conditions were determined. From this, the required pile depth under ULS and SLS could be determined. These key design parameters were obtained using Brom's (1964) equations for lateral resistance of piles in both cohesive and cohesionless soils. Note this analysis considered a simplistic laterally loaded pile scenario and vertical effects have not been considered.

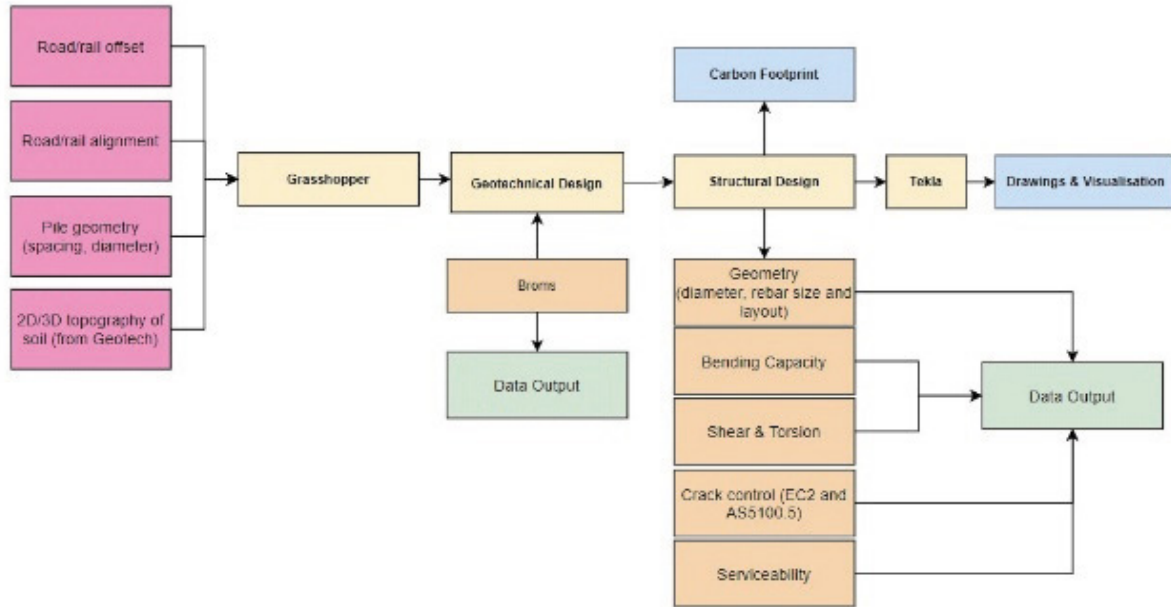


Figure 1. Modular workflow for pile design tool

Design parameters				
Section geometry				
Pile diameter, $D =$	1050	mm		
Nominal cover, $c_{nom} =$	75	mm		Refer Basis of Design report
Longitudinal reinforcement				
Bar diameter, $d_{st} =$	40	mm		
Number of bars, $n_{st} =$	20			
Transverse reinforcement				
Bar diameter, $d_{sv} =$	16	mm		
Link spacing/pitch c/c, $s =$	150	mm		
Material property				
Capacity reduction factor, $\Phi =$	0.7			tbl. 2.3.2
Concrete characteristic strength, $f_c =$	40	MPa		
Concrete modulus of elasticity, $E_c =$	32800	MPa		tbl. 3.1.2
Longitudinal steel yield strength, $f_{sy} =$	500	MPa		
Transverse steel yield strength $f_{sy,t} =$	500	MPa		
Steel modulus of elasticity, $E_s =$	200000	MPa		
Maximum nominal aggregate size, $d_g =$	10	mm		
Design Loads				
Shear force, $V^*_{ULS} =$	1000	kN		
Bending moment, $M^*_{ULS} =$	200	kNm		
Minimum bending moment, $M^*_{ULS} =$	789	kNm		cl. 8.2.4.3(a)
Axial load, $N^*_{ULS} =$	-100	kN		-ve compression

Figure 2. Original spreadsheet for design shear strength of circular reinforced sections

When a project progresses to detailed design, Oasys ALP, a lateral pile design software, can be substituted into the Grasshopper workflow replacing Brom's calculations to determine shear forces and bending moments induced along each pile when subject to lateral loads and bending actions at top of pile.

2.4 Structural pile design

Based on the key design actions, the pile reinforcement required to withstand the design actions was determined according to AS 5100.5:2017. An established spreadsheet for pile shear capacity design, shown in Figure 2, was converted into a more practical digital tool.

We leveraged a framework developed in-house, known as ArupCompute, to script the calculations rather than Excel. One method of querying this tool was through a web interface shown in Figure 3. Coding this tool presented several key benefits:

- All calculations were verified once coded
- Any change to the coding for the calculation would alert the user/engineer
- Reduced the chance of human error in dragging incorrect cells, modifying formulae in Excel, or using unverified design spreadsheets

The pile section analysis was also conducted parametrically by drawing on the work of colleagues in Germany who developed a Grasshopper plug-in for Oasys AdSec. AdSec works by defining a reinforced concrete cross-section, applying relevant load cases, and analysing the pile under both ULS and SLS conditions to primarily determine ULS utilisation, Figure 4, and SLS crack widths.

Case	Load			ULS Status	Utilisations	
	F_x (kN)	M_{yy} (kNm)	M_{zz} (kNm)		Load	Deformation
1	-4400	150	0	✓	65.9%	36.24%
2	-220	220	0	✓	88.62%	54%

Figure 4. AdSec ULS results for two critical load cases

Any changes to the pile geometry would immediately update the analysis inputs and subsequent design process. This was controlled by the engineer to allow AdSec to run only when required, rather than after every update. AdSec was then used in combination with PowerBI to identify which piles were most highly utilised, drastically reducing computation times, as summarized in Table 1.

Table 1: Timed run for analysis of twenty-five piles in AdSec*

Method	Task (test run 25 piles)	Time
Traditional method	Create individual AdSec files for each pile and manually apply loads	~1300s
Parametric method	Run each pile through AdSec (full creation of section per pile, apply loads, analyse)	~80s
	Create list of design actions for all cases and piles, run through single AdSec section**	~4.5s
	Run single max load case through single AdSec section**	~2.5s

*Assumes pile cross-sections are identical for all twenty-five piles

**Only one section initially loaded into AdSec, and design actions updated

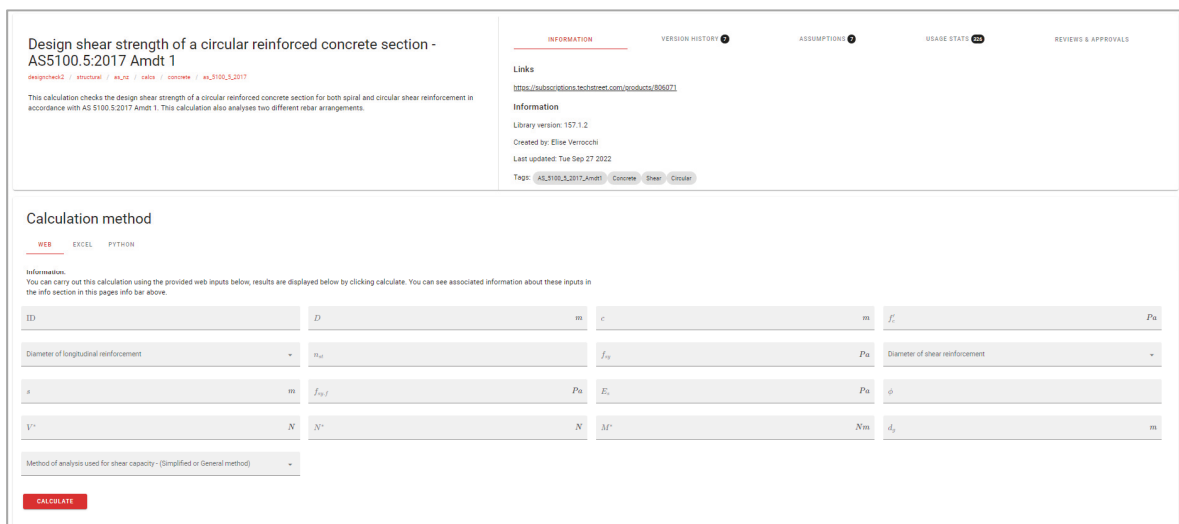


Figure 3. ArupCompute interface for design shear strength of circular reinforced sections

2.5 Design rationalisation

Structural pile design for a noise wall is often rationalised. This means, instead of each pile being designed individually based on its design actions and utilisation, piles are grouped based on the magnitude of their design actions to keep piles as close to 100% utilisation as possible. Therefore, instead of having one pile cross-section for the entire wall, you may have three to four different cross-sections implemented based on how highly utilised each pile at each location is.

Unlike a traditional design method, this workflow provides a design benefit due to the speed in which analysis can be carried out. Hence, each cross-section can be analysed to calculate the utilisation for each permutation. Consequently, the most optimum of the cross-sections can then be assigned to each pile.

2.6 Data visualisation

Parametric design enables the design of each structural element within the pile wall, therefore data visualisation of key metrics such as pile length, pile utilisation, total material quantities, and embodied carbon is possible. This was carried out using

PowerBI, a data visualisation tool to display minimum required pile length, pile utilisations, crack width, and embodied carbon (Figure 5).

2.7 Drawing automation

With the analysis performed and design carried out, the next step in the overall workflow was to link the design work with the drawing automation process. Key parameters, including pile diameter, longitudinal reinforcement diameter, and number of longitudinal reinforcing bars, was uploaded to a database. Arup technicians then extracted and subsequently ran this data through their parametric workflow to generate 3D models and associated engineering drawings. The power of this process is that for any change in the geometry or loading during the analysis and design stages, the design can be re-run with minimal manual steps and ultimately the resultant information can be reflected in the models and engineering drawings within only a few minutes. Meaning it took only a few minutes to re-generate a set of ready-to-print engineering drawings, offering up to a 90% time saving. This further highlighted how parametric workflows can considerably speed up the drawing production process, particularly when there are changes to the design.

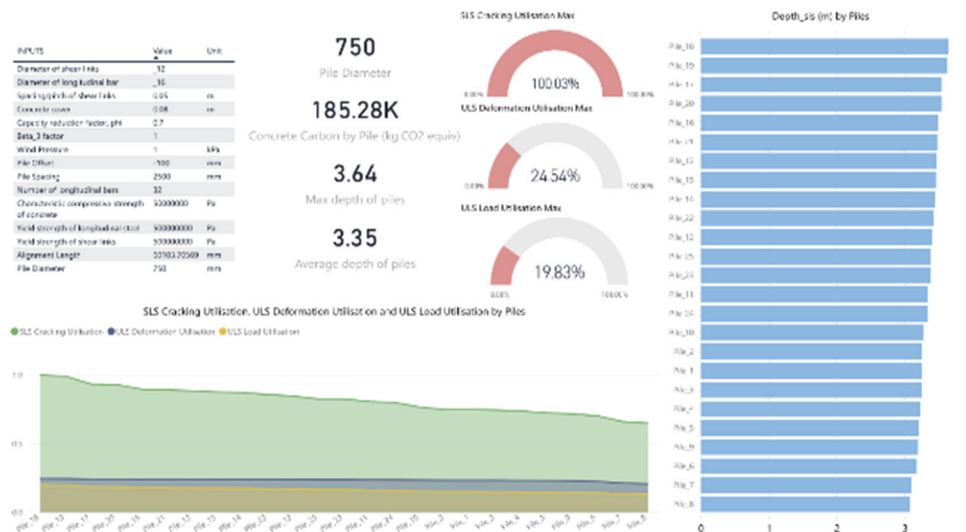


Figure 5. PowerBI data viewing dashboard produced for one noise wall design

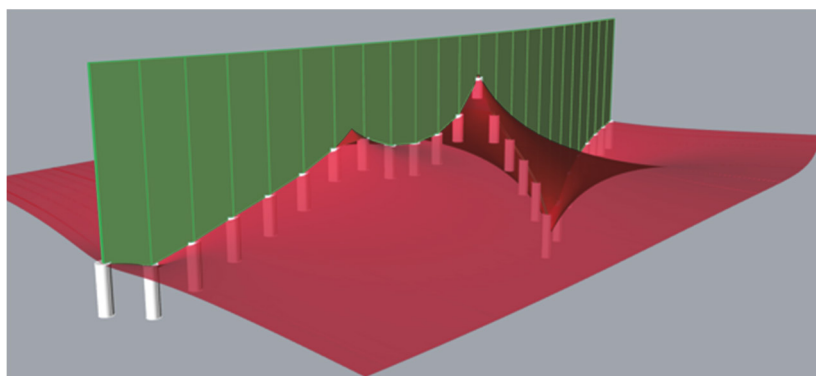


Figure 6. Real-time Rhino visualisation of topography and pile length with the topography exaggerated for display purposes

2.8 Ability to interrogate the tool

A fundamental consideration during tool development was ensuring that the tool did not resemble a “black box” and was instead completely interrogable. This was achieved through the focus on modularity, allowing the outputs to be interrogated at each step, in addition to using ArupCompute and its auto-generation of complete calculation sets to alleviate engineers’ concerns surrounding providing inputs to an un-interrogable tool.

Not only was the tool easy to interrogate numerically, the noise wall layout and pile length were also displayed visually and updated in real-time in Rhino, as shown in Figure 6. This allowed the engineer to see the topography of the ground in which the piles were being constructed and the variation in pile length under different ground conditions.

2.9 Embodied carbon

Sustainability has become a key metric on projects and is calculated primarily through total embodied carbon. Hence, it was essential to include carbon calculations within the script to enable comparisons between different design methodologies. The Environmental Performance in Construction (EPiC) database (2019) was used to calculate total embodied carbon for cradle-to-gate (stages A1-A3) analysis of the piles.

3 LESSONS LEARNT

There were important lessons learnt from the process of developing a parametric pile design workflow. One of the major challenges encountered during the development of the tool was the magnitude of the task at hand, including branching out of our structural engineering domain to engage and understand geotechnical inputs and requirements. Specifically, managing the data output from ALP and modifying it such that it could be fed into the Grasshopper tool.

4 NEXT DEVELOPMENTAL STEPS

As with any automation tool, there are always additional features that can be added to refine and expand the current workflow. With continual global development of the Arup AdSec API, this will expand the functionality of the section analysis in Grasshopper whilst accelerating the process of running through larger datasets. Furthermore, with more sophisticated geotechnical plug-ins for Grasshopper in the pipeline, more accurate geotechnical analysis can be carried out as part of the workflow to further refine the design process.

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6 CONCLUSION

This case study proved how powerful and essential parametric workflows can be within engineering design. By identifying manual processes within our traditional workflows to automate, computational times can be dramatically reduced, up to 94% time saving in pile cross-sectional analysis computation time compared to traditional methods. This allows for more time for engineers to interrogate the inputs and outputs of each stage of the design process whilst further optimising the design presented to the client. In turn, savings in time and budget can be realised in addition to reducing the embodied carbon for cradle-to-gate of noise wall design.

7 REFERENCES

- Broms, B. B. (1964). “Lateral Resistance of Piles in Cohesive Soils.” *Journal of the soil mechanics and foundations division*.
- Broms, B. B. (1964). “Lateral Resistance of Piles in Cohesionless Soils.” *Journal of the soil mechanics and foundations division*.
- Crawford, R.H., Stephan, A. and Prideaux, F. (2019) *Environmental Performance in Construction (EPiC) Database*, The University of Melbourne, Melbourne.