

## USING DIGITAL INNOVATION TO AID DESIGN DELIVERY OF CUT AND COVER BOXES IN SEISMICALLY ACTIVE COUNTRIES

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**Abstract:** *The current project is a 5.7 km extension of the existing metro line in a highly seismic location. As part of this scheme, six underground stations will be constructed that will connect communities and the region.*

*The scope involved the design of cut and cover box structures in a highly seismic region that had varying geology, extent of liquefiable soils, external stakeholder's influence, large number of spectrally matched ground motions (30), anticipated future loading conditions and oversight developments, and the threat of future climate change. To consider all these variables within the design it was necessary to evaluate many design scenarios. It was estimated that almost 200 2D non-linear time-history finite element analyses were required for assessing the seismic and static load combinations at different design stages. From the onset, it was apparent that processing the associated quantities of data would be highly time and labour intensive. To meet the programme expectations of the design and build contract whilst delivering the design to high standards, a digital delivery strategy was employed.*

*The design involved using a series of calibrated 2D time-history analyses to identify critical timesteps and associated earth pressures to feed a 3D structural model. The strategy involved creating several digital innovations which would aid each stage of the design including scheduling, calibrating, running, extracting, comparing, and reporting the analyses. A framework of identifying, scoping, validating, implementing, and maintaining each digital tool was adopted to optimise its benefits.*

*The use of these tools resulted in an estimated saving of 40 work weeks. Moreover, the tools improved understanding of the soil structure interaction and visually presented the information which helped in communicating risks to various stakeholders. The automation enabled a more holistic design approach considering each element, often resulting in cost and carbon savings from design efficiencies.*

### Introduction

Seismic design is the process of designing structures to withstand the loading and displacement from earthquakes. It involves considering the effects of, ground motions, soil characteristics, and structural properties, on the safety and performance of the structure during an earthquake.

Fixed base seismic design is the most basic form of seismic design, which assumes the structure to be attached to the ground rigidly. A slight improvement is springs, either frequency dependent and independent, which provide flexibility and absorb seismic energy. A more advanced form of seismic design is to consider the complex interactions between the soil and the structure using soil-structure interaction (SSI) models which can be 1D, 2D or 3D. These models can accurately predict the behaviour of the structure during an earthquake for larger or more complex structures.

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A time history analysis is a type of SSI analyses which applies the ground motion to the bedrock and allows it to propagate up the soil and through the structure. This approach accounts for the stress and deformation development over the earthquake duration which can improve accuracy, but increases the complexity.

### Project Background

The digital innovations implemented in the seismic analysis of a 5.7km extension of a metro line in a highly seismic area is discussed in another accompanying paper in the conference ( Ghosh et al. 2023). The project included sections below ground and above ground sections, in urban areas and with cut cover boxes as well as U sections. The focus of the paper is obtaining the seismic demands on the cut and cover box structures, for a maximum and operating design earthquake return periods. The project had to consider varying geologies, extent of liquefiable soils, external stakeholder's influence, anticipated future loading conditions and developments, and the threat of climate change. Temporary works design was outside the scope but could impact the seismic response of the structure and had to be assessed. The seismic response was to be predicted using Spectrally Matched Ground Motions (SMGM) (10 crustal, 10 inslab and 10 interface).

### Analysis Methodology

The primary project objective was to identify the loads on the structure imposed by an earthquake which induces critical combinations of internal forces. For static design, a 3-D structural model was developed over several design stages with detailed structural elements however, the model was static and represented the soil using springs and pressures. To assess the soil structure interaction, 2D finite element time history analyses were used at several sections across a given structure. The loads at each section were stitched together to generate the load profile for the 3D structure. The complete design process is shown in Figure 1.

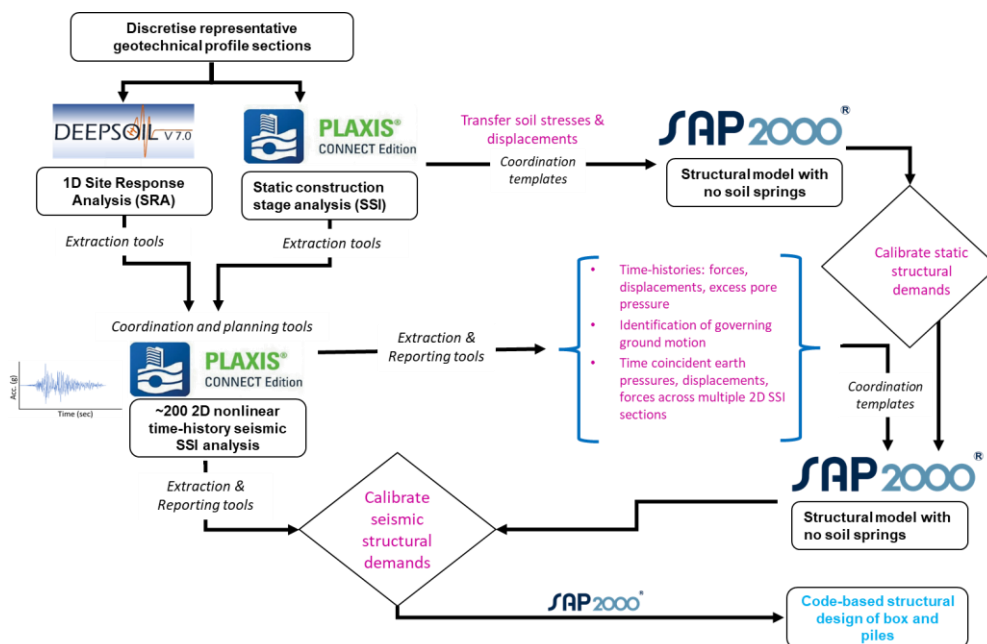


Figure 1. Seismic design flow chart

The scope required assessment of 30 SMGM for the maximum design basis earthquake and 20 SMGM for operating design basis earthquake. The structure was required to withstand the action of the mean motion. The analysis methodology was developed at a previous design stage and includes the following steps:

1. Discretizing the geology along each structure into representative sections
2. At each section assessing all SMGM in a decoupled (1D site response) analysis using DeepSoil to identify 5 representatives motions of each type (Inslab, Crustal and Interface).
3. Based on the preliminary mean motion assess the critical section/combination at representative section considering various parameters including construction (temporary

- support scheme), geometry, future (infrastructure and grade levels), surrounding infrastructure, external loads and surcharges and direction of shaking.
4. Analysing the critical combinations for all the identified motions in a dynamic PLAXIS 2D time history analysis and identifying the mean motions for each section and design motion for the structure.
  5. Identifying critical time steps for each section for the desired motions to provide equivalent static load profile for structural models.

**Challenges**

Table 1 details the challenges associated with running static and seismic (time history) analyses. The challenges listed were key motivators for the development of the digital innovations.

Challenge	Analysis Considerations	
	Static	Seismic
Determining the governing condition	Relatively simple to deduce from structure, oversite conditions, external influences, and loading. A few analyses may still be required to confirm this.	Natural frequencies of the earthquake, soil and structural elements will all vary, so determining the governing condition requires numerous analyses.
Running the analyses	Models take up to 2 hours to run, involve less time to set up.	Models take up to 24 hours to run, involve more time to set up.
Extraction and post processing the data	Data from a single instance in time with the critical loads and displacements.	Results from thousands of time instances, critical loads and displacements must be deduced at specific time instances.

*Table 1. Static and Seismic Approach Comparison*

**Coordination and planning**

A critical aspect of the project was resource and data management. The key challenges were twofold: completing all the of analyses within the given time frame and efficient-coordination and data exchange between the structural design team and the seismic analysis team. These challenges were addressed by the implementation of the Gantt chart plotting tool and the data sharing templates, respectively.

**Gantt Chart**

The time taken for each 2D analysis to be set up and run varied from 7 to 48 hours, and the number of computers available was a limited. Multiple analyses could not be run simultaneously on one computer and whilst analyses could be scheduled to run sequentially this option was limited by the local memory on the computers. By limiting computer downtime through effective planning, project delivery can be accelerated. To achieve scheduling benefits, an accurate prediction of analysis duration was a prerequisite. The other requirements were for the schedule to be easy to adapt and interpret.

A Gantt chart plotting tool using Excel was developed to plan the running and extraction of models. The relationship between the duration of the Earthquake motion and duration of analysis was established from experience then allowances were provided considering the required time for model creation and results extraction. This meant that for a given analysis only a start date was required, the end date and duration would automatically be determined. Conditional formatting would then be used to create a Gantt chart. A progress tracker would be manually updated over the course of the analysis and reflect the real time progress. This culminated in an easily interpretable visual representation of the planned work/progress as seen in Figure 1.

Determining the critical path, managing personal and computer resources, updating progress, and setting the schedule dates were still manual undertakings. Consideration was needed for the demand on team members in the analysis process (e.g., Multiple analyses set to finish at the same time would require multiple available team members to conduct the results extraction) and to avoid scheduling any manual work out of office hours (e.g. It was useful to set long analyses to run over the weekend, but extraction would not be able to take place until the weekdays).

*Templates and data sharing*

Each seismic analysis run would produce load and displacement time histories for the structure. The structural analysis used static pressures from results corresponding to instantaneous times, at which the greatest internal forces or strains were present in each structural element during the earthquake. These instantaneous times are key time steps. Only data from the key time steps would be shared with the structural design team to simplify the sharing process.

Standard data sharing templates were produced to ensure only data at the key time steps was shared with consistent formatting and nomenclature. Keeping formatting consistent enabled the structural team to input data into the model by a standard methodology, reducing the likelihood of human error and expediting the design process.

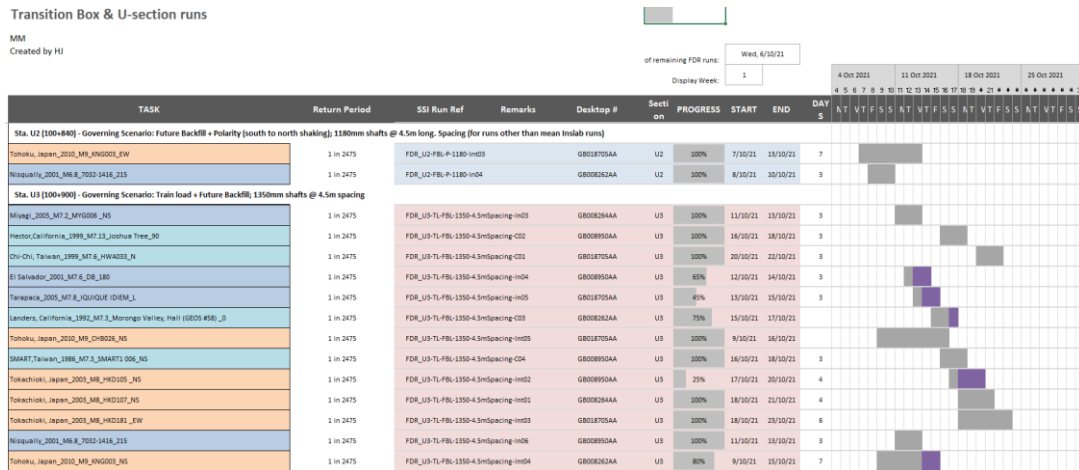


Figure 1. Automated Gantt Chart Plotter

Data Extraction and post processing

Seismic events can have significant impacts on the built environment and its occupants. It is crucial to understand the internal forces and demands acting on the structural elements. However, extracting and mapping this information is a challenging and time-consuming task that requires a significant amount of data processing. This section presents two tools that can aid in this process by extracting and plotting 1D SRA results, and time history plots in relevant locations.

The substantial number of anticipated SSI analyses that needed to be considered meant that from the onset the plan was to automate the data extraction process. Even prior to the coupled analyses, the number of simplified decoupled soil column (1D) site response analyses imposed a need for the project to adopt digital innovations.

*1D SRA (1 Dimensional Site Response Analysis) Visualizer tool*

1D SRAs were conducted using the software DeepSoil, that would output the result of each time history analysed into a different excel sheet. This meant for each analysis case there were 30 separate excel sheets produced with a total of over 850 produced. The tool was driven by a need to compile, visualize, holistically compare and interpret results.

The 1D SRA Visualizer tool, based on Python, was a data extraction tool with visualization and reporting capabilities. The tool had a graphical user interface (GUI) aimed to be straightforward and easy to use which also produced high-quality, detailed plots automatically of the type shown in Figure 2. The tool compared shear wave velocity, peak ground acceleration, and shear strain profiles between 1D SRA and Finite Element results. These plots served several purposes including:

- Allowing quick understanding of ground behaviour under seismic action
- Calibration of finite element models
- Deciding initial motions for SSI analysis, 5 motions of each type were selected to represent behaviour of all 30 motions.

A realized benefit of the data visualizations is that engineers could easily apply judgement, often resulting in reduced analytical efforts. An example was, for some soil columns the interface motions had comparatively smaller displacements and accelerations from a site response

analysis. This pattern was easily recognized in the plots, reducing the number of 2D analysis from 15 to 11 (10+1). One interface motion was still analysed to verify that the presence of the structure did not create drastic resonance effects.

In addition to extracting and producing detailed high-quality 1D SRA results, the tool also provides, maximum frequency-controlled discretization. This functionality was incorporated to automate the creation of building of the 1D soil column. These functions significantly accelerate the calibration exercise, potentially increase its precision, enhance results interpretation, and contribute to decision-making. The discretization functionality saves time and enables users to dictate the visualization of the layers whilst simultaneously developing the inputs for the analysis, ensuring a coherent set of results is produced as seen in Figure 2. Finally, the tool was developed with intent to reuse on different projects.

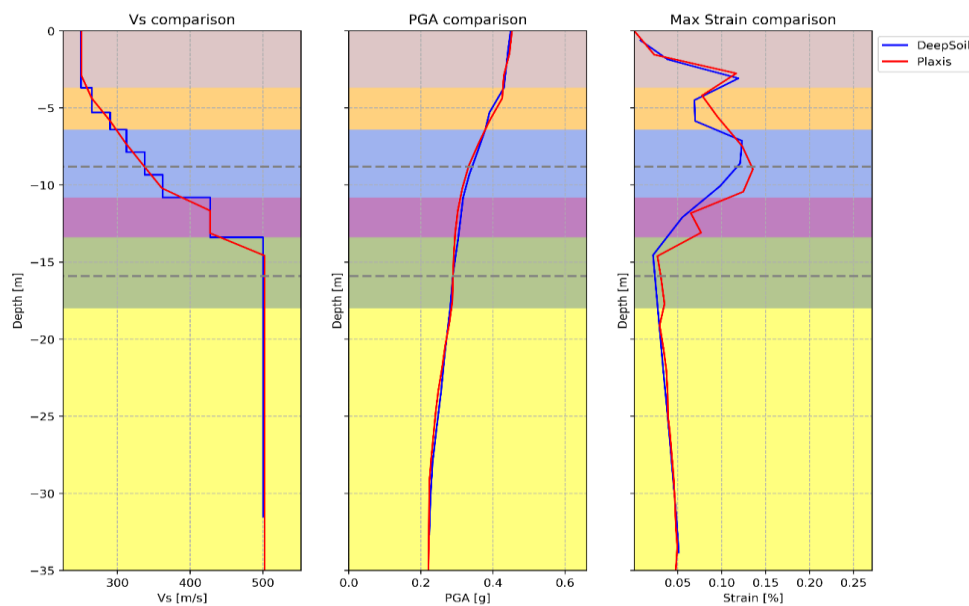


Figure 2. Outputs from 1DSRA visualizer tool calibration functionality PLAXIS with DeepSoil

#### Time history extraction tool

A vast amount of data is generated with a time history analysis, presents multiple problems. A typical time history analysis for the project was about 50GB of data which needed to be extracted in a manner which was easy to manipulate. Excel is typically used to manipulate and process the data e.g., find max/min. This process would need to be repeated for each numerical analysis. PLAXIS 2D has Python integration, which was a major advantage conversely, PLAXIS stored the outputs of the analysis in large databases which had to be searched to extract the desired outputs. The search would take significant amount of time to manual extract the results from the software would take 8-10 hours, with manual inputs every 10-15 minutes. A multitude of methods were used to expedite the extraction process some of which are:

- Only extracting relevant information, reducing the amount of searching
- Having multiple instances open, extracting different desired outputs simultaneously
- Pre-process points can be defined in PLAXIS, creating a separate database which is faster to search in. However, only certain data types can be pre-processed e.g., internal forces cannot be pre-processed but displacements from the same nodes can be.

Overall, this reduced the processing time to 4-6 hours per analysis, even with the efficiency gains across the over 200 analysis the total extraction time was not acceptable. To aid in the extraction multiple Python-based extraction scripts were developed. The different scripts addressed the different structural layouts and several types of desired outputs. The tool assists in finding critical time instances by extracting displacement and force time histories at specified locations. Timesteps will be specified in the script which would extracts results along the entire structure and produce a set of 1D plots.

The tool significantly accelerates data extraction, eliminates the need for repetitive manual extraction, and reduces the risk for human error, thereby enhancing health and safety. The

presented extraction tools offer significant benefits to the time-consuming and challenging task of extracting and mapping structural demands during seismic events. These tools enable faster and more holistic extraction of analysis data, which can help in decision-making and optimizing designs. The maximum benefit is achieved from the consistent manner of the results which was produced for the 162 SSI analyses, eliminating ambiguity when transferring results between teams. The tool reduced the extraction time from 8-10 manual hours to only 20 minutes (the script will continue running without input for 4-5 hours). The script could also work overnight, across the weekend and on holidays once set up, significantly accelerating the program.

**Interpreting and reporting**

When dealing with projects that involve enormous amounts of data, it is crucial to present the data in a format that is easily interpretable by people. Data visualisation is a field which incorporates principles from psychology, statistics, and graphic design. The field commonly utilizes charts, graphs, and other visual aids to help condense the data and make it more understandable for people. Data visualisation leverages visual processing of the brain which studies have shown to be one of the brain’s most dominant capacity. Taking advantages of visual processing to quickly find patterns, trends and compare groups or quantities is the essence of data visualisation. This can be observed in Table 2 and Figure 3, it is much easier to discern trends (e.g., which is greatest) and compare the groups with Figure 3. However, it is equally important to strike a balance between presenting enough information without overwhelming the audience. Information overload can lead to decreased decision quality thus, even when using data visualisation, it is essential to condense the data. The most common technique to condense information is filtration which allows to group or omit data, as necessary.

Group	EI Salvador RF 180	Miyagi NS	EI Salvador RF 90	Nisqually 215
Max Bending @ -3.5m (kN.m/m)	-658.16	-753.21	-629.56	-687.85

Table 2. Example data set in table format.

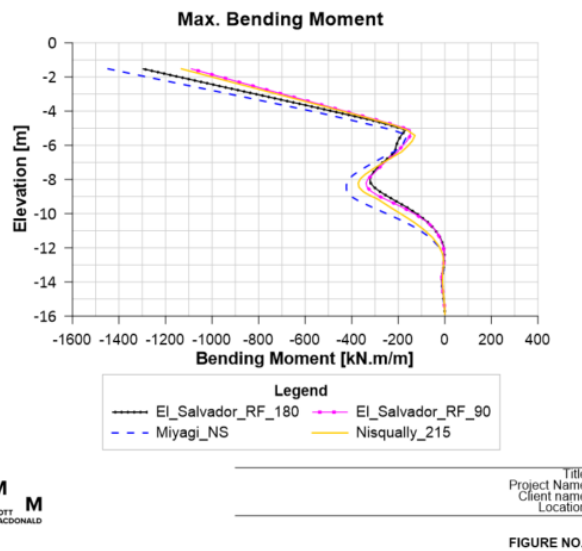


Figure 3. Example data set in graph format.

*Graph plotting tool*

Results from the 2D non-linear time-history SSI needed to be plotted graphically to present the loads and displacements from the work undertaken in the seismic design report. The following graphs were required in sequence:

1. Comparison of load envelopes of structural members under unique design scenario using preliminary mean motion
2. Comparisons of the load envelopes of structural members under representative ground motions to identify the design ground motion.
3. Load and displacement time histories to identify the key time instances of the design ground motion.



4. Loads and displacements along structural members at the identified key time instances to present the seismic design loading.

The data for each box section resulted in 600 plots per section, all of which needed to be produced (and re-produced where changes were needed) quickly and with consistent formatting. The plotting software Grapher was utilized to automatically produce and modify graphs “en masse”.

Within Grapher, templates to plot the aforementioned graph types for each structural member (e.g., base slab, piles) were produced. Templates were then copied and adapted for the structural designs of each analysis section. Visual Basics scripts were produced alongside each template which would “pick up” and plot data linked to specified variables from results file and a title block file by utilizing several nested loops. Once templates and scripts (automated graph plotter tool) had been made, it took approximately 15 minutes to setup and 1 minutes to run a template group (typically 16 graphs per group). An example of the graphs produced is shown in Figure 3.

Automated graph plotting provided several benefits, such as uniform and consistent plotting, easy mass production, and the ability to change multiple plots automatically without having to reproduce work. Once these were developed, templates and scripts were simple to use and adapt for each graph type. Overall, it saved a substantial amount of time compared to manual plotting. However, it still required a thorough QA/QC protocol to spot errors/mistakes and an internal log of analysis runs for post-processing.

#### *3-dimensional displacement visualization tool*

The project utilized 2D numerical models to evaluate the impact of seismic action on the structure, but these models had limitations due to simplifications, such as the use of 2D sections that might exclude 3D behaviours. To address this limitation, a 3D structural model was developed, but it did not include soil and applied seismic action as an instantaneous static pressure. Earth pressures were obtained perpendicular to each surface of the permanent structure at critical time steps from the 2D SSSI model, and a pressure load surface was developed based on the earth pressures from all the 2D sections and applied as an instantaneous load to the structural model. Multiple time instances were selected to reflect the greatest internal forces of each element. Each time instance would be reflected as an additional load case in the static structural model.

However, there was a risk of neglecting strain induced forces caused by the differential movement of two adjacent sections e.g., two sections moving in opposite directions resulting in large stress in the wall connecting the sections. The relative movement of 2D sections presents a 4D problem, 3 spatial domain and 1 time domain as at each time instance in a time history analysis a different displacement will occur on the structure. Typically, reducing the distance between adjacent sections (which requires additional analysis and additional instantaneous load cases) or using a 3D analysis could mitigate the problem. An alternative solution that was adopted was to identify time instances where the structure experiences differential movements and use these as additional load cases in the static structural model.

Even with all the data associated with the movement of the sections it is difficult to understand the behaviour of the structure. Trying to decipher at which time instances the greatest relative movements occur just from data is exceedingly difficult. *Data visualization was used to create charts that show the relative displacements between sections of the structure at different time instances* (see Figure 4). *Multiple charts were produced for each time instance, one for horizontal displacements and another for vertical displacements. A script was developed to generate the charts using displacement data from several nodes in each section as inputs. The script used the same data format as the previously discussed template to facilitate data transfer between tools.* The 3-dimensional displacement visualization tool had a 4-stage process which was repeated for each time step whilst producing the charts listed as:

1. Data sorting (separating data vertical and horizontal displacements for each time step)
2. Transformation, the displacement at each section were recorded in a local orientation, this displacement had to be transformed to a single global orientation system to compare.
3. Scale the data appropriately to allow the visualisation
4. Plot deformation data against undeformed shape.

A chart at each time step would result in information overload e.g., a 60 second time history with a timestep of 0.02 second will result in 3000 charts. This is for a 1 motion for 1 load case, just reading, opening, and closing all these charts would strain computers. To remedy this, the tool would produce an animation by changing the deformation in each frame to the deformation at

each time step, sequentially. The animation speed could be specified by selecting number of frames per second. For the same motion and load case the tool would normally produce a 2-minute video which is easier to interpret compared to 3000 charts. The tool also utilised filtration techniques to allow users to interrogate the data. The interrogation features of tool include a drop down to select time step, a manual scale override (select the scale), and a section filter to allow selection of desired sections. These features made interrogation straightforward and were based on non-script excel functionality e.g., pivot tables, which meant processing would be instant. Some limitations of the tool include:

- Required familiarity e.g., screen recording had to be initiated manually prior to running script, and coding knowledge was required to produce the animations but not interrogation
- RAM intensive using less powerful desktops resulted in glitches in the animation
- Can be misleading as it only shows the displacements of selected nodes and represents elements between the nodes as rigid. These elements will instead behave flexibly and have local deformations. This approach should not be confused with 3D analysis.

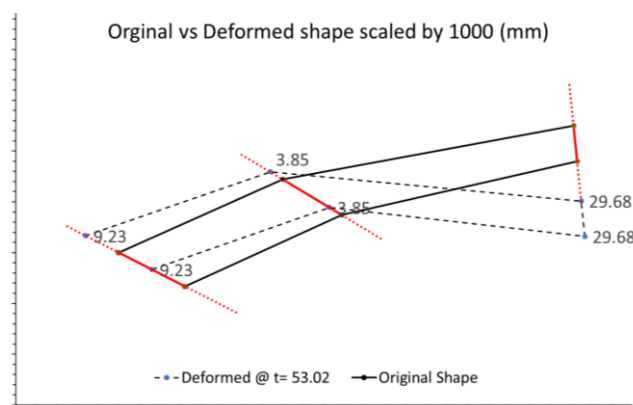


Figure 4. Deformed shape @  $t=53.02$  (example data set).

#### Direct results comparison tool

One of the key challenges in the project was to identify the governing scenario under seismic actions considering the factors mentioned in the introduction. These factors not only had an impact on the stresses within the structure and/or soil but could also impact the natural frequencies of the systems. This could result in a different condition being governing for static and seismic load cases, furthermore the presence of liquefiable soils added complications. The governing conditions were determined by comparing the outputs of several analyses however, the outputs must be compared holistically. Finally, the scope required the design to satisfy loading from the mean motion. To identify the mean motion, a comparison of the various SSI analyses results was required.

The comparisons could be conducted manually, using the templates which automatically produce summary tables, and plots. Alternatively, a tool which would compare templates and build comparison tables and comparison plots can be used. To create a complete and formatted comparison of all the charts, would require 4-5 hours for each comparison if done manually. Typically, to reduce the amount of time for each comparison, only selected items would be compared, however this could risk missing out some information. The direct comparison tool was created to generate a full comparison between two template excel sheets, keeping consistent formatting and producing summary tables. The tool takes advantage of user forms to create a GUI making it user friendly.

The direct comparison tool was developed such that it could be used on any project which has a consistent template and worked in a 4-stage process as shown in Figure 5. Two different comparisons methods/options were developed to meet the unique needs of the project.

1. Internal referencing: would copy all the data from the templates and produce a comparison. This would take 5-7 minutes and could be shared/interrogated as the raw data was contained within the comparison.
2. External referencing: this method only contained the comparison plots which referenced data in the original templates. This would take 1-2 minutes and required less computing power however, it could not be shared or interrogated directly.



Upon reflection a few improvements were made through the project lifecycle such as:

- The summary table generations were made optional such that comparisons of non-project specific templates could still be made without error.
- Limits were introduced on the number of open excel sheets to prevent crashes
- Guidance document was created for common errors e.g., file path exceeds character limit.

One of the key challenges for the tool was allowing the script to be used on different templates and projects whilst also meeting each requirement of this project. One such challenge was the renaming of data series for the comparison plots. For each plot in different templates the series title will reference different cells. Originally it was proposed for a selection window to appear for each instance where a data series required renaming. Unfortunately, the solution required more user interaction than desired, specially, when comparing large amounts of charts. To overcome the challenge, the renaming functionality was incorporated into the template to be used prior to running the direct comparison tool. Enabling both the project specific functionality and the tool to remain non project specific. Retrospectively, a few aspects could still be improved including:

- Renaming functionality could be developed as project specific “Add-ins”
- A limit was imposed on the number of open excel books to avoid the code crashing. A better alternate incorporated in other tools (1DSRA extraction tool), was to force close irrelevant open excel workbooks.

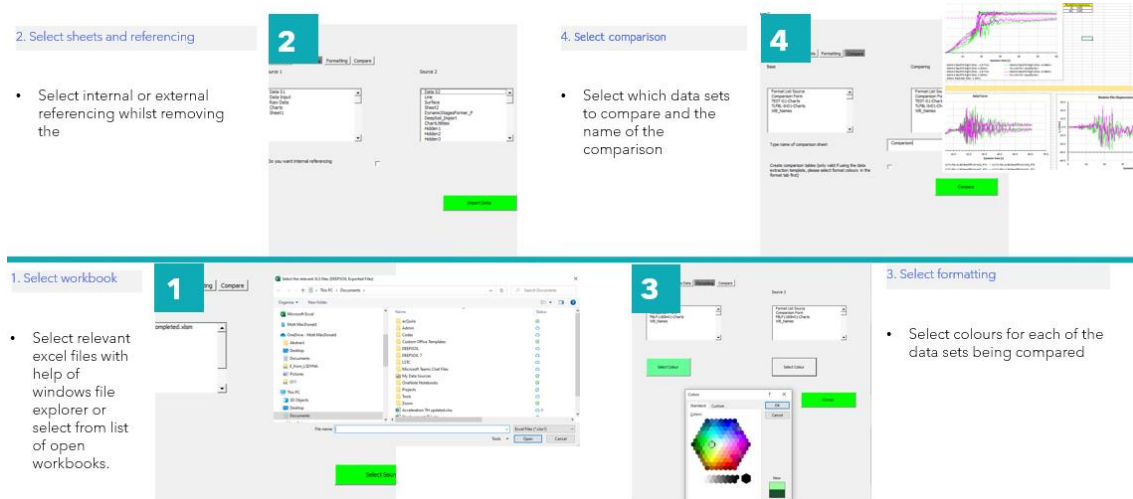


Figure 5. The 4 stages of the direct comparison tool

## Discussion and conclusions

### Lessons Learnt

When commencing tool development, it is advantageous to consider the availability of pre-existing and readily available tools, apps, and templates that can be adapted to suit the specific project needs. For instance, offerings such as Gantt chart template containing conditional formatting for visualisation can expedite the development process. Additionally, developers should evaluate development aids such as script recording tools and advanced AI to support and accelerate the development process.

Furthermore, to ensure the development of high-quality tools, it is essential to establish a robust quality assurance and quality control process. Engineers must have a deep understanding of both the engineering and scope of the tool. Initially, manual completion of tasks can familiarise engineers with the process and expected results. To enhance adaptability in outputs and processes, it is recommended to make outputs editable such as exporting graphs in PDF form, which could allow for manual text edits such as anonymising charts for a paper (Figure 3).

It is important to allocate sufficient time and resources to tool development at the outset of a project. Although the requirements will vary based on the experience levels of team members, investing in tool development is also an investment in upskilling team members for future projects. Therefore, careful consideration and planning are necessary to ensure the success of tool development initiatives.

*Conclusion*

Although the primary driver for the development of each tool was potential time savings, there were many other benefits of employing a digital strategy. Table 3 presents the development time, total time saved, and benefits gained on the project by employ the tools. Overall, not only does digital solutions offer considerable time savings but also enhance the capabilities of the engineers to deliver an optimized design.

<b>Tool/Script</b>	<b>Deliverable</b>	<b>Justification/ Benefits</b>	<b>Develop- ment time</b>	<b>Time saved (Manual – Automated)</b>	<b>Challenges</b>
Coordinated Templates	Cross discipline sharing	Consistency Compatibility	10 hours	50 hours	Human error, QA/QC still critical
Gantt Chart plotter	PLAXIS analysis schedule	Time and resource saving	5 hours	165 hours	Balancing the plan with available resources
DeepSoil 1D SRA Result Extraction	1D site response comparison	Time saving Reducing human error	75 hours	120 hours	Requires experience in coding and tunnel design
Python 2D Result Extraction	200 FE model results extracted	Time saving Reducing human error	75 hours	975 hours	Over reliance and easy to not interrogate the data
3-D displacement visualization	Improved under- standing of 3D	Improved interpretation	15 hours	90 hours	Required excessive preparations prior to running script
Direct Result Comparison	20+ formatted comparison	Improved interpretation	22.5 hours	70 hours	Sharing and referencing
Graph Plotting	Consistent plotted 600+ graphs	Time saving Consistency	50 hours	300 hours	Learning curve for script writing, human error, QA/QC critical

*Table 3. Tool Benefit Summary*

This project was large scale which created a mandate for the project team to develop tools to efficiently deliver within the desired time frame. The project also enabled and encouraged the development of such tools however, it is imperative for the benefits to outweigh the development costs. Recognizing when to develop and implement tools is key to optimizing benefits. Table 4 provides recommendations when the tools similar to those discussed in this paper should be implemented.

<b>Tool/script</b>	<b>Recommended point of implementation</b>	<b>Pre-requisites/ learning</b>	<b>Reusability</b>
Coordinated Templates	At any scale	Basic excel skills	Templates can be adapted
Gantt Chart plotter	Running > 10 analyses	Basic excel skills	Easily adaptable for other time history analyses, limited use otherwise
DeepSoil 1D-SRA Results Extraction	5 or more site response comparison	Intermediate coding skill	Yes, no adaptation needed if the same software is used.
Python 2D Dynamic Analysis Result Extraction	10-15, 2D SSI analysis (dependent on how much data needs to be extracted)	Advanced coding skills	Requires coding competence but is adaptable for similar projects using the same software
3-D displacement visualization	Situationally dependent, when possible	Basic coding and advanced excel skills	Limited- Will require new template for each project
Direct Result Comparison	5+ comparisons adapt functionality to scale	Advanced coding skills	Made for reuse
Graph Plotting	Plotting >5 graphs with the same base template	Beginner coding skills, development aids can be used	Scripts and templates easily adapted for plotting different data sources

*Table 4. Tool Recommendations*