SLATT UNDERGRADUATE RESEARCH FELLOWSHIP FINAL REPORT

SCHOLAR NAME:	William Tjaden
FACULTY ADVISOR:	Yazan Khasawneh Ph.D, P.E.
PROJECT PERIOD:	Spring Semester 2021
PROJECT TITLE:	Long Term Performance of Wind Turbine Foundation through Numerical Modeling
CONNECTION TO ONE OR MORE ENERGY-RELATED RESEARCH AREAS (CHECK ALL THAT APPLY):	**( ) Energy Conversion and Efficiency** **( ) Sustainable and Secure Nuclear** **( ) Smart Storage and Distribution** **( ) Transformation Solar** **( ) Sustainable Bio/Fossil Fuels** **(x) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS

Summarize your research goals and provide a brief statement of your accomplishments (no more than 1-2 sentences). Indicate whether you were able to accomplish your goals by estimating the percentage completed for each one. Use the next page for your written report.

RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Evaluating Long Term Performance of Wind Turbine Foundations Through Numerical Modeling	Start up model for a simple footing with hypothetical loading and soil conditions	10%

RESEARCH OUTPUT

A plot with change of rotational stiffness with time

CATEGORY	INFORMATION
EXTERNAL PROPOSALS SUBMITTED	In preparation
EXTERNAL AWARDS RECEIVED	
JOURNAL ARTICLES IN PROCESS OR PUBLISHED	
BOOKS AND CHAPTERS RELATED TO YOUR RESEARCH	
PUBLIC PRESENTATIONS YOU MADE ABOUT YOUR RESEARCH	
AWARDS OR RECOGNITIONS YOU RECEIVED FOR YOUR RESEARCH PROJECT	
INTERNAL COLLABORATIONS FOSTERED	
EXTERNAL COLLABORATIONS FOSTERED	Dr. Muhannad Sulieman (Lehigh University)
WEBSITE(S) FEATURING RESEARCH PROJECT	
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	

RESEARCH EXPERIENCE

I got to learn about finite element and dynamic nonlinear analysis, which is the start of my Msc research in the Fall 2021

FINAL WRITTEN REPORT

Introduction

The objective of the project is to utilize dynamic finite element modeling to capture the response of the wind turbine foundations to a large number of cyclic excitations generated by the wind loading. The accumulation of small plastic strains will result in degradation of the rotational stiffness of the soil supporting the wind turbine foottting. The degradation of the foundation soils stiffness will result in a shift of the wind turbine natural frequency, bringing it closer to the operating loads frequency (Khasawneh et. Al., 2021). If the natural frequency of the wind turbine matches the operational load frequencies, the structure will experience amplification/ resonance thus amplifying the vibrations experienced by the structure, which will lead to additional loss of foundation stiffness that will result in deviation from the serviceability requirements.

The modeling software used is Bentley System's PLAXIS 3D finite element analysis software. The software allows the modeling of both the structural elements of the foundation and the surrounding soil to captures realistic dynamic and static soil-structure interaction.

Soil Calibration

The data for the soil calibration is provided by Dr. Muhannad T. Suleiman from Lehigh University. Initial calibration of the soil models highlighted in a significantly lower angle of internal friction than what was expected for the soil type that was tested. The calibration yielded results closer to organic peat rather than the sandy-clay mixture that was actually tested. These inconsistencies highlight the need for the data to be reprocessed. While the data undergoes reprocessing, a hypothetical and simplified soil model was used to move forward with the project. Figures 1 1through 3 show the calibration that was achieved at different effective confining pressures.

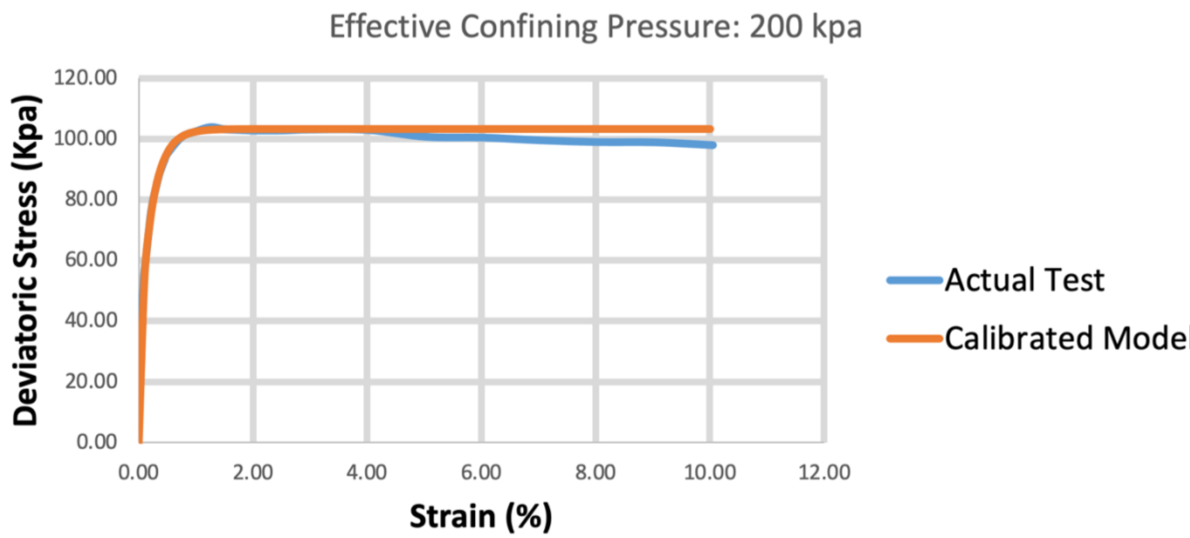


FIGURE 1: SOIL CALIBRATION @ 200 KPA

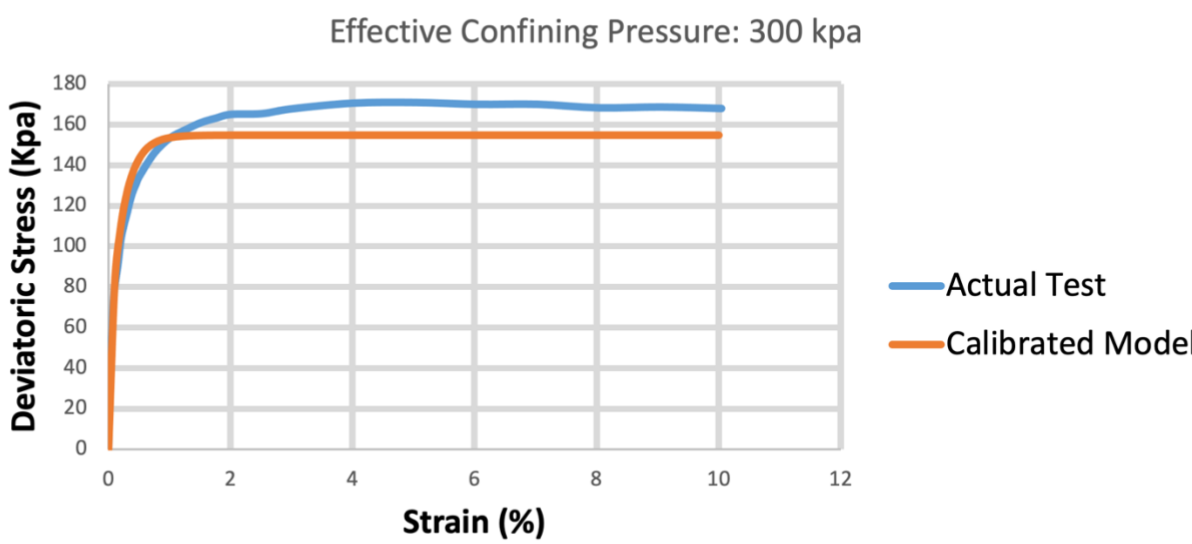


FIGURE 2: SOIL CALIBRATION @ 300 KPA

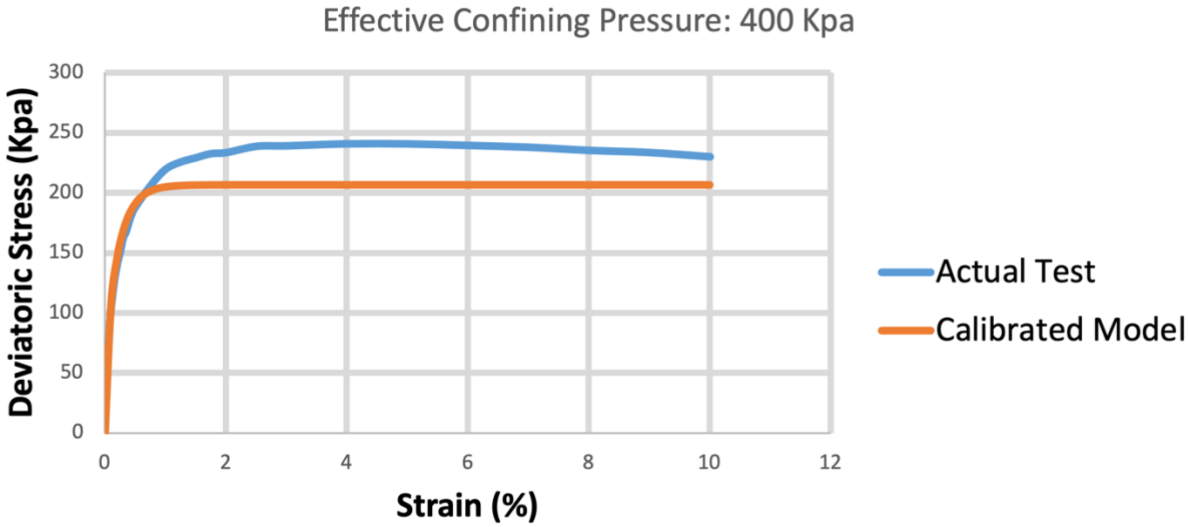


FIGURE 3: SOIL CALIBRATION @ 400 KPA

Model Elements

The model simulates three distinct elements that are critical for the model to simulate actual wind turbine foundation. These elements are loading scenarios, soil characteristics, and foundation elements. There are two forms of loading that replicate actual loading on wind turbine foundations. Figure 4 shows a simplified rendition of the loading scenarios. The overturning moment was modeled by two points loads placed on equidistant points on the foundation (coupled loading). The coupled points loads were placed in equal but opposite directions to stimulate the overturning moment. The second point load simulated the weight of the wind turbine tower and mechanical hub as well as horizontal sliding force. The overturning however plays a more significant role in the degradation of the rotational stiffness. The design loads the model experienced were not factored as unfactored loads are more indicative of what the structure experiences throughout its lifetime (for serviceability). Extreme loading scenarios will be investigated in future models to inform future design of their possible implications.

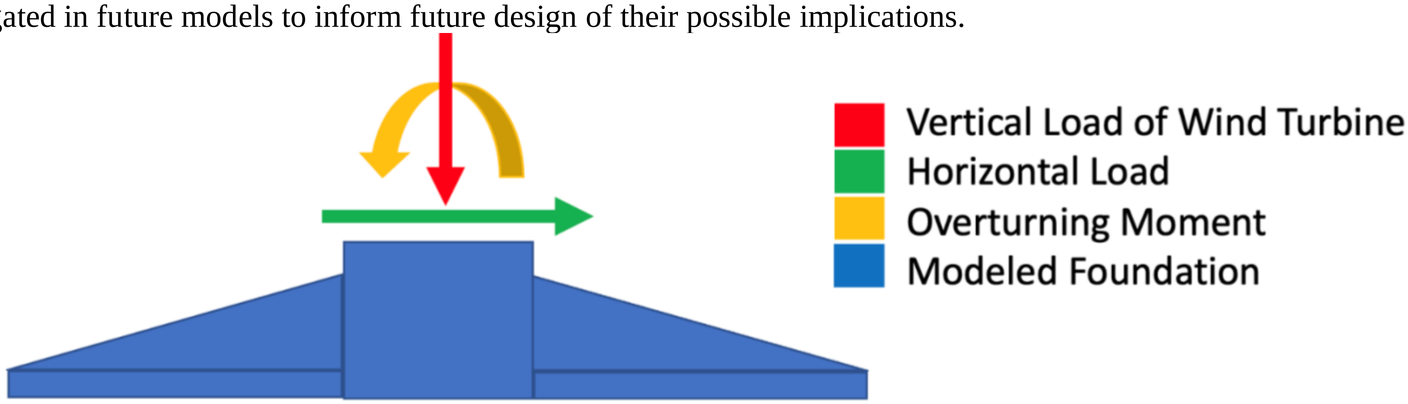
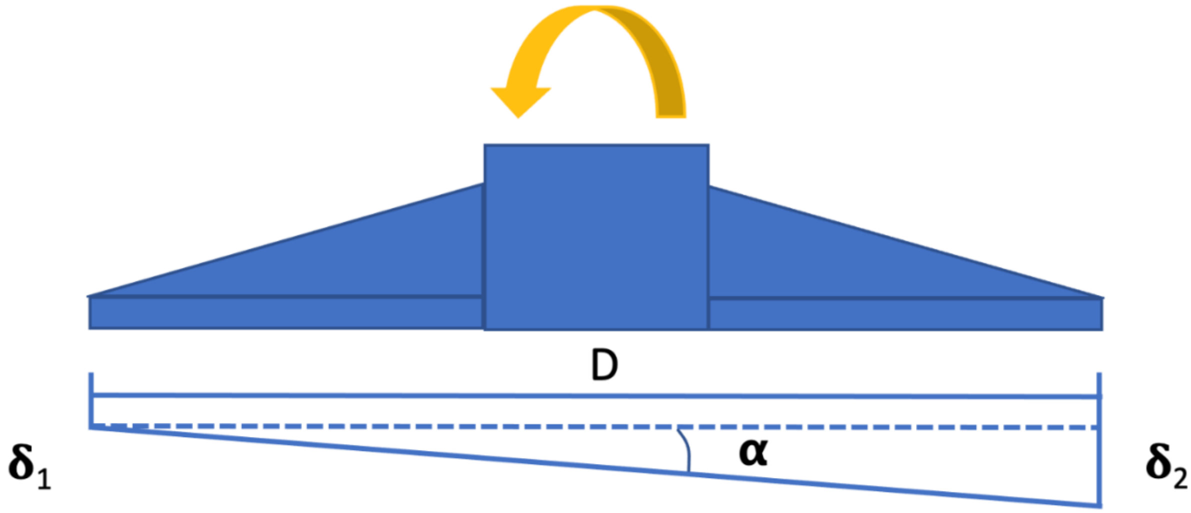


FIGURE 4: LOADING CONFIGURATION

Rotational stiffness is a ratio of the moment applied to the wind turbine divided by the rotation angle due to the applied moment. The moment applied remains the same but overtime the angle achieved gets greater and greater due to the reduction of the foundation soil stiffness. Equation 1 & 2 in Figure 5 represent how the rotational stiffness is calculated. The blue figure is indicative of the modeled gravity foundation. Alpha is the angle created from the rotation of the foundation. The increase in alpha due to greater settlement on either side subsequentially decreases the stiffness(K_θ).



$$\text{Equation 1:} \quad \alpha = \tan^{-1}\left(\frac{\delta_2 - \delta_1}{D}\right) * \frac{\pi}{180}$$

$$\text{Equation 2:} \quad K_\theta = \frac{M}{\alpha}$$

FIGURE 5: ROTATIONAL STIFFNESS DIAGRAM

The foundation was modelled as a plate element within PLAXIS. The plate was given properties similar to that of structural concrete. The thickness and modulus of elasticity govern the stiffness and rigidity of the plate. A less rigid plate resulted in an uneven pressure distribution. The foundation is shown in Figure 6 as the blue circle.

Figure 6 shows the finite element mesh for model. The finer the finite element mesh is the more computational time, for the purpose of those initial runs a coarser mesh was selected, more refinements to the model will be required in the future during the course of the research. The foundation and the soil immediately surrounding the blue plate are finer than the soil far from the footing..

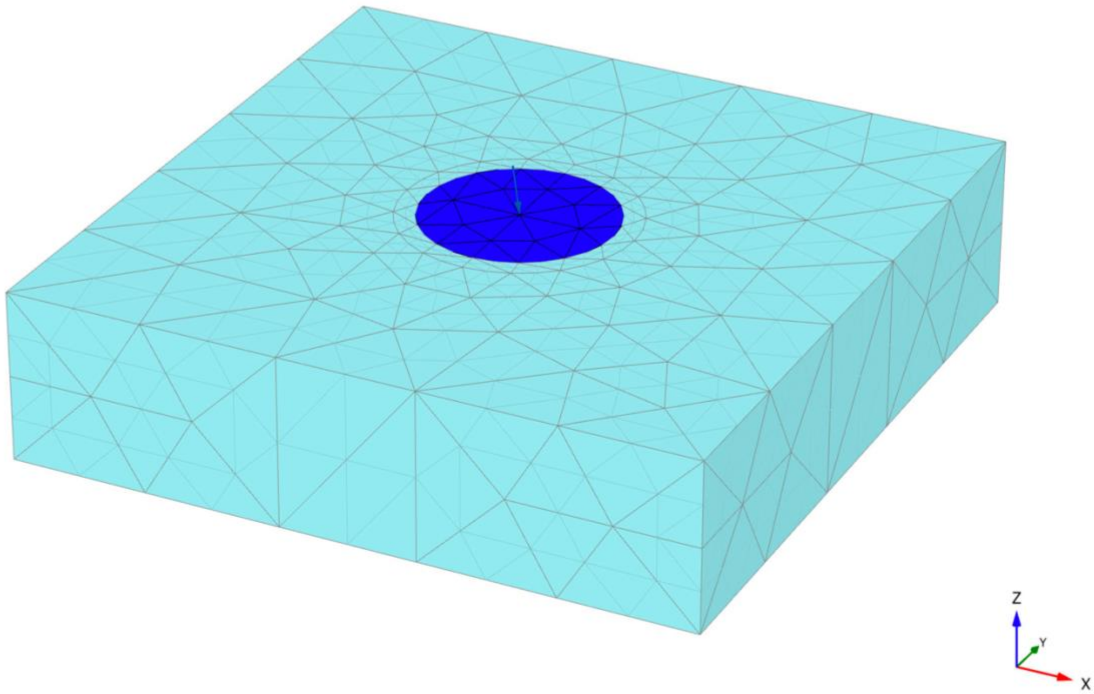


FIGURE 6: FINITE ELEMENT MESH

Limitations

The limitations of the current model are as follow:

- While the model does work under current conditions, the computational time it very long to capture actual long-term stiffness degradation (design life of the WT structure). Therefore, a supercomputer is needed in order to simulate dynamic loading for 25 years
- This model only analyzes one of type foundation. The final research product will incorporate deep foundations.

Results

The results demonstrated the degradation of the rotational stiffness with number of cycles (even though the model was run with only 90 minutes worth of cycles). Figures 7 and 8 show that small amplitude plastic strain accumulations lead to a degradation of the foundation rotational stiffness over time. The stiffness will degrade until it reaches a close to "steady state" with much smaller rate of degradation when compared to the initial degradation. Figure 9 shows the shear strain the soil experiences at the edges of the foundation and under the foundation. Figures 10-11 show the displacement field in the vertical direction and the displacement concentration locations.

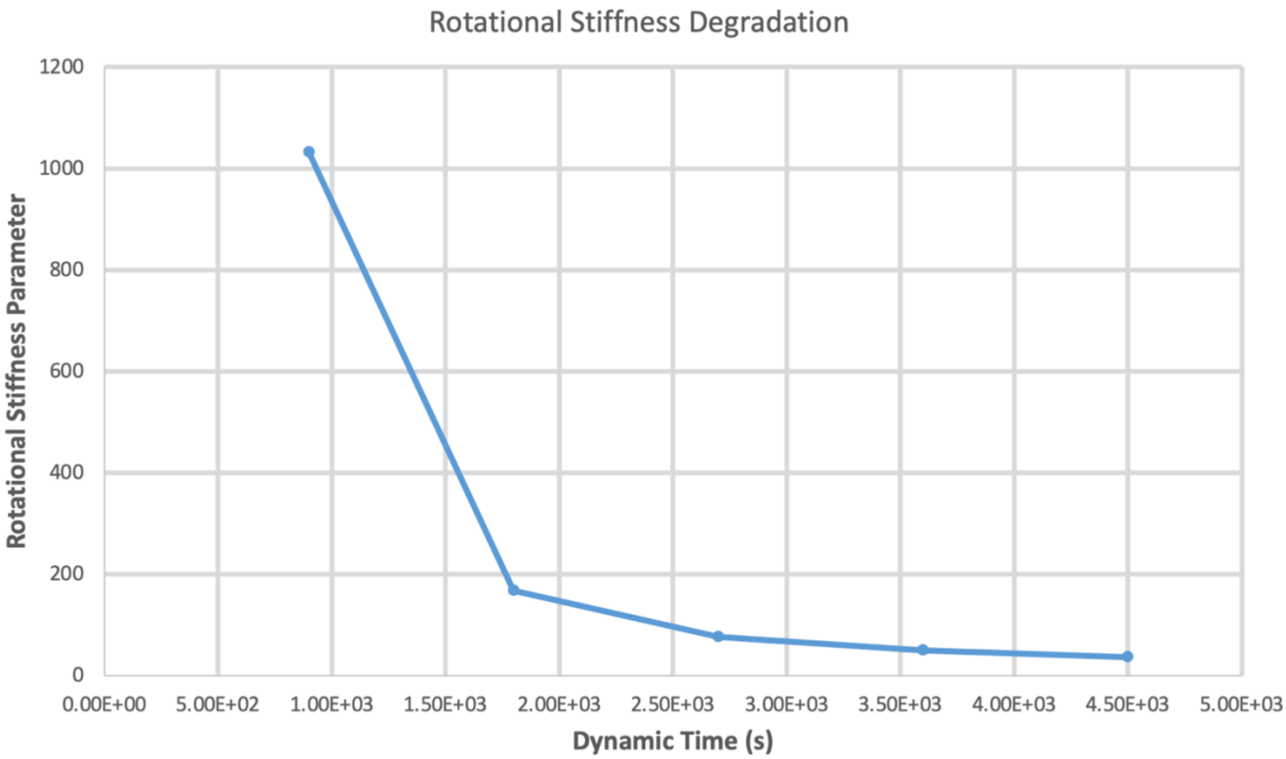


FIGURE 7: ROTATIONAL STIFFNESS DEGREDATION

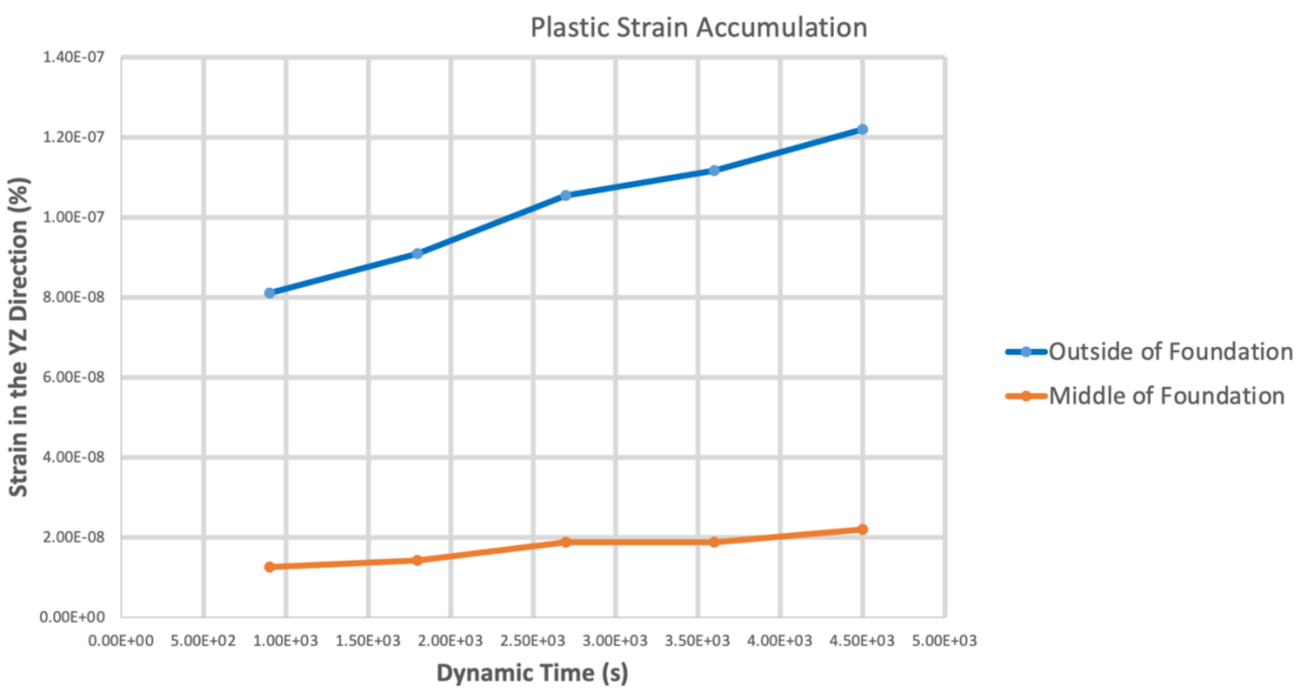


FIGURE 8: PLASTIC STRAIN ACCUMULATION

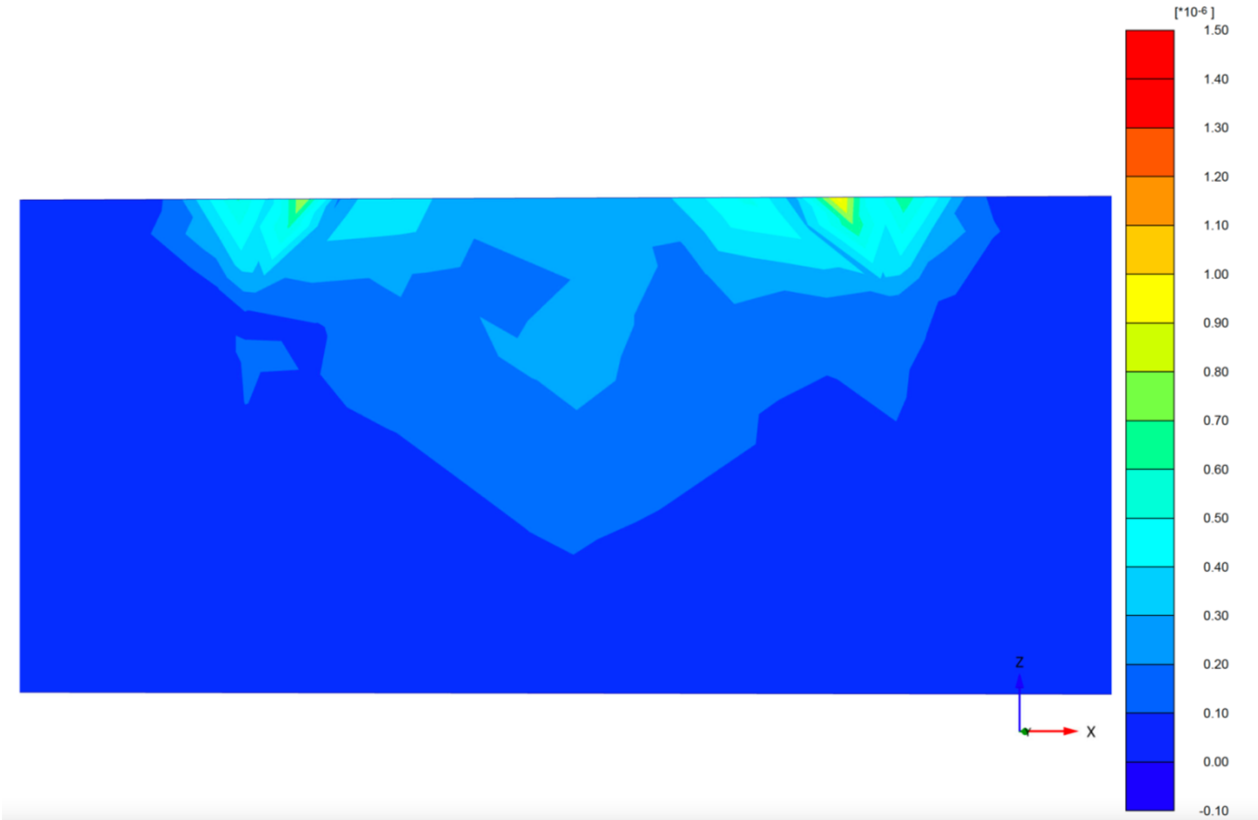


FIGURE 9: SHEAR FORCE CONCENTRATION

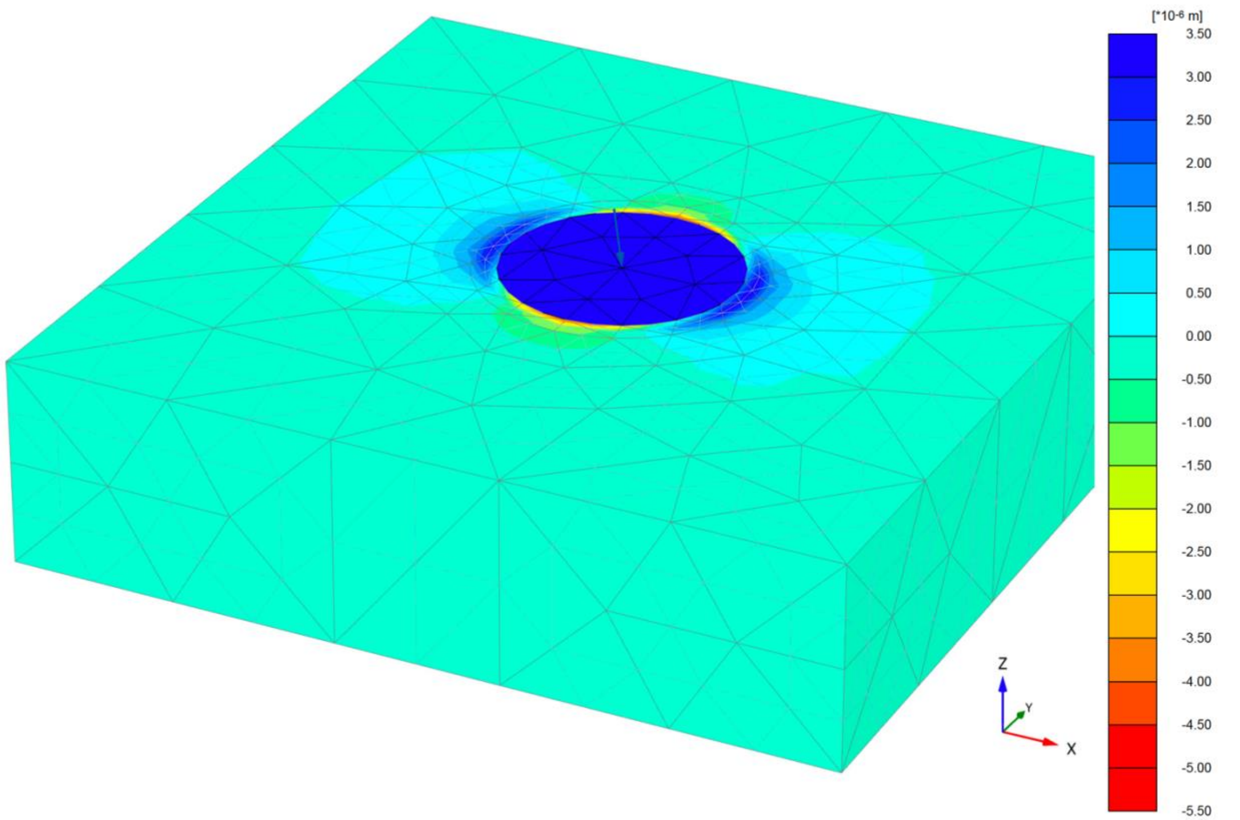


FIGURE 10: DISPLACEMENTS IN THE Z (VERTICAL) DIRECTION

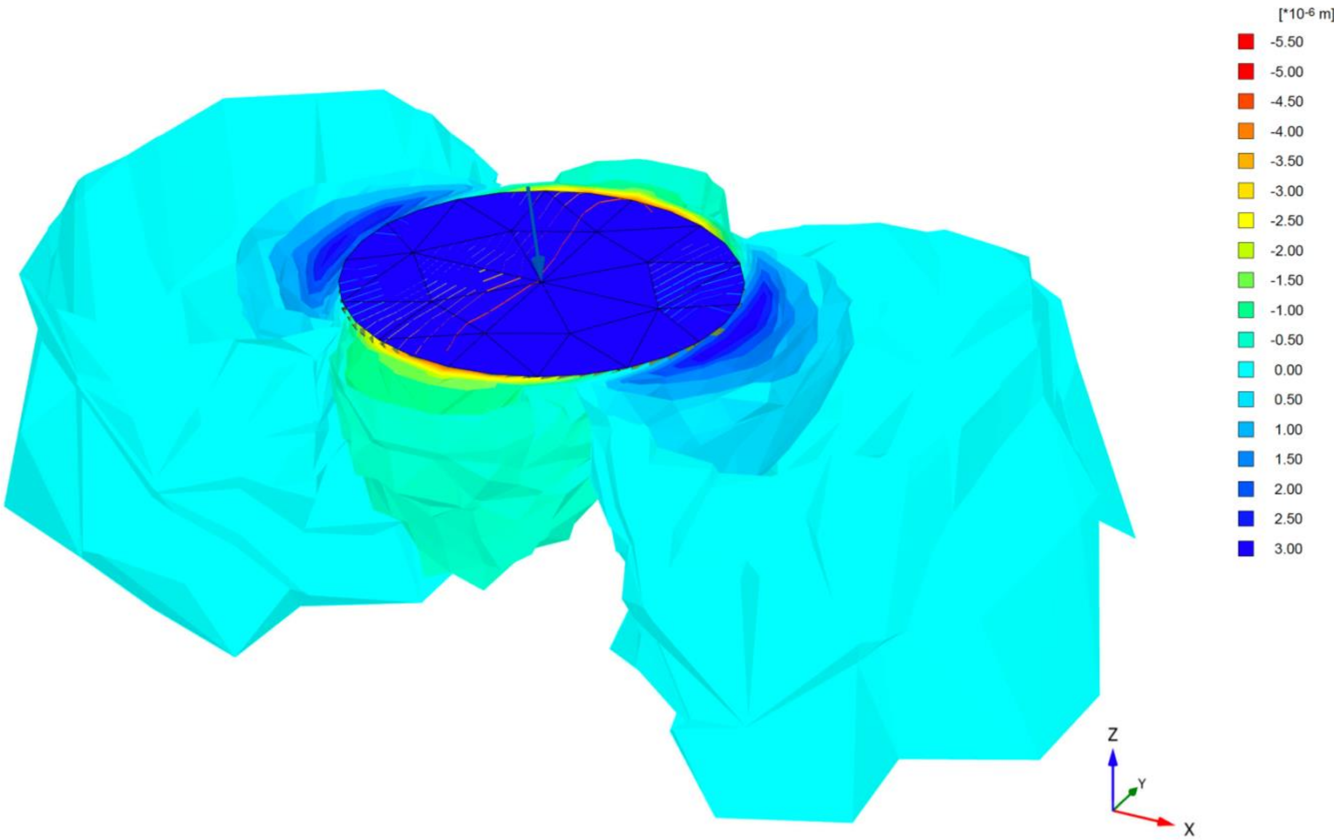


FIGURE 11: DEFORMATION CONCENTRATIONS

Conclusion

The work done this semester proved to be successful in learning the software and fundamental behavioral principals of wind turbine foundations. Studying the long-term soil response to cyclic loading plays an integral role in design smarter, more economical, and lasting wind turbine foundations. With a greater understanding of long-term behavior, engineers will hopefully be able to confidently and safely re-power wind turbines saving clients’ money and utilizing the full structural life of the foundation. As stated in the limitation section, future models will need to run on fasters computers in order to capture the long-term stiffness degradation in the foundation soils. Future models will integrate soil constitutive models that are calibrated to capture cyclic tri-axial laboratory tests on cohesive soils. Future models will also incorporate actual loading time history to accurately pinpoint the stresses and strains that the structural system experiences throughout its lifetime.

References

[1] Brinkgreve, R. B. J., E. Engin, and W. M. Swolfs. "PLAXIS 3D user manual." *PLAXIS bv* (2020).

[2] Khasawneh, Y., Nasim, M., Nafisi, A., Javadi, S., and Duan, L. (2021) “Wind Turbine Intermediate Foundation Performance through Frequency Analysis.”, Proceedings IFCEE 2021 Conference, Dallas, TX.

[3] Suleiman, M. 2021. Personal Communication, March.