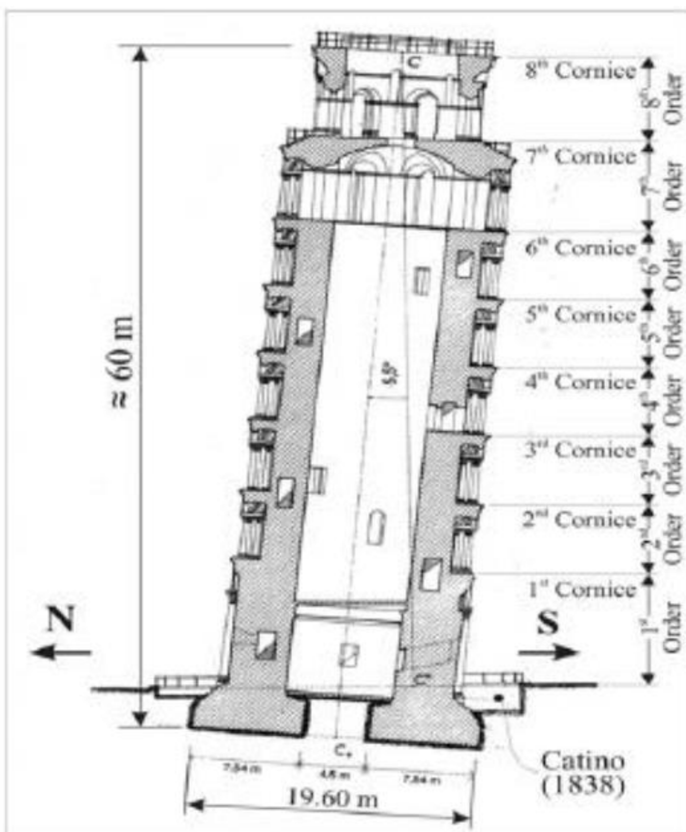
UCONN
UNIVERSITY OF CONNECTICUT

Soil Mechanics
Department of Civil and Environmental Engineering

Term Project - Fall 2021
The Leaning Tower of Pisa: Settlement calculations

Background information:

The construction of the Leaning Tower of Pisa began in 1173 and due to two long breaks, it went on for 176 years. Those breaks were most likely caused by political events. The first break came in 1178, and by that time, the construction work had only reached the 4^{th} order of the final Tower, which is illustrated in Figure 1.



Weight	142 MN
Height of the centre of gravity	22.6 m
Overturning moment	327MNm
Average foundation pressure:	≈ 500 kPa

Figure 1: Cross-section of the Tower (Burland, Jamiolkowski, & Viggiani 2009)

The second break came in 1278 after the tower had reached the 7th order of the finished Tower. Completion with the rise of the bell Tower was first achieved in 1360 and although completion would have taken almost 15% of the time had it not been for the two shutdowns, these have actually proven to be crucial for the Tower Existence. Had they built the Tower giving it no time to consolidate, the weight of the Tower would have caused an undrained bearing capacity failure in the underlying soil and the Tower would have been history already after the first construction phase.

By the time of the final stage of construction, the tower had already leaned significantly, as evidenced by the changed centerline direction of the 8th order, that was added last.

The dimensions of the Tower are shown in Figure 1. The diameter of the foundation is 19.6 m and the total weight of the tower at the end of construction is 141,640 kN (~142MN) resulting in an average foundation pressure of $q = \frac{141640kN}{\pi(\frac{19.6}{2})^2 m^2} = 469kPa$ (rounded up as 500 kPa in Figure 1).

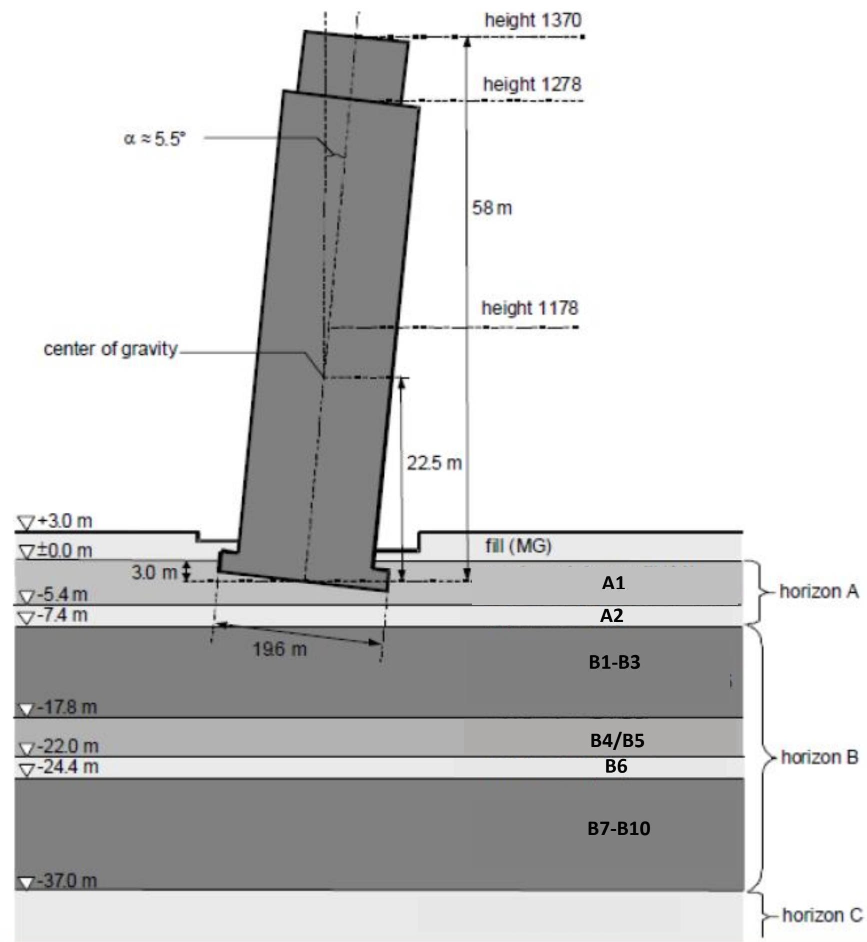


Figure 2: Geology of the subsoil beneath the Tower (Leoni & Vermeer 2002)

Term Project - Phase 2:

After the lab tests were done, the soil layers at the construction site were compacted to attain a relative compaction of 95% at the optimum moisture content (as obtained in the lab). You have already analyzed the laboratory data in Phase 1 of the project. Based on those results, please fill in the following table (Table 1), which will serve as the input for Phase 2 of the project.

Table 1: Geotechnical characteristics of the soil layers – From Phase 1 calculations

		Soil Type	**γ (kN/m³) Field unit weight**	**w (%) Water Content**
Layer 1	A1+A2			
Layer 2	B1-B3			
Layer 3	B4-B5			
Layer 4	B6			
Layer 5	B7-B10			

The initial tilting of the tower was caused by a variety of reasons, including distortion settlement of the sand and silt in Horizon A (Mitchell et al., 1977). Tilting progressed with the various stages of the construction and only reached the current tilt of 5.5^o (Figure 1) in 1990. It is beyond the scope of this term project to fully understand the causes of the tilt or the time evolution of it. We would assume that one side of the tower experienced substantially higher load than the other and will make some simplifying assumptions to apply the Soil Mechanics principles you learned in this class. **Due to the simplifying assumptions and data taken from two different sources, the actual differential settlement value would vary from the one you will be calculating as a part of this project.**

The consolidation data for the clay layer 2 is given in Figure 3 below. You will use the red dataset (shown using the arrowheads) to determine the necessary parameters to complete Table 2 shown below. **A clean graph of the red dataset has been provided in the attached Excel file titled "Oedometer_test_results".**

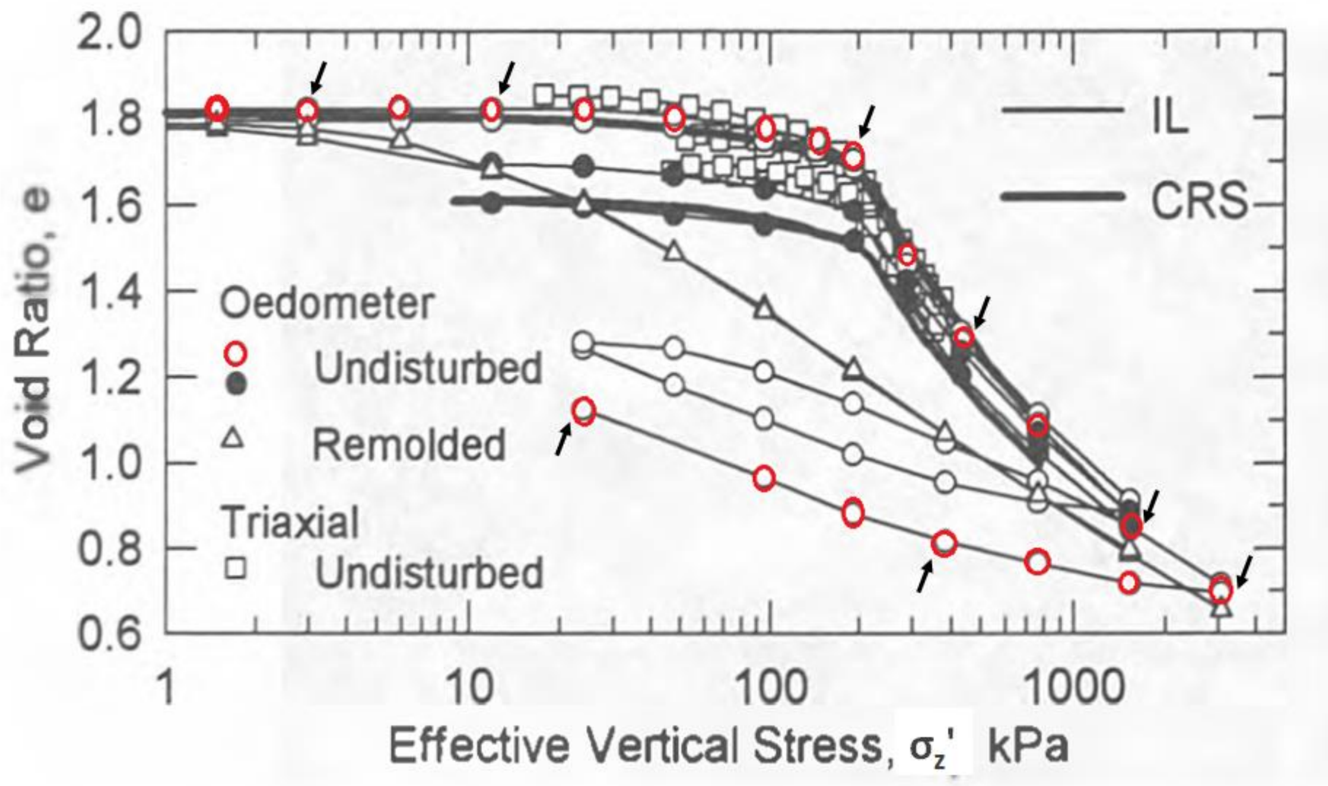


Figure 3: 1-D Oedometer test results for clay layer 2 (Mesri et al. 1997)

Table 2: Consolidation data for the soil layers (raw data from Kristiansen 2012; Mitchell et al. 1977)

		OCR	Cc	Cr
Layer 1	A1+A2			
Layer 2	B1-B3	tbd	tbd	tbd
Layer 3	B4-B5	2	0.15	0.04
Layer 4	B6			
Layer 5	B7-B10	1	0.42	0.05

You will make the following **assumptions**:

- The fill layer at the top of Figure 2 can be ignored, as it was added later in the history of the tower.
- The **groundwater table** is located at 2 m below the ground surface (±0.0 m) and the **foundation** is at 3 m below the ground surface.
- The tower is upright with a **circular** foundation. The stress increase in the midpoint of each clay layer can be calculated using the approach you learned in Module 6 (point under the center of a circular footing).
- Assume that the **north side is experiencing 65%** of that stress increase ($\Delta\sigma_z$), while the **south side is experiencing 135%** of the stress increase. That means you can assume the

tower as **two circular loadings** at each side with 65% stress increase on the northside and 135% of the stress increase on the south side.

- Assume the settlement only occurred in **clay** layers.
- Laboratory testing of the consolidation was performed on a sample taken from Layer 2 at a depth of 12.6 m from the ground surface.

Assignment:

1. Using the data and assumptions given, calculate the 1-D primary consolidation settlement of each of the **three clay layers**, in the north and in the south side of the tower separately, as well as the differential settlements across the tower.
2. Submit an Excel spreadsheet showing all calculations. **The names of all the group members should be clearly mentioned at the top of the calculation sheet (preferably the top row)**. Please upload the Excel file to HuskyCT. **No email submission will be accepted.**
3. **Only one member is required to submit the assignment.**
4. The dead line for this phase of the project is **12:59 PM on December 3rd**.

References

Kristiansen, M. 2012 An under-excavation model for The Leaning Tower of Pisa, MS Thesis, Norwegian University of Science and Technology.

Leoni, M., & Vermeer, P. A. (2002). 3D creep analysis of the Leaning Tower of Pisa. Stuttgart: Institute of Geotechnical Engineering Stuttgart.

Mesri, G., Heiden, J.E., Shahien, M., 1997a. Geotechnical characteristics and compression of pisa clay. In: Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany. pp. 373–376.

Mitchell, J.K., Vivatrat, V., and Lambe, W.T. 1977. Foundation performance of the Tower of Pisa. Journal of the Geotechnical Engineering Division, ASCE, 103(GT3): 227–249.

Burland, J. B., Jamiolkowski, M. B., & Viggiani, C. (2009, July 01). Leaning Tower of Pisa: Behaviour after Stabilization Operations . International Journal of Geoengineering Case Histories , ss. 156-169.

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