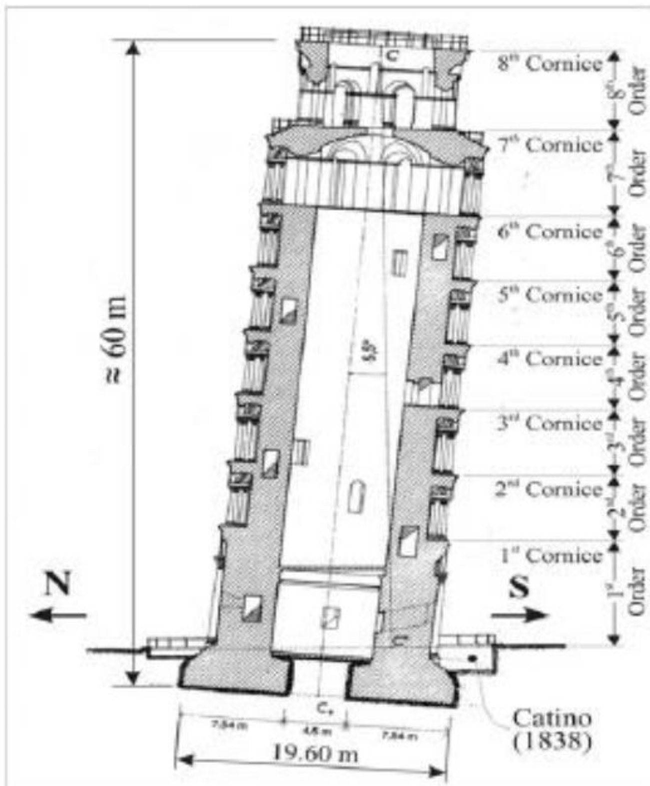
Term Project - Fall 2022
The Leaning Tower of Pisa: Settlement calculations

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 4th 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 8^{th} 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).

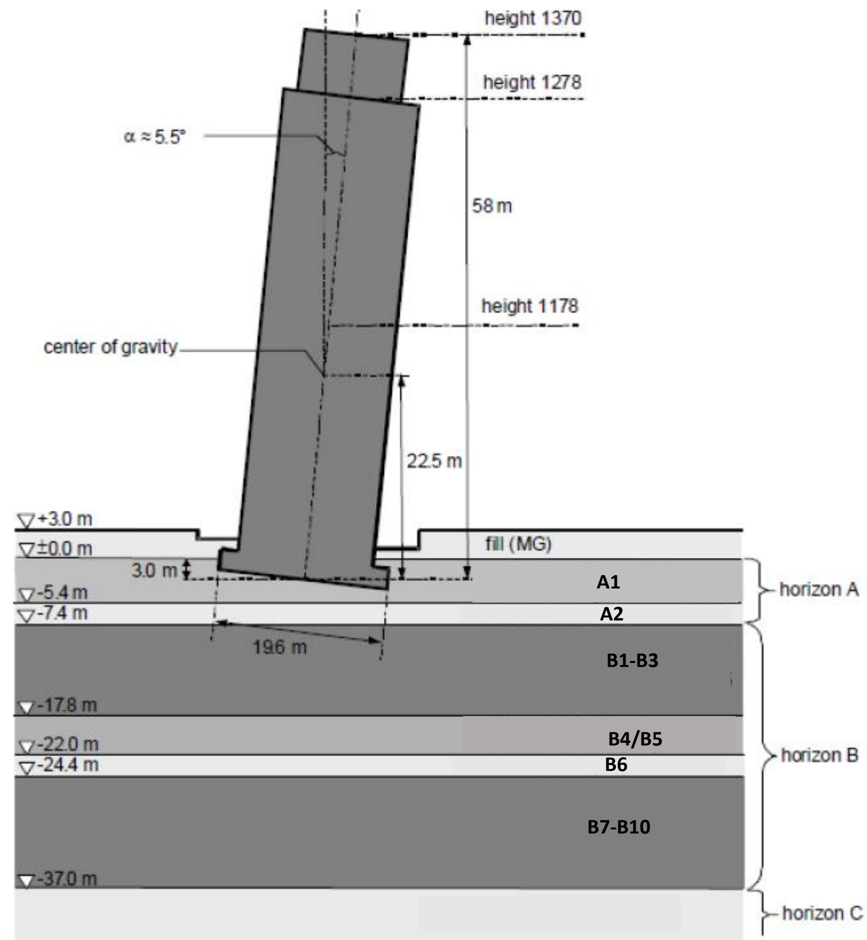


Figure 2 Geology of the subsoil beneath the Tower (Leoni & Vermeer, 3D creep analysis of the Leaning Tower of Pisa, 2002)

Term Project - Phase 1:

The soil underneath the Tower can be divided into three distinct layers – horizon A, horizon B, and horizon C, which are illustrated in Figure 2. One sample collected from Horizon A (A1+A2) and four samples collected from Horizon B (B1-B3, B4+B5, B6, B7-B10), were sent to the laboratory for testing. Horizon C consists of dense sand, which extends to a considerable depth (Kristiansen, 2012). Grain size distribution, Atterberg Limits tests, and proctor compaction tests were conducted on those samples. Below are the results from those tests:

Grain Size Distribution and Atterberg Limits:

	Mass of the sample retained on the sieve				
Sieve Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
	A1-A2	B1-B3	B4-B5	B6	B7-B10
4	0	0	0	0	0
10	22	10	13	149	14
20	50	9	19	161	14
40	103	8	9	234	23
60	90	11	23	211	12
100	95	12	17	287	13
200	60	16	12	187	11
Pan	30	125	102	56	123
Liquid Limit	55	65	45	55	55
Plastic Limit	40	20	20	40	21

Proctor Compaction Test Results:

Layer 1		Layer 2		Layer 3		Layer 4		Layer 5	
A1-A2		B1-B3		B4-B5		B6		B7-B10	
Water Content (%)	Weight of the mold +wet soil (lb)	Water Content (%)	Weight of the mold +wet soil (lb)	Water Content (%)	Weight of the mold +wet soil (lb)	Water Content (%)	Weight of the mold +wet soil (lb)	Water Content (%)	Weight of the mold +wet soil (lb)
13	9.78	62	9.17	23	9.98	9	9.60	38	9.77
14	9.87	63	9.32	24	10.05	10	9.72	39	9.85
15	9.96	64	9.42	25	10.16	11	9.82	40	10.08
16	9.96	65	9.56	26	10.11	12	9.93	41	9.93
17	9.96	66	9.51	27	10.07	13	9.90	42	9.93
18	9.91	67	9.39	28	10.05	14	9.88	43	9.90

Weight of the mold = 5.7 lbs ; Volume of the mold = 1/30 ft^3

Assignment:

1. Plot the Grain Size Distribution Curves and classify the soil samples according to USCS.
2. Determine the Maximum Dry Unit Weight of the five samples.
3. Determine the Optimum Moisture Content of the five samples.

Deliverables for Phase 1:

1. An Excel spreadsheet showing all calculations as mentioned in the 'Assignment' section.
2. The group formation is handled separately using CATME (you should have received an email with a survey link by now).
3. Due date: **10/21/2022** by 11:59 PM

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.