Environmental Geology – Dr. Warren Norton

CIVIL ENGINEERING AND ENVIRONMENTAL GEOLOGY: A CASE STUDY

By Sharon Royer

When an architect prepares to construct a new building, he must first have some understanding of the land he is building on and the surrounding area. The environmental concerns of any one architect may include: the rock types present, the porosity and permeability of the rocks, the cohesiveness of the soil, the amount of surface runoff (Montgomery 428) . . . and the list goes on. All of these elements can have effects of varying degrees on a manmade structure. Hence, the relationship of civil engineering and environmental geology is forged. The importance of this relationship can most clearly be seen in situations where it has been overlooked. An excellent example of one such situation is the Leaning Tower of Pisa. The apparent “engineering” flaws of the Leaning Tower are actually due to the soil it was built on, and no structural fault of the engineer. However, the failure of a building, structural or otherwise, reflects on its builder. Architects today should learn from the results of the oversight of the unfortunate builder of the tower in Pisa.

WELCOME TO PISA

Pisa, Italy is located on the Arno River, eight miles from where it empties into the Ligurian Sea. Pisa is only 13 feet above sea level, located on a flat and largely treeless plain. Its climate is moderate with an average rainfall of 42 inches (Wooll bert 79). The location is known worldwide for the Cathedral Square. In the Square one of the seven wonders of the modern world can be found—a white marble bell tower called the Leaning Tower of Pisa (Pisa).

THE LEANING TOWER THEN & NOW

Construction of the tower began in 1173 under the direction of the architects Bonanno of Pisa and Williams of Innsbruck (Waxman 80). Soon after construction began, the ground began to sink and the tower began to tilt toward the north. Therefore, workers made the columns of the third story slightly taller on the sinking northern side to compensate. In 1178 work was stopped in the middle of the fourth level because of political turmoil. When construction continued in 1272 the tower shifted again, only this time towards the south. Hence, columns on the southern side of the fifth story were altered and made slightly taller. Construction was stopped in 1278, after the seventh story was completed, due to political upheaval once again. From
1360 to 1370 the eighth story and the bell chamber were added to complete the tower. Again, alterations were made to compensate for the tilt by angling the bell chamber towards the north. “These efforts, combined with the slow time scale of construction (which gave the building’s foundation time to compress and thereby gain strength to compensate for the slant), have so far prevented the tower from toppling over” (Heiniger 64-65). Shortly after completion, in the 15th century, the unstable ground of Pisa was disturbed by extensive silting, a change in the level of the land, and a change in the river’s course (Pisa). Unfortunately, these changes did not serve as stabilizing agents.

The completed tower measures 177 feet in height (Perkins 162), and 52 feet in diameter (Waxman 81). The walls are 13 feet thick at the base, narrowing to between 6 and 7 feet thick at the top. Around the first story there is a row of arches supported by 15 columns. The next six stories each have 30 columns, with the uppermost story having 12 (Perkins 162). A series of 296 steps leads the way from bottom to top (Waxman 81). The construction took nearly 200 years to complete (Heiniger 64).

Today, the tower is 17 feet out of the perpendicular, southward (Pisa). The tilt of the bell tower has increased an average 6.5 inches per century (Montgomery 436). In 1989 the tower was believed to be slowing its tilt. It had inclined 0.03 inches, which was compared to an average of 0.045 inches over the past 30 years (Famed 11). However, measurements by two Pisa University professors showed that the tilt increased by 0.046 inches in 1990, and had already increased 0.039 inches by April of 1991. The tower was closed to tourists in January of 1990 for the first time in 800 years (World 8), after a similar bell tower at the Cathedral of Pavia collapsed in 1989 (Heiniger 63).

WHAT PUT THE LEAN IN THE LEANING TOWER?

The reason that the Leaning tower of Pisa leans is an unstable subsoil. The layers of clay and soil underneath the tower have compacted unevenly. In fact, the land under the entire piazza is slowly sinking, but in some areas subsidence is quicker than in others; the Leaning Tower of Pisa was built on one such spot. The first 7 meters of soil below the tower are a mixture of mud, clay, and sandy soil (See Appendix A: Sand and sandy soils, silts and clays). Next, down to approximately 20 meters, is a strip of Pancone clay (gray-azure in color). There is a boundary of sand between these first two layers that is “horizontal under most of the Piazza dei Miracoli, except below the tower, where it forms a bowllike depression” (Heiniger 64). The remainder of the subsurface, down to about 70 meters, is alternating layers of clay and sand (Heiniger 64).
RECENT DEVELOPMENTS & SUGGESTIONS FOR THE FUTURE

Over the centuries many committees have met to debate what should be done about the Leaning Tower. The need for action has increased since the "rate of increase of the tilt [has] tended to accelerate in recent decades, perhaps in part because of a drop in the water table" (Lean 57). Engineers’ ultimate goal is to reduce the tilt from 5.3 degrees to 4.3 degrees from the perpendicular (Lean 57). They do not plan to completely straighten the tower. Due to the tower tilting in various directions during its early construction, it has become curved and "will never stand truly upright" (Heiniger 63). The presence of a straight Tower of Pisa would not do much for Pisa’s tourist trade and economy either.

Efforts to correct the tower’s tilt have not always had the desired effect. In 1935 attempts were made to seal the base in order to protect it from excess water leaking in. This was accomplished by drilling into the foundation at an angle and filling the holes with a cement grouting mixture. The end result was a tilt increase of six times the preceding year’s. In November 1995, it was reported that technicians decided the tower needed more stabilization. This was to be accomplished by installing underground cables as anchors. First, they froze the ground with liquid nitrogen. Then, they removed a section of the base in order to install the cables. However, the tower started to sway and the tilt increased 1.1 millimeters (Muzzi 22).

There have also been successful efforts to correct the tilt, especially recently. In 1992 steel cables were put around the first level of columns "to contain stresses at this most vulnerable point" (Lean 57). Steel bands have also been added to the second story, which receives a great deal of pressure and is in danger of collapse. In June of 1993 further action was taken. The tilt was decreased slightly by over 750 tons of lead ingots laid on the northern side of the base (Heiniger 66). This proved to be a successful counterweight to the tower’s over 14,000 tons of marble (Cowell 4). The end result was a decrease in tilt of 2.5 centimeters over nine months (Heiniger 66), giving engineers an additional five to ten years to search for another solution (Cowell 4). Efforts such as these are termed "temporary stabilization" (Lean 57).

In June 1995 engineers began to install a second concrete ring around the tower. "They will anchor the ring to a layer of sand fifty meters below ground by means of steel cables extending down from the northern side" (Heiniger 66). This ring is eventually intended to replace the lead ingots and surpass their force. Also, motion monitors have been installed inside the tower to detect slight shifts in tilt. It was determined in September that the tower’s top moved 0.24 millimeters south over two days (Heiniger 67).
Other, more radical, suggestions are being considered for future use. Electro-osmosis may be used to compact layers of clay ten to twenty meters underneath the tower. This would be accomplished by inserting large electrodes into the soil that would generate an electric field. The field would then attract water that could be removed from the northern side, allowing the clay to compress. This in turn would allow the northern wall to slowly sink even with the southern wall. Similarly, a drilling mechanism may be installed to extract a small amount of soil from the northern side, achieving the same sinking effect (Heiniger 66).

CIVIL ENGINEERING & ENVIRONMENTAL GEOLOGY

In order for these new ventures to be successful there will have to be an intimate knowledge of Pisa’s land. This will be accomplished by engineers and geologists working together toward a mutual goal. The rapidly emerging field of soil engineering will play a vital role in the success or failure of different methods used on the Leaning Tower of Pisa. This comparatively new field studies the behavior of unconsolidated materials. Materials such as sand, silt, or clay have been viewed simply as “soil” by engineers, but an understanding by geologists of how these were formed reveals crucial engineering properties. “Engineering and geology thus go more or less hand in hand; application of geology to exploration for engineering works benefits engineering, and the excavations and borings made by engineers benefit geology” (Schultz 7). Hopefully, the solution to the 823 year old problem of the Leaning Tower of Pisa can be found by careful, accurate research by environmental geologists; and applied by equally careful, accurate engineers.

Works Cited


ANON. “Famed Pisa tower this year leaned less than normal.” Atlanta Journal Constitution 31 December 1989: 11.


