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Outstanding Structure: The Leaning Tower Of Pisa

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Abstract : **The Leaning Tower of Pisa is the most famous example of soil related problems from this era. Its stabilization process proved to be one of the greatest challenges faced by the civil engineers and architectural conservationists. This paper aims at giving information about the tower itself, its construction and the underlying geology. The paper also discusses the history of the tilting and describes the temporary remedial measures undertaken and permanent stabilization proposed.**

1. INTRODUCTION

The town of Pisa is situated some 10 km from the Lingurian Sea, having developed around a port near river Arno, is best known for its 'Leaning Tower'. The Leaning Tower of Pisa is a freestanding white marble bell tower, of the cathedral of the Italian city of Pisa, known worldwide for its unintended tilt to one side. It was constructed in three phases between 1173 and 1370. It is situated behind the Cathedral and is the third oldest structure in Pisa's Cathedral Square after the Cathedral and the Baptistry (as shown in the Fig.1). Its main purpose was to visually attract people to the cathedral. The tower began to tilt during construction, caused by an inadequate foundation on ground too soft on one side to properly support the structure's weight. The tilt increased in the decades before the structure was completed, and gradually increased until the structure was stabilized by efforts in the late 20th and early 21st centuries.

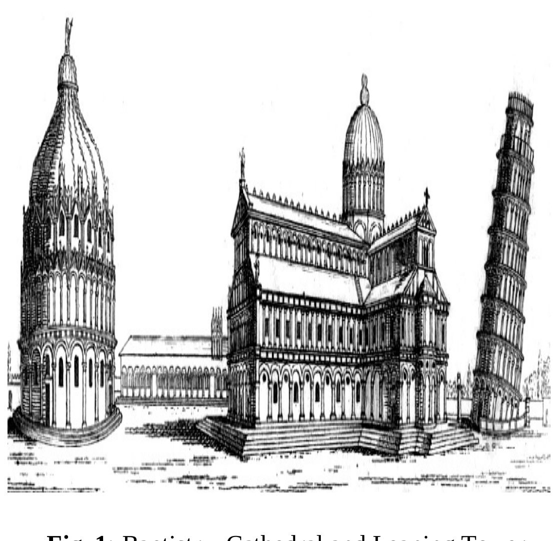


Fig. 1: Baptistry, Cathedral and Leaning Tower

The height of the tower is 55.86 metres from the ground on the lower side and 56.67 metres on the higher side. The width of the walls at the base is 2.44 metres and weighs around 14,500 metric tonnes [1]. Its masonry foundations are 19.6 m in diameter and have a maximum depth of 5.5 m below ground level. The tower has 296 steps on the South side and 294 steps on the North side of the Tower. Prior to restoration work performed between 1990 and 2001, the tower leaned at an angle of 5.5 degrees, [2][3][4] but the tower now leans at about 3.99 degrees [5]. This means that the top of the tower is displaced horizontally 3.9 metres from where it would be if the structure were perfectly vertical [6].

2. HISTORY OF CONSTRUCTION

The Leaning Tower of Pisa was actually constructed vertical but it started to tilt southwards during construction. The Tower is built as a hollow masonry cylinder surrounded by six colonnades with columns and vaults rising from the base cylinder. The inner and outer walls of the cylinder are faced with tightly jointed San Giuliano marble, while the annular cavity between these facings consists of miscellaneous rock fragments and mortar, forming a typical medieval infill masonry structure [7]. A spiral stairway winds up within the walls of the Tower. The North-facing stairway has two stairs lesser then that of the South-facing stairway.

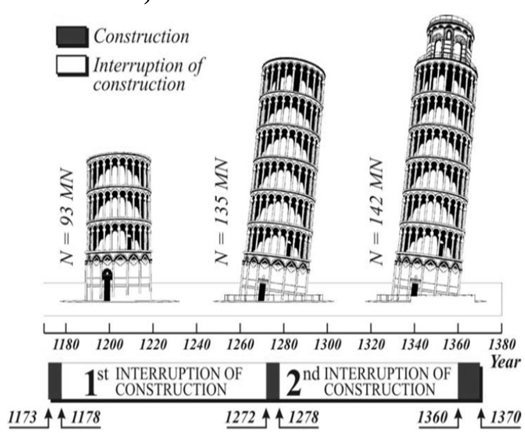
Construction of the tower occurred in three stages across 199 years (as shown in the Fig.2). Work on the ground floor of the white marble campanile began in 1173, during a period of military success and prosperity. This ground floor is a blind arcade articulated by engaged columns with classical Corinthian capitals.

The tower began to sink after construction had progressed to the third floor and beyond in 1178. This was due to a mere three-metre foundation, set in weak, unstable subsoil, a design that was flawed from the beginning. Construction was subsequently halted for almost a century because of Pisa's wars with its neighbouring city, Florence. This allowed time for the underlying soil to settle. The construction was resumed in 1272 under Giovanni di Simone, architect of the Camposanto.

The architect took notice of the lean in 1185, so the builders accommodated the tilt by adding extra height to the upper stories on one side of the Tower. Because of this, the tower is actually curved [6]. The extra weight caused the upper part of the Tower to lean in the opposite direction. Construction was again halted in 1284, when the Pisans were defeated by the Genoans in the Battle of Meloria.

The seventh floor was completed in 1319. It was built by Tommaso di Andrea Pisano, who succeeded in harmonizing the Gothic elements of the bell-chamber with the Romanesque style of the tower. The bell-chamber was finally added in 1372. There are seven bells, one for each note of the musical major scale. The largest one was installed in 1655.

Fig. 2: History of Construction (Adapted from Burland J.B. et al 2009)

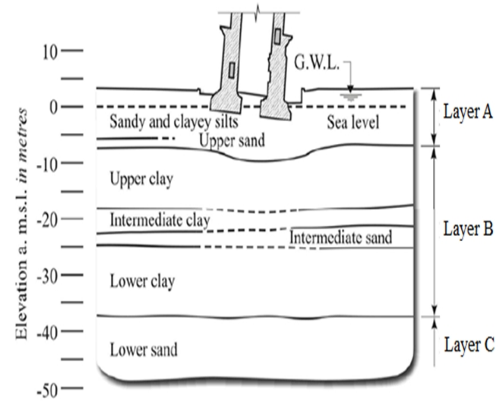


After a phase of structural strengthening, during 1990-2001, the tower is currently undergoing gradual surface restoration, in order to repair visible damage, mostly corrosion and blackening. These are particularly pronounced due to the tower's age and its exposure to wind and rain [8].

3. UNDERLYING GEOLOGY

The ground underlying the Leaning Tower of Pisa consists of three distinct layers (as shown in Fig.3). Layer A, about 10 m thick, composed of soft sandy and clayey silt deposits laid down in shallow water (lagoonal, fluvial and estuarine conditions) less than 10,000 years ago. Layer B, which extends to a depth of 40 m, consists of very soft sensitive normally consolidated marine clays laid down up to 30,000 years ago. This stratum is laterally very uniform and due to its high sensitivity, loses much of its strength if disturbed. Layer C, extending to a depth of 60 m, is dense marine sand. The water table in Layer A is between 1 m and 2 m deep. The soil borings done around and beneath the Tower shows that the contact between the Layer A and the marine clay of Layer B is dished beneath, due to the weight of Tower. This indicates that the average settlement of the Tower is between 3.0 m to 3.5 m, which shows high compressibility of the underlying soil [7].

Fig. 3: Soil Profile (Adapted from Burland J.B. et al 2009)



4. TILTING OF THE TOWER

By 1178, the Third floor was complete. It was at this stage when the architect noticed that the tower was leaning on the north side, and the construction was on hold because of neighbouring wars. The tower kept shifting to one side over the years, at a rate of around 1.2 millimeters from the vertical every year [9]. The extreme north and south have subsided by 1.86m and 3.75m respectively which means the differential subsidence is 1.89m. Today, the restored Tower of Pisa leans at a 3.99 degree angle.

Weight of the tower was the main factor but fluctuations of the water levels also contributed to the tilt and rotation of the tower. The reason the Tower tilts southward is because the soil under the south side of the monument is more compressible than on the north side. Careful monitoring and measurements of the lean, however, didn't begin until 1911. Engineer and site manager of the restoration project, Paolo Heiniger says, "The Tower has begun tilting at a rate of about one-tenth of an inch per year and accelerating. At this rate, the tower would be in danger to fall in twenty to twenty-five years." (Popular Science, 2000, pg. 72) Objectives

5. REMEDIAL MEASURES TAKEN

The Tower of Pisa's structure was subject to two main risks: Firstly, structural failure of the fragile masonry and Secondly, collapse due to the breaking up of the subsoil around the foundations. Many ideas have been suggested to straighten the Tower of Pisa, including taking it apart stone by stone and rebuilding it at a different location [10]. But as per the internationally accepted conventions for the conservation of valuable historic monuments, essential character should be preserved, with their history, craftsmanship, and enigmas. Thus, it is required to keep any invasive or visible intervention in the Tower, to an absolute minimum.

So, the builders began to apply the scientific methods to various aspects of construction. These efforts attempted to determine the behaviour of the structures mathematically, and develop analysis and design methods based on these understandings. Initially, these efforts focused essentially on structural issues.

In 1966, a restorative attempt involving drilling was aborted due to further southward leaning of the Tower. In 1985, another boring attempt likewise caused an increase in the lean. In 1990, the Italian Government closed the doors of the Leaning Tower to the public for safety reasons [11].

In 1992, to prevent the Buckling of the Tower, plastic coated Steel Tendons were built around the south side of the Tower up to the second floor. Temporary stabilization of the foundations was achieved during the second half of 1993 by providing the Lead counterweight of 660 tonnes on the north side of the foundations via a post-tensioned removable concrete ring, cast around the base of the Tower at plinth level. This caused a reduction in inclination of about one minute of arc and reduced the overturning moment by about 10%. Again, in September 1995 the load was further increased to 900 tonnes in order to control the movements of the Tower during an unsuccessful attempt to replace the unsightly lead weights with temporary ground anchors. In late 1995, the engineers overseeing the restoration replaced the Lead counterweights with the underground steel cables. Engineers also tried the freezing of the subsoil with liquid nitrogen, but this caused the lean to increase and the project was called off.

Many other possible methods of inducing controlled subsidence of the north side were investigated, which included drainage by means of wells, consolidation beneath the north side by electro-osmosis and loading the ground around the north side of the Tower by means of a pressing slab pulled down by ground anchors. None of these methods proved satisfactory.

Scientists and Engineers detected that soil extraction was the key to bring the tilt back to stable conditions. This was done by studying the Physical Models, then by Numerical Modelling, and finally by means of large-scale trials.

6. PERMANENT STABILIZATION PURPOSED

The Tower is founded on weak, highly compressible soils and its inclination has been increasing inexorably over the years to the point at which it was in a state of leaning instability. Any disturbance to the ground on the leaning side would have been very dangerous, ruling out conventional geotechnical processes such as underpinning and grouting. So, the scientists and the engineers used the innovative method of soil extraction, which induced a small reduction in inclination which is not visible to the casual onlooker. This technique has provided an 'Ultra-soft' method of increasing the stability of the Tower, which at the same time is completely consistent with the requirements of architectural conservation.

A key finding from the model studies and numerical analysis was the existence of a critical line located about half a radius in from the northern edge of the foundation. If soil extraction beneath the foundation took place north of this line, the response of the Tower was positive, but if extraction took place south of this line the Tower would become unstable [12].

Thus, the soil was extracted at a slow pace from the North side, and the tower was held with the help of massive cable harness to prevent the event of sudden destabilization. As a result the tower started to sink on the North side, therefore reducing some of the stress that was building up on the south side. The soil was extracted from two layers of earth: the top layer of sandy soil and the second of marine clay. While soil is being removed, the ground compression surges and clay consolidates, giving a stronger foundation. By using this method, engineers succeeded to lean back toward the center by 20 inches (50 centimeters), where it was in 1838. The top of the tower now leans just over 13 feet (4 meters) off center [9][13].

The application of the techniques essentially required the advanced computer modelling, large-scale development trials, an exceptional level of continuous monitoring, and daily communication and control.

On 16 June 2001 a formal ceremony was held in which the Tower was handed back to the civic authorities. It is hoped to open the Tower to the public in the Autumn of 2001. The Tower was re-opened to the public on 15 December 2001.

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