Tilted Buildings: Causes and Solutions

An Online Continuing Education Course for Engineers

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Tilted Buildings: Causes and Solutions

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Summary of the Course

To straighten a leaning building is never easy. There are no standard solutions. On the other hand, there are several, usually historical, leaning structures that have not been rectified, mostly because, in their current shape, they are a touristic attraction - the best example being the famous Leaning Tower of Pisa. This does not mean, however, that the inclination of load-bearing walls can be ignored.

Even though, in some cases, the problem can be treated in terms of serviceability limit states (the deformation is only decreasing the comfort of ‘normal use’ of the building), in others – it may be a signal of the forthcoming structural failure. The situation must always be treated individually – if the problem concerns a residential building, then cracks on the walls, not-opening doors, difficulty moving the lift vertically upright, or tilted ceilings, which often coincide with the leaning of the external walls, are always the reason of worry and such a building needs to be straightened.

The reasons for the problem usually lie in uneven settlement of the ground, which, in turn, may be caused by various problems, such as the presence of too soft, too weak, unconsolidated, or expansive soils under the building, varying groundwater table, mining activity, etc. Solving the problem by just straightening the building is often not enough. To prevent further deformations, a detailed analysis of the possible causes is necessary. Sometimes, it may be helpful to review similar cases.

The course contains a general overview of selected inclined buildings, starting with well-known historical examples and ending with individual houses spread around the world. Since the problem of instability mostly affects structures with a critical height-to-width ratio, tall and narrow structures (towers) dominate the work. The aim of the course was to describe the reasons for the problems and present solutions that have been successfully applied and can also be useful to engineers and designers to prevent similar situations.

1 - Introduction

In the case of a leaning structure, it is often the serviceability limit state (SLS) exceeded that causes the announcement of the structure’s failure. The allowable criterion shall be, however, determined individually for each object by means of a static strength analysis, possibly complemented by a permanent monitoring of the building. Even if the construction of a deflected building is stiff and the walls are currently not cracked, such an object gets subjected to additional internal forces due to eccentricity. In extreme cases, when the inclination is significant, the structural statics of the object may be impaired. First of all, the problem concerns slender objects for which the ratio of height and width is high (e.g., towers, belfries, chimneys). This can lead then to the so-called ‘leaning instability’ when the overturning moment generated by a small increase in inclination is equal to or larger than the resisting moment generated by the foundations. Straightening of the building is then required immediately in order to avoid a failure, or even a collapse, caused by exceeding the ultimate limit state (ULS). It has been noticed that it is easier to achieve critical slenderness in the case of a circular foundation than in the case of a more conventional rectangular one.

Leaning of a building is often treated as a permanent, irreparable failure. As a consequence, the structures inclined by more than 5% have usually been demolished without accounting for a possible straightening. On the other hand, if the inclination is smaller and concerned 'only' as a serviceability problem (ground and/or structure deformations, cracked walls), with no clear danger of collapsing, the decision on rectification works is often postponed, or the problem is simply ignored. However, especially when a residential building becomes inclined, this can become a huge inconvenience for its inhabitants. Based on the research by Kawulok [1], it was stated that an inclination of 20 - 25 mm/m strongly affects the users, while an inclination above 25 mm/m often causes such a decrease in comfort that further use of the object becomes impossible. Apart from the negative influence on the users' well-being, other problems may occur, like instability of the equipment elements (furniture, windows, doors, etc.), issues relating to water drainage (a reversed gradient of pipes or gutters, etc.), as well as the malfunction of lifting devices. The level of the discomfort depends on the intensity and duration (seasonal or permanent) of the problem. In public utility facilities or industrial objects (especially the ones containing technological lines), a failure to comply with any of the serviceability limits states sometimes means that the object cannot serve its basic functions anymore.

One of the most frequent reasons for the inclination of construction objects is the intensive underground mining exploration. This problem concerns many strongly urbanized areas in the world. The effect of coal extraction from successive underground layers is summing up on the surface, which results in deformation of the ground, causing unequal subsidence of buildings and, consequently, the inclination of the buildings found in such a subsoil. Rectification of the damaged objects usually requires long-term and tedious settlement submissions between the owners of the building and the mine - as the responsible party.

The most problematic in terms of straightening are historic buildings, as their geotechnical or structural documentation is often unavailable. Additionally, these structures are usually located in historic city centers or remain under the protection of cultural heritage organizations, which makes the conservation works even more difficult and frequently results in the postponement of the rectification. It is also worth noticing that sometimes, thanks to the peculiarity of the inclined buildings, they become tourist attractions. The most well-known and analyzed example is the Leaning Tower of Pisa, attracting millions of tourists per year due to its abnormal presentation. The attempts to stabilize its inclination were made several times, with the use of various methods, but accelerated in 1990 after the collapse of a similar tower in Pavia in 1989. The interior of the tower was closed to tourists for 12 years, which resulted in a 45% drop in their number and, consequently, a decrease in the city's income. The object was made available for use in 2001, after it had been straightened enough for safe usage, yet to leave the distinctive lean. This example shows that a complete straightening of a building is not always desired.

2 - Main Reasons

The inclination of an object seldom results from a single problem. Usually, it is a range of factors within which we may search for the dominating one. They may be classified into three groups:

- Subsoil properties (e.g., too low bearing capacity, insufficient ground preparation for foundations, uneven consolidation, and change in groundwater conditions);
- Foundations (e.g., too shallow embedment, inappropriate type);
- Anthropogenic factors (direct or indirect human activity, e.g., mining exploitation, underground constructions).

In the subsections below, some selected case studies are presented, in which the inclination of structure, resulting from the factors listed above, was observed. The cases where the failure happened in a sudden way, e.g., due to the presence of quick clays or liquefaction of loose uniform and fully saturated sands subjected to seismic loads, are not included.

2.1. Problems associated with subsoil properties

The natural heterogeneity of subsoil (diversification of thicknesses, interlayering, differing compressibility and degree of pre-consolidation, etc.) must always be borne in mind during design, as they constitute the main reasons for uneven subsidence. An unexpected change of consistency of soil under a foundation, caused, e.g., by natural groundwater fluctuations, flooding, or drought, or an abrupt application of load in the case of fine soils, can lead to the decrease of bearing capacity, which usually is also followed by a building inclination. These were the reasons for the tilting and, in some cases, a further failure of many well-known objects. It shall be mentioned here that the problem of a gradual inclining of objects due to the phenomena occurring in the ground refers almost exclusively to the cases where cohesive and/or organic soil is found under the building. It eventuates from the low water permeability, i.e., the long (lasting many years) consolidation time and/or creep. Non-cohesive soils rarely cause such problems as the process of their volumetric changes under loading often ends before the building is put into use.

The famous examples of objects vertically inclined due to the presence of weak cohesive soil:

1) *Mexico Metropolitan Cathedral in Mexico City*(Fig.1), which was constructed between 1573 and 1813. The object has been settling for ages, during which many (ineffective) attempts were made to correct the failure. The maximal inclination occurred in 1989 when the difference in lowering the opposite elevations (i.e., western tower and apse) reached 2.4 m. In 1995, the inclination to the south equaled from 0.11o to 1.15°, and towards the east - from 1.72° to over 2.86°. Building works in Mexico City have always been an incredibly difficult task as almost all the area is underlain by soft lacustrine clays with high levels of saturation, low shear strength, and exceptionally high compressibility.

Fig.1- Mexico Metropolitan Cathedral in Mexico City

The subsidence was caused by the change in groundwater conditions as the result of excessive exploitation of aquifer layers under the city and the fast lowering of the groundwater table (from 3.5 m in 1972 to 7.4 m in 1990). However, according to Puzrin et al. [2], the most significant factor for the cathedral's tilting was the uneven compressibility of the subsoil due to the differences in the stress history of the ground. The city was basically the Aztec empire with multiple historic constructions (e.g., pyramids), which were demolished in the 16th century after the Spanish conquistadores' arrival. When building the current Mexico City, secondary consolidation of the ground was initiated in the places of the previous Aztec buildings, while in the other places, primary consolidation was active. The historical data revealed that the cathedral was built partially on the remains of an Aztec temple. Thanks to the stabilization work (under excavation) conducted in 1993 – 1998, the inclination of the walls decreased by 0.34° from an average initial value of nearly 1.15° (the rectification procedure is described below).

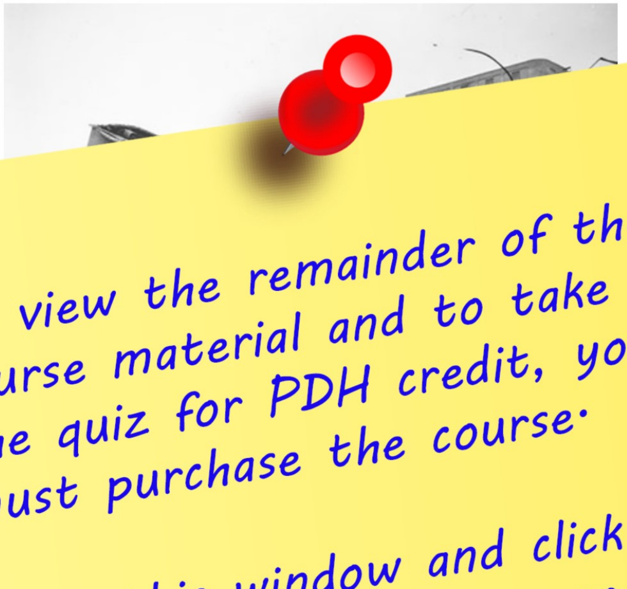
2) *Leaning Tower of Pisa*

The inclination of another very well-known object is the leaning tower of Pisa (Fig. 2), whose maximal inclination reached 5.5°, was also connected with the presence of compressible cohesive soils and the variation of the piezometric levels of groundwater on both sides of the object and so, the uneven consolidation of marine clays in the profile. It is worth mentioning that this object probably avoided the earlier failure thanks to the long-term breaks during its construction, which caused the gradual dissipation of the accumulated excess pore pressure in the clays. Some of the methods applied for the stabilization of the tower are described shortly in the next paragraphs.

Fig. 2- The Leaning Tower of Pisa

3) *Failure of the Grain Elevators in Transcona (Canada) in 1913*

The remarkable case was the too-high velocity of loading and the inappropriate recognition of the ground conditions (to insufficient depth; effective instead of total shear strength parameters) that caused not only inclination but collapse of the object (reaching ULS), was the failure of the grain elevators in Transcona (Canada) in 1913 (Fig.3). The structure consisted of a reinforced-concrete work-house and an adjoining bin-house, which contained five rows of 13 bins, each 28 m in height and 4.4 m in diameter. After the completion of the building works, the bins started to be filled in. When 87.5% of the elevators' capacity was achieved, the object started to settle at the western side, reaching 30 cm within one hour. During the following 24 hours, almost 27° of the vertical inclination was achieved. The eastern side of the object started to hang 1.5 m above its original level, while the western side deepened by 9 m. It was the classical example of failure caused by the insufficient bearing capacity of the ground. Under the object, a stiff clay (with undrained shear strength c_u = 54 kPa), typical for this region, was encountered. However, locally, 7.5 m under the surface level and within the loading range of the object, there was also a weaker, unrecognized clay (with c_u = 31 kPa), whose bearing capacity determined the collapse. This story reveals the importance of appropriately planned *in situ* and/or laboratory tests. The elevators were restored for further use in 1914. However, there were as many as three different techniques applied to rectify them – they all are mentioned in the next paragraphs.



4) Huzhu in Tia

Other examples of ob hu in
Tianmashan Hill in the known as
Yunyan Pagoda, in Suzl China.
The masonry structure, height of
18.8 m, was built in the reaches 6.5^o towards
the south (1° more than er of Pisa). Most probably, its tilting was
caused by the non-homo layers, for which stiffness varied with depth. Due to the lack of reliable documentation, these assumptions have been based on the research carried out on soil extracted in the close vicinity of the construction. It consisted mainly of silts and clays. The reasons for the Tiger Hill Pagoda's leaning were similar; the inclination occurred towards this side of the tower, where the layer of bearing soil was thinner. The construction of the 47-meter-high object, vertically inclined by 2.32 m (2.8^o), was based on a foundation, which sits half on the rock and half on the soil - this additionally enhanced the difference in settlement. The pagodas have not been straightened until now.