

Inclined Buildings – Some Reasons and Solutions

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Abstract. To straighten a leaning building is never easy. There are no standard solutions. On the other hand, there are several, usually historical, leaning structures which have not been rectified, mostly because in the current shape they are a touristic attraction - the best example being the famous Leaning Tower of Pisa. This does not mean however that 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 the other – 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 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 of the problem lie usually 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 of 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 paper contains a general overview of selected inclined buildings: starting with the well-known historical examples and ending with individual houses from the Region of Silesia. Since the problem of instability mostly affects structures with critical height to width ratio, tall and narrow structures (towers) are dominating in the work. The aim of the study was to describe the reasons of the problems and present solutions that have been successfully applied and can be also 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 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 the 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 [1]. Straightening of the building is then required immediately, in order to avoid a failure, or even a collapse, caused by exceeding of the ultimate limit state (ULS). It has been noticed that it is easier to achieve the critical slenderness in the case of a circular foundation than in the case of the more conventional rectangular one [2].

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 [3], 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 [4], it was stated that inclination of 20 - 25 mm/m strongly affects the users, while inclination above 25 mm/m often causes such decrease of the comfort that a 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 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 to any of the serviceability limit states sometimes means that the object cannot serve its basic functions anymore [5].

One of the most frequent reasons for 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, inclination of the buildings founded 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 the historic city centres or remain under protection of cultural heritage organizations, which makes the conservation works even more difficult and results frequently in 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 analysed 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 [6], [7]. The interior of the tower was closed for tourists for 12 years, which resulted in a 45% drop of their number and, consequently, in a decrease of 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 [8]. 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, change of 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 born 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 draught; or an abrupt application of load in 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 of tilting and, in some cases, 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 a 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 do rarely cause such problems as the process of their volumetric changes under loading often ends up before the building is put into use.

One of the famous examples of the objects vertically inclined due to the presence of weak cohesive soil is the Mexico Metropolitan Cathedral in Mexico City, 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 [9]. In 1995, the inclination to the south equalled from 0.11° to 1.15° , and towards 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 level of saturation, low shear strength and exceptionally high compressibility [10]. The subsidence was caused by the change of groundwater conditions as the result of excessive exploitation of aquifer layers under the city and 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 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 [2]. Thanks to the stabilization works (under excavation), conducted in 1993 – 1998, the inclination of the walls decreased by 0.34° from an average initial value of nearly 1.15° [9] (the rectification procedure is described below in section **Chyba! Nenašiel sa žiaden zdroj odkazov.**

The inclination of another very well-known object - the leaning tower of Pisa, 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 [11]. It is worth mentioning that this object probably avoided the earlier failure thanks to the long-term breaks during its construction, which caused gradual dissipation of the accumulated excess pore pressure in the clays. Some of the methods applied for stabilization of the tower are described shortly in the paragraphs **Chyba! Nenašiel sa žiaden zdroj odkazov.**

The remarkable case, in which it 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. 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 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 [2]. This story reveals the importance of the appropriately planned *in situ* and/or laboratory tests. The elevators were restored for further use in 1914, however there were as much as three different techniques applied to rectify them – they all are mentioned in the paragraphs **Chyba! Nenašiel sa žiaden zdroj odkazov.0 0**

Another examples of the objects leaning due to the ground conditions are two Chinese pagodas: Huzhu in Tianmashan Hill in the Songjiang District of Shanghai and Tiger Hill Pagoda, known also as Yunyan Pagoda, in Suzhou in Eastern China. The first one belongs to the oldest stone pagodas in China. The masonry structure based on the octagonal shape, of dimensions reaching 4 x 4 m and height of 18.8 m, was built in the 11th century. Currently, the inclination angle of the object reaches 6.5° towards south (1° more than inclination of the leaning tower of Pisa). Most probably, its tilting was caused by the non-homogeneous soil layers, for which stiffness varied with depth. Due to the lack of any reliable documentation, these assumptions have been based on the research carried out on a soil extracted in the close vicinity to the construction [12]. It consisted mainly of silts and clays. The reasons of the Tiger Hill Pagoda's leaning were similar, the inclination occurred towards this side of the tower, where the layer of a bearing soil was thinner [13]. The construction of the 47-meter-high object, vertically inclined by 2.32 m (2.8°), was based on a foundation, which sits half on the rock and half on the soil - this additionally enhanced the difference in settlement [14]. The pagodas have not been straightened until now.

An existence of a lens of a soil of very different compressibility under a corner of a footing is probably the most common reason of tilting of buildings. For instance, Rossiński [15] described a case of a 13-storey residential building in Rzeszów (south-eastern Poland), whose one edge settled by approximately 35 cm, while the other by 'only' around 14 cm, giving a distinctive inclination. The object was founded on soft and very soft organic soils with a 2 m deep sand lens under one corner. The bearing soil occurred at the depth of 12 m. This object was finally straightened by means of the combined methods described in the paragraph 3.3.

It shall be born in mind that inclination of a building can also result from uneven expansion of soil under the object, not only compression. This problem concerns the soils containing naturally occurring expansive minerals, e.g. montmorillonite clays, but may occur also in anthropogenic soils built of e.g. power plant slag or active fly ash. An example of such a failure can be the 18 m high lime silo at a glass factory in Dąbrowa Górnicza (Poland) [16], which tilted by 0.65° - an amount enough to affect the serviceability of the object. The reason of the differential swelling occurred to be a power plant slag of varying thickness, that was backfilling a retaining wall, behind which the structure was placed. The slag contained free CaO, which caused the material to swell. To stabilize the structure several solutions were suggested, including horizontal and vertical drainage, a jet-grouting wall to cut-off the water inflow and anchorage.

2.2. Problems associated with foundations

The excellent example of failures caused by the insufficient depth of foundation and selection of inappropriate foundation materials may be the inclination of many well-known towers in Venice, e.g. the belfry of Chiesa di Santo Stefano church, the Campanile on the St. Mark's Square, or the belfry at the San Giorgio dei Greci church. The presence of weak and compressible soils also contributed in these cases (the upper layers consist mainly of saturated sands, silts and clays), however, if the foundations had been protected and executed in the appropriate way, the tilting could have been probably avoided or limited. The type of foundation most often performed for the important Venetian

objects (e.g. belfries) was pile foundation. Due to the high costs and time-consumption of their execution, the piles rarely exceeded the length of 3 m and diameter of 25 cm, thus the foundations only partly met the requirements – the load was transferred to the weak compressible soil, instead of to the underlain bearing soil. Additionally, the majority of the wooden piles have not been replaced since the beginning of the previous century [17]. The wooden foundations tend to be a good solution only in the case of constant level of groundwater, because at water table fluctuations the material starts to rot. A regular conservation of such piles is indispensable.

Similar were the reasons of leaning of the over 27-meter-high tower of the late medieval church in Suurhusen (Germany). Its inclination equals 5.19° , which has been enough to take place in the Guinness World Records Book as the most inclined tower in the world, that is unintentionally tilted [18]. The church was built in the 13th century in the muddy area, with the foundations made of oak trunks, which during the years, were conserved by the groundwater. In the 19th century the surrounding area was drained, which initiated decomposition of the wood and caused the tower to tilt. The church steeple was closed to the public in 1975 for safety reasons, but reopened in 1985 after being reinforced. The same factors caused also the uneven settlement of Albert Memorial Clock in Belfast [19] - the object was straightened by means of underpinning (described in section 0)

As far as the inappropriate width or depth of the foundation is concerned, it can be supposed that deeper embedment depth of the Pisa's tower would also reduce or prevent its tilting – the tower foundations are placed at the depth of only 2 m with the width of its base 20 m [20]. One of the countermeasures applied during the last stabilization works of the Pisa tower was joining its foundations with the surrounding catino wall, which increased the effective area of the foundation.

2.3. *Problems connected with anthropogenic activity*

The conventional underground mining, in order to extract coal, oil, rock salt or other resources, has been realized for ages in many countries in the world. Such exploitation damages the rock mass and as a consequence the successive rock and soil layers deform, which is finally observed at the surface. In Poland, these issues are particularly relevant in the area of Upper Silesia, where the intensive underground exploitation of coal is conducted under strongly urbanized terrain. It has been estimated that in Silesia there are around 12,000 buildings per year [21] suffering from damages due to this reason. The problem concerns also other similar regions in the world, e.g. the Ostrava-Karvina coal basin in Czech Republic or Ruhr District in Germany. One of the most affected cities in the Upper Silesia is Bytom, having over 100-year-old mining history. The mining works have resulted here in particularly strong deformations of the ground. It often happens, that the mines, instead of using the expensive hydraulic backfill to fill in the space left after coal extraction (which would decrease the surface deformations), prefer to pay a compensation for the costs of houses' refurbishment. One of the documented examples of the vertical building inclination caused by mining was the 4-storey tenement house described by Sternik & Gromysz [22]. It was built in the traditional masonry technology as a single structure with a full basement, without expansion joints and with direct continuous footings. In the subsoil, there were bearing, medium compacted sands and gravels, as well as compressible, very soft organic soils. The building was inclined in the northern direction by approx. 1.15° , and from 0.17° to 0.45° towards west. It has been proved that the vertical inclination was caused by the mining subsidence, accompanied by the uneven settlement of the weak soil, which was activated at the end of the 60's of the XX century, when the last floor was added to the existing building. In order to stabilize the building and protect it from further tilting, underpinning (section 0) of the foundations has been proposed.

The other example of mining damages in Silesia is the 11-floor block of flats in Katowice, described by Gromysz [23]. It was built as 2-segment large-panel object in the „Fabud T” system. The building being 32 m high achieved the inclination of 1.55° . It was straightened by means of hydraulic lifts (described in section 0).

The straightening of old, historic buildings is one of the biggest problems connected with mining damages. It is particularly difficult in case of sacral objects, which due to the lack of inner walls, are characterized with low stiffness. Such an object is e.g. the monumental, wooden church of St. Nicolas, located in Upper Silesia, in Mikołów – Borowa Wieś. The church was built in 1737 and moved to the current location in 1938. Directly under the foundation plate, there are bearing sandy medium compacted soils. The building is located in the mining area with a fault zone in the rock mass. Thus, extraction of coal caused there not only the ductile deformations (horizontal stretching), but also brittle ones - forming a kind of linear terrain steps; both caused leaning of the church: the maximal wall inclination was 2.29° . The building was repaired several times [24] - the final rectification, recovering the vertical position, was conducted in 2011 by means of the uneven construction lifting method, described in section 0

Another example of a historic object leaning due to the mining damages is the church of St. Peter of Alcantara in Karvina - one of the major mining centres in Czech Republic. It was built in 1736 from brick. Currently the embedment depth of the church is 37 m (!) deeper than the original foundation and it is inclined by 7° towards south. This led to calling the object "Czech Pisa". The only reported interventions to stop the building from leaning and collapse were repeated reductions in the church's tower to decrease the leaning instability [25].

It is worth mentioning that one of the most inclined building in the world is the Glynne Arms, called „The Crooked House”, in Staffordshire in Great Britain. It was built as a farmhouse in 1765 and suffered strong coal mining subsidence in the middle of 19th century causing the tilting of 15° . Just like the Pisa's Tower, this building became a tourist attraction after it had been supported with buttresses and girders in 1940 [26].

Not only coal mining is responsible for anthropogenically caused tilting of structures. For example, the St Chad's Tower in Wybunbury (UK) had been steadily, for ages, tilting towards the north-east direction 5 to 10 mm per year due to the salt mine activity. The tower is located on stiff clay of thickness from 1.5 m to 4.9 m, and under it, there is fine sand, boulder clay and saliferous beds [27]. It has been rectified in 1832 as described in the paragraph **Chyba! Nenašel sa žiaden zdroj odkazov.**

The inclination can be caused also by influence of some underground constructions in the strongly urbanized area. The example can be the construction of the underground car park at the Palace of Westminster in 1970's and building of the Westminster Station of the London's underground in 1990's, described by Burland [6]. They caused e.g. slight inclination of Big Ben. The tower reached the inclination equal to 0.26° towards the north-west direction. The compensation grouting technique (see section 0) was used to prevent further leaning of the Clock Tower.

3. Methods of rectification

Distinguished can be three main groups of rectification methods, i.e. elimination of building deflection:

- forcing settlement of the higher parts of the structure, e.g. by means of ground removal;
- lifting the lower parts of the structure;
- simultaneous lowering of the higher parts of the object and lifting of the lower parts.

They have been shortly described below. Of course, it should be emphasized, that none of methods will be effective unless the reasons of the uneven settlement are determined and hampered. Straightening the object requires a specialized and experienced team and should always be accompanied with long-term monitoring.

3.1. Lowering the higher parts of the building

In these methods, the properties of the subsoil underlying the building are modified. In particular, the changes relate to soil compressibility, stress state, water content, etc. Straightening is achieved by controlled reduction of stiffness of the soil under the foundation. The volume of the layers gets reduced, forcing uneven settlement. Consequently, the object returns to the correct orientation in the space. Advantageous is the fact that the structure of the building during such works does not have to

be interfered with. Additionally, if the modifications are applied to larger ground volumes, the way the load of the building is transferred to the subsoil does not change as well. These methods can be used for rectification of buildings independently of the number of floors, type of foundation (slab, individual or continuous footings) and for most subsoils (natural, anthropogenic) [28]. The disadvantages include however: the increase of the embedment depth, which may, depending on the situation, because flooding of the basements or the need to rebuild infrastructure around the object; possible damage to the straightened building during cutting of soil layers; tedious preparatory works; the need to provide large access spaces around the rectified object. This is often a time-consuming work. Apart from these, the modification of soil properties is often difficult - the settlement of the object must be monitored very carefully to not get rapid soil deformations under the rectified object, which might cause a loss of control over the rectification process.

3.1.1 Under excavation. This method is also known as ‘gravitation-drilling’ or ‘soil extraction’: the appropriate amount of soil is extracted, in a highly-controlled manner, by means of boreholes, from beneath the raised part of the building. Depending on the needs, the holes are drilled vertically, horizontally or at an angle. The drilling rig is moving on specially prepared guide casings at the bottom of the previously prepared excavation in the immediate proximity of the rectified object. The subsoil deformation can be additionally adjusted by pouring water into the holes [27], [29]. Under the weight of the rectified object, the holes are made tight, which in turn leads to a controlled uneven settlement of the object and thus to its rotation.

This method has been used to correct the uneven settlement of many buildings [29], [30], [31], including the ones mentioned above: St Chad’s tower [27], Transcona elevators [32] or Metropolitan Cathedral of Mexico City [9]. This procedure was also originally proposed by Terracina [20] as one of the methods for the permanent stabilization of the Pisa’s Tower in 1962. The International Committee for the Safeguard of the Leaning Tower of Pisa reconsidered the idea at the end of the 20th century. After promising numerical analyzes and field trials, the operation began in February 1999 with the implementation of a preliminary series of 12 extraction holes with a slope of about 30 degrees, penetrating not more than 1 m under the tower’s base. In order to prevent unexpected construction movements during the drilling works, two sub-horizontal steel stays were installed at the height of 14 m connected to the tower and to two anchoring steel frames located behind the building. Approximately 7 m³ of soil were extracted by the use of a hollow-stemmed continuous flight auger housed inside a contra-rotating 168 mm diameter casing. As a result of this procedure, the northern edge settled 12 mm, and the southern was raised by 1.5 mm. Taking into account the positive result of the initial drilling, the operation continued from February 2000 to February 2001. 41 extraction holes were drilled, extracting 38 m³ of soil (69% from under the foundation and 31% from the ground on the north side of the tower). The assumed goal of reducing the inclination of the tower by half a degree (up to 3.99°) was achieved [7].

3.1.2 Loading ground. This method consists in loading the ground on the higher side of the structure. It requires a long time and is always at least partially reversible, since after removing the load, the soil layers are recompressed. Loading ground was again one of the treatments applied to level the Tower of Pisa - the northern side of the tower foundation was loaded with 600 tons of lead weights, at a distance of 6.3 m from the tower axis. The ballast loading lasted 10 months and resulted in a clear, though slight (1 minute of arc per year), reduction of the construction tilt. The treatment reduced the overturning moment by about 10% [1], however was not an aesthetic solution, so could not be treated as a permanent one in this case.

3.1.3 Drainage system / Electro-osmosis. Reduction of water content of fine soils decreases their volume, so can be applied locally to induce subsidence and lower a lifted part of an inclined building or to decrease a volume of a swollen soil. Such a controlled drainage was suggested e.g. as one of the methods to stabilize the expansive anthropogenic fill in Dąbrowa Górnicza as mentioned in section

2.3. To accelerate consolidation of silty or clayey soils, that are characterized with very low water permeability, electro-osmosis can be used. It is based on the electro-kinetic phenomenon consisting in causing the flow of water in the ground through the electric field applied to a certain part of the ground medium. The use of electro-osmosis for land drainage has been practiced in geotechnical engineering for a long time [33] and the computational procedures are well known in the planning and design of the electro-osmosis installations. The electro-osmosis was another method proposed to permanently stabilize the Leaning Tower of Pisa. The idea was to reduce the volume of the top layer of clay underneath the foundations on the north side. However, due to unsatisfactory results of field trials, this technique was abandoned [34]. On the other hand, a new drainage system was used successfully to decrease the fluctuations of groundwater table around the Pisa's Tower, which was also proved to be one of the reasons of its tilting [1].

3.2. *Lifting the lower part of the object*

Within this group of the methods of correcting the deflection of buildings two may be distinguished: hydraulic lifts and underpinning.

3.2.1 *Hydraulic lifts.* The rectification of buildings is executed by uneven lifting by means of hydraulic jacks. The object intended for straightening requires a number of preparatory procedures, including: chiseling out the niches for lifts, preparation of necessary reinforcement of the structure, installation of the jacks in the load bearing walls of the lowest floor of the building, temporary cut off of central heating, gas, water supply and sewage disposal systems. The rectification process itself runs in three phases. In the first phase, the building is torn apart by sequential displacement of the individual jacks. This results in an irregular gap running from the jack to the jack. The second phase is the parallel lifting of the object by 2 - 3 cm. This is necessary, so that in the next step, the edges of the straightened upper part of the building and the parts remaining in the ground do not catch up with each other. The third, fundamental phase of the rectification, is levelling of the horizontal surface of the building through uneven lifting of its upper part. Once the rectification process is completed, the repair phase is executed, i.e. walling up the gaps and the cavities left by the jacks, plastering the walls, execution of concrete floors in the basements to the desired level.

At present, in Poland, three ways of rectification of buildings through uneven lifting have been developed. They differ in the types of lifts used and the method of their control: force controlled lifts, displacement controlled lifts and membrane lifters. The particular systems, due to the load capacity of a single lift, are assigned individually to the given type of the rectified object [35].

Among the many advantages of this solution (incl. short time required, no discomfort for the users who can stay at the facility), its undoubted disadvantage is the change of the foundation's static work schema from the uniformly distributed load, which occurs when the building rests on a foundation, to the pointwise concentrated load resulting from jacks [36]. Therefore, it is necessary to always check the bearing capacity of the building, the foundations and the subsoil for such changed conditions.

Even though the method, as such, has been implemented relatively recently (e.g. in Poland, on a wider scale, in 1994), its principle was already used in 1914 during rectification of the bin-house in Transcona. The jacking screws were placed in the western (lower) part of the structure under the previously freed pillars. The purpose of this operation was to lift the building just above the groundwater table (still 4.3 m below the original embedment depth) and to rotate it to its original vertical position, which turned out to be successful [2].

The method of hydraulic lifts was used e.g. for rectification of the 11-storey apartment block of flats in Katowice, mentioned in chapter 2.3. Fifty membrane lifters were used in that operation – they consisted in oil-filled membranes with the initial height of 60 mm and the diameter of 520 mm. After filling with oil, they were able to increase in height by 60 mm. The membrane lifters were placed in the holes cut in the ground floor in the places, where the wall plates were resting on the foundation ribs. The small thickness of the walls (200 mm) required their local widening to provide full support of the lifts against the higher part of the building. Before the lifters were pumped in the designed

sequence, the walls were reinforced by means of steel sections attached to the both sides of the wall. The object's rectification was successful, prevented a construction disaster and restored the full functionality of the building [23].

The uneven lifting was applied also to straighten the St. Nicholas church in Mikołów (section 2.3.). In 1996 a concrete diaphragm slab was made over the brick and stone foundations and the old wooden foundation beams were replaced with new ones; in 2006 the building was rectified and the gap between the slab and walls was filled with a concrete beam. In 2010, after another mining activity, the church needed another repair. This time hydraulic jacks were installed in the holes made in the concrete beams and rested against the diaphragm slab to not interfere with the wooden construction elements. Eventually, the building was brought to the original vertical position, raised by about 20 cm and prepared for possible future repeat of the procedure.

3.2.2 Underpinning. Underpinning of foundations is a typical geotechnical method used to transfer loads of an existing building from the weak and compressible soil to some deeper and stronger strata. Its main aim is to stabilize the structure, but it is possible to use this technology also to reduce structure tilt by supporting the lower part of the object. Various technologies may be used for this purpose, e.g. jet grouting, pushed or drilled micropiles [22].

The work-house of the Transcona Grain Elevator was e.g. rectified with the use of underpinning: 1.5 m diameter piers were inserted under each of the 24 columns of the building and rested against the rock below [2]. Underpinning was applied as well to stabilize the settlement of the Albert Memorial Clock in Belfast. It has been used also to reduce the tilting of the Big Ben in London caused by tunneling works conducted in its close proximity [6]. There, the compensation grouting technique was adopted, that involved injecting under high pressure to the ground, at selected locations, a mixture of cement, sand and water with high binding abilities. In the first place, sixteen 50 m long steel injection pipes were installed radially outwards from a vertical shaft into the London Clay layer under the building's foundations. The maximum spacing of the pipes was 2.5 m. In total, 24 grouting episodes were undertaken and 122 m³ of the grout injected between February 1996 and September 1997. This operation prevented the predicted damage to the Big Ben tower and stabilized its settlement.

3.3. Combined methods

Combined rectification methods can be considered as a combination of straightening by lowering or removing the soil and uneven lifting or underpinning.

Worth mentioning here is the 'one-way lever' method. It consists in raising the excessively lowered part of the building while simultaneously extracting the soil from the opposite part. It was used in practice e.g. to straighten the 13-floor building in Rzeszów, described in paragraph 2.1. The cellular mat foundation of the object was reinforced and a cantilever was added to it. Next, Wolfsholz type piles were introduced under the cantilever and six hydraulic lifts were inserted between the piles and the cantilever. On the other hand, the raised part of the building was under-excavated. The hydraulic jacks were used to lift the deeper foundation parts, while the upper part was lowered. Eventually, the maximum settlement decreased by 3 cm, while the opposite edge lowered by 13 cm, giving the settlement difference of only 5 cm [15]. This type of procedure can only be applied when the direction of inclination of the building is parallel to its structural system and the bearing soil is not too deep.

4. Concluding remarks

As it can be concluded based on the various case studies described in this paper, the most important to prevent tilting of buildings is a proper identification of the ground parameters and awareness of the possible consequences when problematic soils are encountered. These include soils of low bearing capacity, permeability and stiffness; expansive soils; interlayered soils – especially the ones with inclined strata. Their presence needs to be taken into account at the design and execution stages of the construction process. Equally important is the proper calculation/prediction of the magnitude, type,

conditions and velocity of loading – especially when the building is to be located in a mining area, where additional straining has to be allowed for.

If the building inclination has already been noted, its rectification must be preceded with a very thoughtful analysis. First of all, it should concentrate on determination of the reasons of the leaning. Indispensable are: geotechnical investigation, geodetic measurements and assessment of the technical condition of the structure. The soil-structure interaction should be modelled (e.g. with the use of numerical or true-scale analogies), to forecast the behaviour of the building during the rectification works. It is recommended to consider various methods of rectification to find the optimum one or their optimum combination.

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