Revitalisation of a Vertically Deflected Historical 16th Century Bell Tower

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Abstract. A wooden bell tower, erected in the 16th century, was vertically deflected due to uneven settlement of the subgrade having insufficient load-bearing capacity. The structure's condition was continuously deteriorating due to the advancing structural deformation. Structure renovation was designed and carried out in two phases. Foundations in the form of piles and strips were executed under the existing structure in the first phase, and then the structure was reinforced and straightened with twelve hydraulic jacks. The damaged above-ground components of the construction and its sheathing were replaced in the second phase. With the designed and executed procedure, it was possible to preserve the historical building in the unaltered form without interfering with the elements of the 500 hundred-years-old structure's construction. Force values and jacks’ displacements were measured during straightening. The construction's behaviour, when eliminating the deflection, was described with the measurement forces in jacks and its displacement.

1. Introduction

Historical wooden structures are usually rested on stone foundations. The load carrying capacity of such foundations, after hundreds of years of use and the impact of unfavourable factors, often turns out to be insufficient [1]. Such structures are subject to uneven settlement, deflections and deformations as a result. In such case, structure renovation is usually performed by its disassembly, construction of a new foundation and then rebuilding the structure in the vertical position. Such procedure causes, however, irreversible changes to historical buildings’ construction. A much more advantageous solution is to perform renovation in such a way as to avoid disassembly of a vertically deflected structure. Unconventional solutions should then be designed and executed, including the construction of new foundations under the existing structure and its straightening [2][3]. Such procedure interferes with the original constructional solution as little as possible and allows to preserve the original value of the renovated structure.

2. Bell tower description

A free-standing bell tower is located in Poniszowice and is 21.47 m high (Figure 1) and is characterised by a rectangular plan, with the dimensions of 7.80 m × 7.86 m at the ground level (Figure 2a). The structure features a wooden frame construction with four main corner pillars, braced with crosswise struts and with locks situated on five levels. Before the renovation described in point 3, the corner pillars with the cross-section of 340/340 mm and the bracings (bracings’ cross-section of 170/170 mm to 200/200 mm) were mounted in a ground beam with the cross-section of 350/350 mm, situated at the structure's floor level. The entire structure was rested upon stone foundations consisting of irregularly
shaped boulders with the diameter of 1.2 m, laid to the depth of 1.5 m below the ground level. It is reported that the bell tower, depending on the references, was erected in 1520 [1] or in 1570.

Figure 1. Historical 16th century bell tower: a) view from southern-western side, b) cross-section (C – C section location is shown in Figure 2a)

Above the level of +10.40 m, the tower consists of an overhanging starling, transiting into an octagonal marquee-shaped shingled roof at the level of +14.7 m. The bearing structure of the starling includes two systems of pillars – an internal one placed on pile caps above the walls of the lower part, and an external one rested on the supports of joist hangers (Figure 2b). In addition, a central pillar is situated along the starling axis, which is a main member of the roof framework. The pillars along the both lines are additionally reinforced with struts and angle braces. A roof above the starling is constructed as a shingled marquee-shaped roof. An indirect shingled roof was made at the level of +4.00 m. The internal access is ensured via a wooden ladder (gangway) leading from the level of ±0.00 to +10.40 (Figure 1b). The structure walls are boarded (sheathing) with 25 mm thick vertical boards with joints covered with outer 20 mm thick battens. Four bells are installed in the structure. The oldest bell, called “Word of the Lord”, with the weight of 200 kg, dates back to 1536. Three new bronze bells were installed in the place of the three bells robbed during the war in 1942, and they are called: “John the Baptist” with the weight of 600 kg, “Our Lady of Częstochowa” with the weight of 400 kg and “Saint Joseph” with the weight of 500 kg.
The existing sheathing comes probably from 1906, when the structure was partly repaired. A centrally positioned door opening is provided in the northern façade; a wooden single-leaf door is mounted in the opening, fitted on a wooden frame with metal hinges. In addition, concrete reinforcements were constructed in the recent years around the stone foundations and partly over the ground beam of the southern wall. The elements were meant to stop the forming deformations and to fill the space between the stone foundations and a ground sill, with such space being formed due to subsoil subsidence.

Three geotechnical boreholes with the depth of 5.0 m each, marked as 1, 2, 3, were executed inside the structure to determine the soil conditions, and their locations are shown in Figure 2a. It was found that a layer of man-made fill materials consisting of sands with clay and silt additions is deposited immediately underneath the tower, with the total thickness of 1.6 m to 2.4 m. The native subsoil, situated beneath, consists of cohesive soils made of sandy clays and silts. The lenses of sandy deposits are deposited among such formations – medium-grained sands with the thickness of 0.3 to 2.1 m.

The subsoil was classified according to geotechnical layers in order to characterise the geotechnical conditions, and two genetic groups of deposits were distinguished: made ground (group I) and quaternary soils (group II). One layer of made ground with the thickness of 1.6 m to 2.4 m, covering the entire studied areas, was assigned to group I. It is formed by sands with clay and silt additions. The formations are young, loose and inhomogeneous. Two layers were distinguished for group II, made of Quaternary soils. Hard-plastic silts and sandy clays were classified as the layer IIa. They are deposited across the whole examined site in the upper part of the profile, near openings no. 1 and 2, from the depth of 1.6 ÷ 2.1 m to 1.9 ÷ 2.6 m (Figure 3). Moreover, in case of opening no. 3, the layer IIa is deposited also in the middle part, at the depth of 2.7 m to 4.0 m, and in the lower part, to the depth of recognition. The layer IIb is made of medium-grained sands in the medium-compacted state. The sands were encountered across the entire examined area below the depth of 1.9 ÷ 2.6 m, to the depth of 2.7 ÷ 4.0 m.

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**Figure 2.** Bell tower plan (location of A – A and B – B sections are shown in Figure 5): a) at the ground level, b) at the level of +10.40 m
3. Bell tower condition
The structure had numerous damages prior to undertaking the renovation. The most serious damage was a well-advanced corrosion of ground beams and the subsidence of the southern tower corners caused by uneven ground settlement. The structure was considerably deflected in the south-east direction as a result of the subsidence of the corners. The deflection value and direction were established by measuring the tilt of the walls at the +1.0 m level (Figure 4a) and of the starling pillars at the +11.4 m level (Figure 4b). The measurements were made with the accuracy of 1 mm/m with an electronic spirit level with the base length of 0.8 m. It was found that the dominating deflection direction is south. Measurements at the level of +1.0 m showed that average deflection in the southern direction is 51 mm/m, and for measurements at the level of +11.4 m - 45 mm/m. The average deflection component value in the eastern direction is, respectively, 10 mm/m and 9 mm/m.

The other important structure damages included: local corrosive damages of the wall boarding boards and battens, local corrosive damages of wooden parts and their losses as well as advanced technical wear of other parts: stairs (gangway), floor, starling, the connection of stairs with a handrail and also handrails were locally missing inside the structure.

Numerous local cracks of the wood (boarding) were seen in the outer tower walls. Some of the wooden parts were destroyed by fungi; partly the destructions were superficial, and locally deep wood recesses were seen, especially dangerous if the pillar interior is destroyed and only the outer shell is preserved. The joints of wooden elements were partly deformed – large cracks existed in them. The pillars near the support on the ground sill were destroyed by fungus. The elements of the southern wall...
were the most strongly corroded constructional members. This results from the build-up of moisture on this side of the tower, because the structure was deflected in the southern direction.

4. Bell tower renovation
The tower renovation was divided into two phases. In the first phase, the structure was straightened and foundations were constructed underneath, and conservatory works for the structure's wooden construction were carried out in the second phase. The designed and executed phases are presented in the points below.

4.1. Construction of foundations and removal of bell tower deflection
Before performing the works interfering with the bell tower elements, the structure was secured. At the level of + 0.60 m, a system of rolled sections was constructed, consisting of ring beam (two 160 running along each of the walls) and bracings (one 160). The sections running along the walls were arranged in such a way that one was inside the tower and the other outside, but underneath the outer sheathing of the structure. The sections were joined with M20 bolts mounted at the spacing of 1 m. If the steel sections were not adhering tightly to the wooden construction, wedges were inserted between the tower construction elements (pillars, struts) and steel reinforcements. This way, the steel sections were enclosing all the elements of the wooden construction of walls. The stiffness of the reinforcement running along the load-carrying walls was ensured by bracings joined with the reinforcement, also made of 160, arranged through the centre of the tower, and also bracings in the corner.

Nine foundation piles were started to be executed after securing the tower. As the distance between the tower and the graves is small (bell tower is located at commentary Figure 1a, Figure 2a), the pillars were executed by a traditional method, with drilling boreholes in the ground with a drilling machine (Figure 8a). The drilling machine was brought inside the tower by stripping down partially the sheathing of the eastern wall. The material extracted from the borehole with a 0.3 m diameter drill was being removed, and after reaching the depth of 5.0 m, a reinforcement in form of one rod with a diameter of 40 mm was introduced into the borehole and then the borehole was filled with a concrete mix. It was necessary to dismantle locally the stone structure foundation when executing the piles. A ground beam was uncovered when extracting the stone. It was found that there are large recesses in the beam, especially from the foundation stones’ side. Due to extensive corrosion and practically the lack of the interior, the ground beam cross-section was not a square with the side length of 350 mm, but it was a U-shaped open section, with the wall thickness of approx. 50 mm. Most of the ground beams broke into pieces when constructing the foundation piles.

The tower straightening process was comprised of several stages, with the tower being restored to the vertical position in the last step. Twelve supports were prepared for jacks in the first place. The supports were located in the axes of the walls under the reinforcements made of rolled sections. Two supports were provided near each corner and one support in the centre of the walls. The newly executed piles, as well as the new expanded stone foundations, were the main elements of the supports. The top surface of the supports was levelled by placing a layer of concrete and by mounting 20 mm steel plates in them. The jacks were placed directly onto the plates, and the location and numbers of the jacks are shown in Figure 5a.

Apart from the supports for jacks, temporary supports were made, which were taking over the tower weight when the jack was being underlain, due to a limited range of piston extension [2]. Each temporary support consisted of two foundation footings situated outside the axes of the walls. One axis was inside the wall, and the other outside. Rolled sections were rested on the top surface of the footings. The tower weight was placed directly on such sections or using wooden blocks and steel distance pieces.

The tower was being straightened with twelve jacks. Piston extension in the individual jacks were forced during the straightening, in such a way that the tower was restored to the vertical position. The southern-eastern corner, having the lowest position, was raised by 542 mm as a result.

The force values in the jacks, and the extension of the jack piston, were recorded during straightening. Figure 5b lists the values of forces occurring in the jacks after raising the structure. The sum of the forces
is 216 kN and it is equivalent to the tower weight. Variations in force values and piston extension for jacks no. 7 and 24 are given in charts in Figure 6. The force values in the jack no. 7 fell to zero three times, which was necessary because the load had to be removed from the jack and the jack had to be overlain. The load was transmitted to indirect supports in the meantime. In case of jack no. 24, due to small height of raising, no unloading was necessary, for this reason variations in force values during straightening were not considerable. After restoring the tower to the vertical position, its weight was taken over by temporary supports.

A reinforced concrete strip foundation was then executed under the tower, representing also a cap of the reinforced concrete piles (Figure 7a). The footing has a square cross-section with the side length of 500 mm (Figure 7b). The longitudinal reinforcement of the footings is made of bars with a diameter of 12 mm and the vertical reinforcement is made of stirrups made of bars with a diameter of 6 mm, spaced every 300 mm. When the footing concrete has reached the strength, the temporary footings of the support were disassembled and the tower weight was rested upon the footing. After performing the construction works, the reinforced concrete footing was secured with bituminous anticorrosive coatings and the area around was tidied up. The phases of the works discussed above are shown in images (Figure 8).

Steel reinforcements were left in the tower walls between the two phases of renovation. They were balancing the horizontal expansion forces transferred by the tower pillars. The steel elements were removed after installing the ground beam.

![Figure 5](image-url)  
**Figure 5.** The force values measured in the jacks after the even raising of the bell tower by 5 mm
Figure 6. The force values and piston extension values measured in the jacks during uneven bell tower raising: a) forces in jack no. 7, b) piston extension of jack no. 7, c) forces in jack no. 24, d) piston extension of jack no. 24

Figure 7. The newly constructed reinforced concrete foundation of the tower: a) foundation plan, b) cross-section
4.2. Wooden structure renovation

The above-ground part of the bell tower was repaired in the second phase of works (Figure 9a). The ground beam elements and the structure boarding were replaced in particular (Figure 9b, c). The completed works were carried out in the following order:

- the sheathing of the walls was disassembled and its preservation condition was evaluated; it was decided to replace the entire boarding);
- the shingled roof covering was dismantled;
- the starling floor, which was degraded and posed a threat to safety, was disassembled, and a gangway and a railing were also disassembled;
- the parts of the bell tower construction, which were in a good condition, were conserved and those degraded were replaced;
- a new floor of the tower made of coniferous larch wood was placed and the gangway, which underwent conservatory works was mounted;
- new shingles were fitted on the tower roof and the wall boarding was put in place;
- the shingles and the boarding were secured and their colours were matched using a decorative protective varnish;
- the whole wood tower construction was raised to determine how much the pillars were destroyed and to repair them (it was decided to cut off the ends of the pillars);
- new ground beams were installed;
- the tower construction was lowered onto the ground beams.

As presented above, the ends of the corner pillars and struts were cut off due to poor technical condition. The length of the pillars was decreased by 0.18 m to 0.25 m. A decision was made to increase the cross-section of the ground beams in order to maintain the height of the tower and the mutual distances between its elements, including the height of the entrance to the structure. The height of the ground beams’ cross-section was increased for this purpose from 0.18 m to 0.25 m (Figure 10).
5. Conclusions
Deflected wooden historical structures, being in the emergency condition due to insufficient load-bearing capacity of the subsoil, can be renovated by stripping them down, executing new foundations and then by reconstructing them. An alternative method, used for a historical 16th cent. tower, was to design and perform special renovation in two phases. In the first phase, the structure was placed onto temporary supports, straightened with hydraulic jacks and foundations were constructed underneath, consisting of reinforced concrete piles and footings. The above-ground part of the bell tower was repaired in the second phase. The wooden ground beams and the boarding of the structure were replaced.
in particular. With such procedure, it was possible to preserve the historical building without interfering with the constructional elements of the 500 hundred-years-old structure.

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