Structural Diagnosis of the Medieval Bell Tower in the Town of Aquileia (Italy)

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Abstract

This paper presents the historical evolution and mechanical analysis of the medieval bell tower in the town of Aquileia, Italy. The main characteristics of the foundation soil are examined in order to comprehend the actual stress-strain state of the tower ten centuries after its construction. Moreover, in order to fully understand the behaviour of the belt tower, the architectural history as well as the construction and the restoration works are examined and presented in detail.

1. Introduction

The town of Aquileia, located at the extreme northern tip of the Adriatic sea, is situated a few kilometers from the lagoon of Grado. Founded in 181 BC, the town of Aquileia originated as a military garrison of the Roman Republic, whose purpose was to hold back barbaric invasions from the east. The city was razed to the ground in 452 AD by the Huns of Attila.

The Aquileia basilica was built in 5th century. Patriarch Massenzio (9th century) built a crypt and a transept. At the beginning of the 11th century the church was transformed by Patriarch Poppo (1019-1042), by building the apse
and transforming the crypt (around 1030). The bell tower (Fig.1, Fig.2) was probably built in that period.

The church was damaged by an earthquake in 1348 and was rebuilt by Patriarch Marquardo. The bell tower, which was greatly damaged by that earthquake and then later by wind and other causes (a lightning bolt hit it in 1468), was partially rebuilt and retrofitted also by the building of a larger stone masonry base. At present the tower is inclined by a few degrees from the vertical axis.

The analyses of the various factors that have contributed to the settling of the tower of Aquileia from a geotechnical and structural point of view are presented. Moreover some important observations by researchers and archaeologists of the past in order to retrace the structural history of the tower are taken into account.

Special attention has been dedicated to the territorial behaviour. Hence, it was possible to make a reasonable separation between the settlements due to natural and to anthropic causes.

The horizontal actions due to wind and earthquake, as well as the vertical loads, are taken into account in order to develop the stress analysis of the tower. The pressures acting at ground level are calculated and the possible stresses and deformations of the soil are analysed and discussed in an exhaustive manner.

Figure 1: A view of the bell tower in the Town of Aquileia (1030 a.C.)
Figure 2: View, vertical and horizontal sections of the bell tower from a survey of 19th century.
2. Historical evolution of the bell tower

From the examination of written documents (i.e. manuscripts and stone engravings), as well as from some logical interpretation of the construction works, it is possible to outline the evolution that the Aquileia bell tower has undergone (Bertacchi 1973). Historical news is reported by the findings of Monsignor G. Vale (1927). Furthermore, the history of the bell tower can be deduced from architectonic and historical changes, architectonic shapes and the materials employed in the construction works as well as from an analysis of the materials led down inside the bell tower.

The following main points must be recalled to understand the history of the construction, namely:

1) from historical news we can say that the tower (i.e.: at that time it seems it was a tower without bells) was erected by request from the Patriarch Poppo at the beginning of the XI century;
2) at the beginning of the XIV century the tower became a real bell tower. Thus bells were present. As a matter of fact in the year 1296 seven bells were reinforced;
3) in the XIII century the bell tower was completed and since that time restoration works are reported, often associated to earthquake phenomena;
4) the basement of the bell tower was enlarged, probably after the quake in 1348, under the supervision of the Patriarch Marquardo. The sides of the square base, which originally measured 11.95 m (Bertacchi 1973), were enlarged to 19.97 m;
5) in the year 1467 the very top of the bell tower was reconstructed;
6) the bell tower was struck by lightning bolts several times and a lightning conductor was installed only in the middle of the 19th century.

Many important events are not mentioned in the history of the bell tower, for instance the earthquakes which occurred and were recorded in the years 1297, 1301, 1348 and 1501.

Neither was the settlement and the inclination of the tower and its possible straightening reported.

In Fig. 2 the main dimensions of the basement of the bell tower are reported both in plant and in cross section.

During its lifetime, the tower was utilized as a bell tower, a prison, a troop-quartering, a reliquary and a lookout.

It also testified the existing conflicts, even at that time, between the Patriarchs, Austrians, Venetians and the Church.

3. The foundation soil

The foundation soil in the central sites of the Roman colony of Aquileia can be identified, considering the data deduced from geotechnical borings and laboratory tests performed on soil samples. Figure 3 summarizes significant classification data relating to stratigraphic structures between 1.70 m and 7.00 m in depth, together with volumetric weights and Atterberg limit values of
Figure 3: Classification of several samples extracted from first 10 meters of stratification structure in Aquileia

Figure 4: Foundation levels of two antique structures in the town of Aquileia
survey samples, from which it can be readily deduced that the plasticity index is quite low. This value is generally less than 17% and has a mean value of $I_p = 10.5$ for the case in question, this characterising soils of silty-clayey grain size.

Oedometric compression tests performed on samples taken from a depth of up to 9 meters from the top soil level yielded compressibility index values $C_C$ (on a semi-logarithmic $e$ vs. $\log \sigma$ graph) ranging from 0.27 to 0.13, increasing proportionally with the plasticity indexes of the samples, and a recompression index value $C_T$ ranging from 0.07 to 0.007. Therefore the $C_C/C_T$ ratio for these samples varied from 12 to 20.

4. Settlement survey evaluation

Before carrying out settlement survey evaluations, we need to consider the compressibility of the alluvium deposits. The cohesive soil layers lying within the first 9 meters from the top surface of the town centre of Aquileia are to be considered as slightly overconsolidated, due to drying.

Over the last 2000 years, the elevation of this area, defined by the lagoon and not very highly anthropised even in recent times, has varied up to 2 meters in height, with alluvium having mostly been deposited by the water courses located between the two rivers, Tagliamento and Isonzo (Fig. 4).

Values for consolidation pressure $\sigma'_c$ indicate that the degree of overconsolidation OCR (given by the ratio between consolidation stress $\sigma'_c$ and effective geostatic stress $\sigma'_v$) ranges from 1.1 to 3.1.

Due to the relatively small temporal influence (assumed to be 2000 years), as also deduced through historical research on the area, and the apparent lack of overload, the overconsolidation pressure value may be attributed to the drying out of alluvium alone.

5. Actions on the tower

The self-weight of the bell tower may be suitably considered as the main vertical load acting on itself. The previously described construction stages and subsequent restoration works are responsible for the differing degrees of eccentricity of the tower sections.

In particular, when examining the geometrical survey, a rectification of the inclination of the upper part of the bell tower is evident.

As a consequence of these circumstances, combined with the construction of the top part of the tower, which was built at a later date, the pressure distribution measured by means of flat jacks is not uniformly distributed (Figure 5).

One of the most noteworthy horizontal loads acting on the belt tower is due to strong winds, a typical feature of the area in which Aquileia is situated. The closest survey point where experimental data regarding wind action may be collected is at Punta Sdobba, for which figure 6 plots average wind speeds and directions measured in the year 1992. As expected, the greatest wind speed
Figure 5: Pressure values (MPa) measured with flat jacks at level + 7.80 m

Figure 6: Measured average wind speeds and directions for year 1992.
recording lies along a N-E direction (i.e. the renowned “bora” winds of this region). Nevertheless, wind action is of notable magnitude also along other directions. Measured average wind speed values in the area are approximately 21 m/s, which is a mean value over 10 minutes' recording. Thus a wind speed value of 25 m/s (in accordance with Italian standards for this zone) may be safely adopted for the calculations.

6. Mechanical diagnosis of the tower

At the present stage of survey, we point out the following items:

a) The cross section is not homogeneous (heterogeneous "sandwich" masonry, as tested by sampling tests);

b) the mean stress value of 0.793 MPa, assumed in a previous analysis (Bertacchi et al. 1980) in order to carry out considerations regarding the soil stress situation, does not yield realistic results on local inspection if referred to the load-bearing walls, but provides only an average stress assessment, thus referring to the overall area;

c) part of the load-bearing capacity can be attributed to the external stony elements of the wall of the heterogeneous sandwich masonry. This assumption is confirmed by results of tests using flat jacks, which have revealed stress values for the external stony elements ranging from 1.1 to 4.2 MPa (Fig. 5);

d) the varying homogeneity of the stony walls referring to the internal conglomerate material, while awaiting results of measurements (i.e. strength and elasticity modulus) on the core samples, is assumed from approximated calculations, with a mean stress value $\sigma_1=2.9$ MPa on the outer walls (measured by means of the flat jacks), a value of the homogenization ratio (between the elastic moduli of internal material and the outer stone) of about 0.015 - 0.020.

7. Stresses and deformations of the ground level

Evaluations of soil settling phenomena (over the last 2000 years) must take into account a number of fixed topographic reference points.

For this reason, it has been assumed that the road network built during the era of the Roman republic at first, and later during the period of the Roman Empire, must have been set more or less at the existing ground level. According to this hypothesis, all variations in elevation must therefore have been caused by various kinds of external factors. The cause of these variations in elevation with respect to the situation existing 2000 years ago is indicated by the sedimentary soil that was found (and measured) in the area.

At this point, we can say that the ground level has undergone a variation of about 1.70 m as reported by Soranzo (1996). This level variation is mainly due to sedimentation phenomena, while consolidation and secondary compression settlement are responsible for less than half of the total settlement.
Conclusions

On the basis of the presented studies, which have taken into account the historical development, the construction phases, the restoration works, as well as the measurement performed on the tower, it is possible to develop the following conclusions:
1) the actual state of the belt tower presents some critical points that require future investigation;
2) the masonry structure is quite complex: stone walls consist of two external load-carrying stone masonry walls, with lose material inside;
3) the mechanical characteristics of the stone masonry walls have been studied by means of flat-jack tests, which have provided maximum stress values of about 4.2 MPa at 7.80 m level. This high stress value may be justified by the fact that most of the load seems to be concentrated mainly on the external stone walls;
4) The settlement developed mostly along a vertical direction, as demonstrated by the small tilt revealed by measurements carried out at various levels along the walls of the bell tower, owing to the fact that the tower took three centuries to be completed.

Further developments of this research deal with the second survey stage, including:
   a) core boring in order to evaluate the actual morphology of the masonry elements, with particular attention to the mechanical strength and consistency of the sandwich masonry structures;
   b) penetrometer tests for the characterisation of the soil foundation;
   c) measurements of the water bearing stratum by means of a piezometer;
   d) dynamic analysis of the tower vibrations, in order to identify the mechanical characteristics of the structures;
   e) wind detection measurements by means of a winder.

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