National Conference with International Participations

**ENGINEERING MECHANICS 2008**

**Svratka, Czech Republic, May 12 – 15, 2008**

# DYNAMIC ANALYSIS OF TUBULAR STEEL WATER TANK TOWER

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**Summary:** *The water tanks belong to structures that should be verified with regard to their wind and earthquake response and resistance. The progress in development of new National and International Standards activates verifications of analytical models, design and execution of new and existing structures. The rules for the design of steel structure and its details are included in Eurocode 3. The design procedure includes also the dynamic analysis of the respective structure. In order to create the appropriate amount of data and limit statements necessary for simplified or more sophisticated analytical models, any knowledge of actual existing structure dynamic behavior is welcome.*

## 1. Introduction

The water tanks belong to structures that should be verified with regard to their wind and earthquake response and resistance. The progress in development of new National and International Standards activates verifications of analytical models, design and execution of new and existing structures. The rules for the design of steel structure and its details are included in Eurocode 3. The design procedure includes also the dynamic analysis of the respective structure. In order to create the appropriate amount of data and limit statements necessary for simplified or more sophisticated analytical models, any knowledge of actual existing structure dynamic behavior is welcome.

## 2. The Description of investigated structure

The analyzed steel water tank tower was designed and constructed at Drahňov in Eastern Slovakia and now serves for field watering. The tower is 97 m high constructed like lattice tower with three corner tubes that create the basic carrying system. Two of tubes have diameter 1.34 m and the third one has 2.54 m. The thickness of tube wall is variable from 20 mm at the foundation and it decreases in top direction through 16, 14, and 12 up to 10 mm. The corner tubes are anchored into R/C foundation slab. The cylindrical water tank is situated on the top of the tower and has diameter 15.5 m, height 6.8 m and its content can reach 500

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$m^3$. The brace is from welded I profiles 2×300/12+322/8. The bottom of the tank is the orthotropic plate with primary and secondary welded I-beams. The sheet of plate is 10 mm thick; the wall of tank has thickness 6 mm. The service content of the tank is limited to 470 $m^3$. In view of expected stresses the steel S 355 for the lower part of the tower and S 235 for the upper part were used. The tower steel structure is welded; the bracing is connected to corner tubes by high strength bolts, (Fig.1). The view of R/C foundation slab is in Fig.2, general soil profile indicates clays, sands, sandy gravel and rather high underground water table. The added artificial compacted gravel layer below the foundation is 0.5 m thick.

Fig.1: General view of steel water tank tower Drahňov

## 3. Experimental Test

In the case of field measurements it is advantageous and reasonable to use all available sources of excitation, either random sources or artificial ones. Small vibration exciters have the advantage of being portable and easily operated. Firm bracing between the load carrying elements of the structure provides efficient transfer of the exciting force to the structure. The relatively small total mass of the applied exciter and possibility of simple installation into the tested structure enable measurements of different systems of buildings, towers and bridges. Beside the measurements of ambient vibrations the mechanical exciter was used like the basic source of excitation of investigated water tank tower. The position of exciter during the tests was inside of the largest corner tube at the mid-height of the first brace. The set of accelerometers was used for measurement of global and local vibrations in the most representing sections and points (Fig.3). For the recording both analogue and digital methods were used including A/D converters, filters, on/off line evaluation and reasonable data acquisition. (Benčat et al., 2000)

The damping of tower determined from free tail vibration and that from steady harmonic vibration varied through damping ratio $\zeta$ = 0.024 for empty tank and $\zeta$ = 0.021 for the full tank. Local vibration damping ratio of the largest tube was determined from impact tests and reached the value up to 0.05.

The recorded signals (Fig.4) were evaluated in laboratory of the Dept. of Structural Mechanic (CEF – University of Žilina) or preferably in situ using amplitude, frequency and amplitude – phase analysis, by method of spectral or correlation analysis using two channel frequency analyser (Bruel-Kjaer) connected via GPIB with relevant software (e.g.DISYS).The main experimental natural frequencies of the tested water tank tower via spectral analysis (Fig.5) are in Tab. 1.

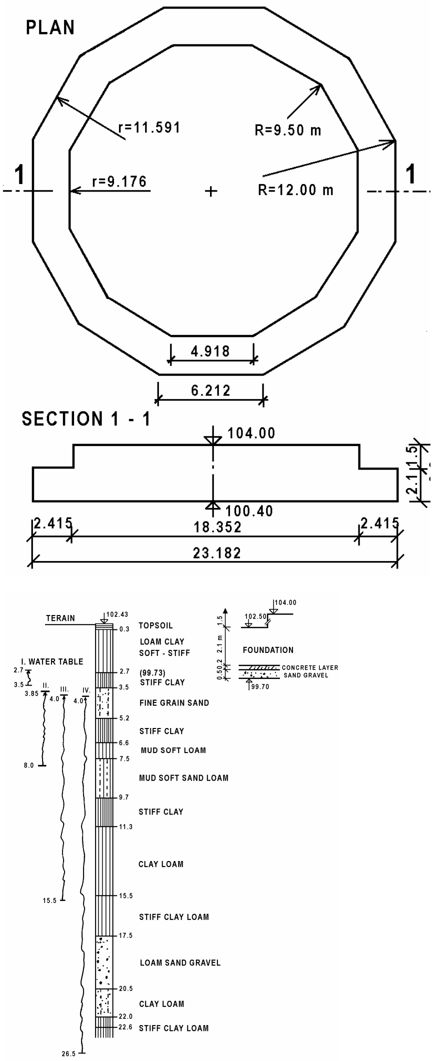


Fig.2: R/C foundation slab below the water tank tower and soil profile beneath

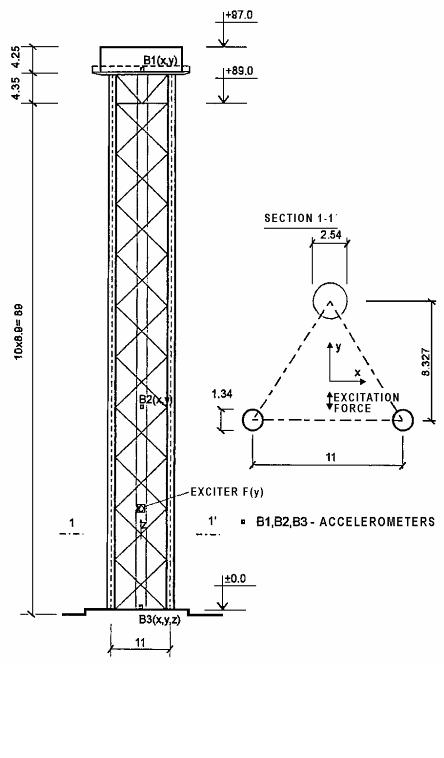


Fig.3: Accelerometers position in the tower (B1x,y, B2x,y, B3x,y,z)

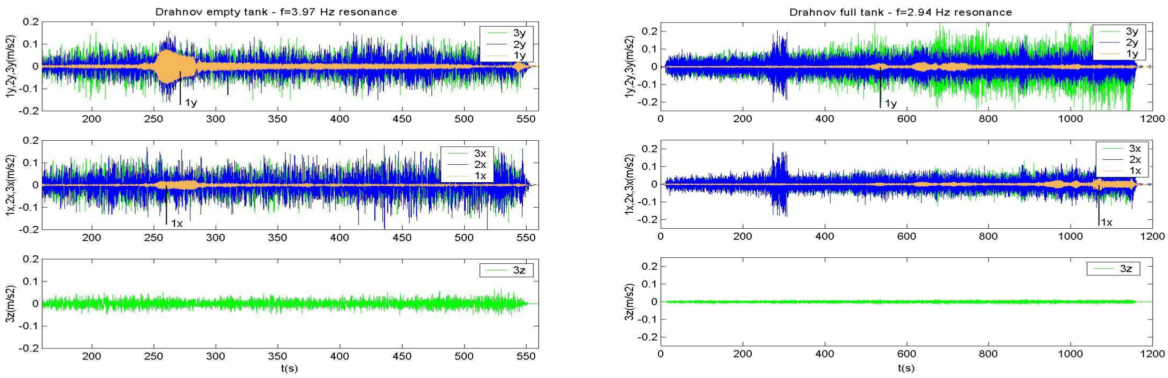


Fig.4: Harmonic response of empty and full water tank tower to mechanical exciter

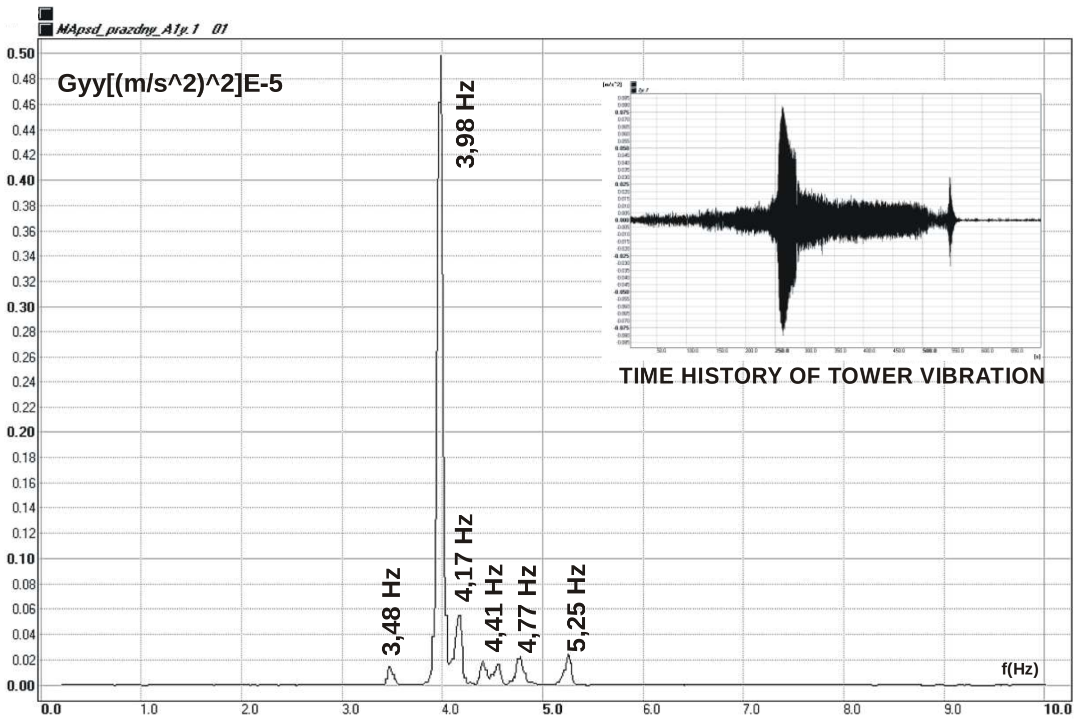


Fig.5 PSD at point B1(y) – Empty Tank

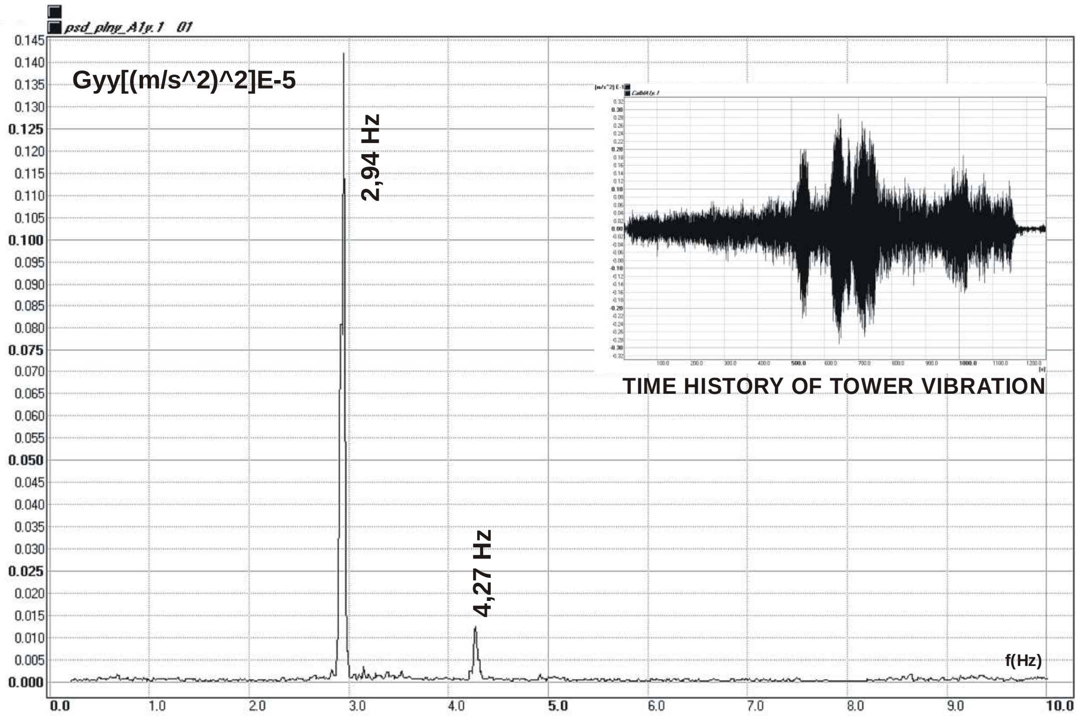


Fig.5 PSD at point B1(y) – Full Tank

## Calculated natural frequencies and modes

The original calculations were performed before any test started. After the results of tests were known, the sensitivity study included few analytical model modifications (Juhásová et al., 2002; Krištofovič, 2001). They are as follows:

a) FEM model that consists of set of beam elements and stiff connection to the base;

b) FEM model that considered boundary springs and beam elements;

c) FEM model with liquid in the tank considered like stiff body, beam elements and stiff connection to the base

d) FEM model with liquid in the tank considered like stiff body, beam elements and boundary springs;

e) FEM model with liquid modeled according Eqs. (1) to (5) in (Juhásová et al., 2002), beam elements and boundary springs.

Calculated modes and frequencies of empty tank when using model b) are in Fig.6, review of calculated and measured frequencies is in Tab.1.

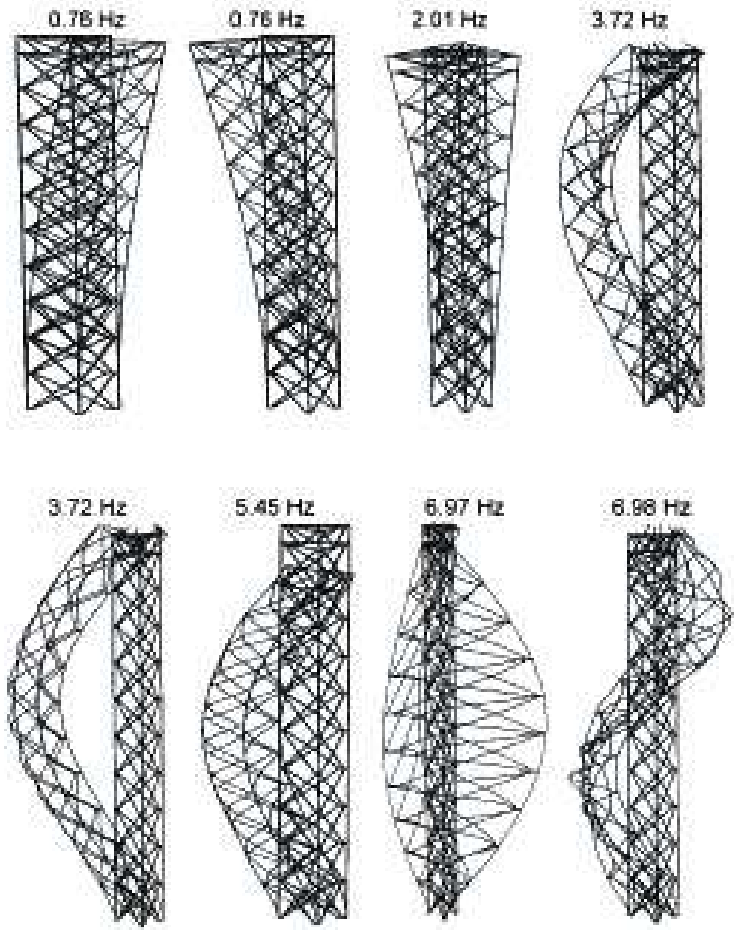


Fig.6: Calculated natural modes of empty water tank tower - model b)

Tab.1: Experimental and calculated natural frequencies of water tank tower (Hz)

| Mode | Experim. | Calculated - empty | | Experim. | Calculated - full tank | | |
|---|---|---|---|---|---|---|---|
| No. | empty | a) | b) | full | c) | d) | e) |
| water | | | | 0.23 | | | 0.18 |
| water | | | | 0.26 | | | 0.20 |
| 1 | 0.74 | 0.85 | 0.76 | 0.61 | 0.34 | 0.31 | 0.56 |
| 2 | 0.87 | 0.89 | 0.76 | 0.67 | 0.36 | 0.31 | 0.61 |
| 3 | 2.03 | 2.07 | 2.01 | **2.94 *y*** | 0.86 | 0.84 | 1.51 |
| 4 | **3.97*y*** | 4.09 | 3.72 | 3.50 | 3.42 | **3.11 *y*** | **3.23y** |
| 5 | 4.27 | **4.14 *y*** | **3.72 *y*** | 4.27 | **3.48 *y*** | 3.12 | 3.25 |
| 6 | 6.45 | 5.64 | 5.45 | 5.01 | 4.34 | 4.14 | 4.47 |
| 7 | 8.67 | 8.67 | 6.97 | 6.30 | 4.74 | 4.58 | 5.47 |
| 8 | 8.91 | 8.78 | 6.98 | 7.30 | 7.17 | 6.63 | 6.50 |
| 9 | 9.22 | 9.62 | 7.12 | 7.50 | 7.22 | 6.70 | 6.68 |

### Forced harmonic response

Dynamic response to mechanical exciter creates harmonic response that could be transferred from measured acceleration to respective deflections. The comparison with calculated response is influenced by differences in calculated and measured modes and frequencies and by the contribution of spurious motions to the measured response. Illustrative results for empty water tank are in Table 2. Calculated response corresponds to analytical model b) at calculated resonant frequency 3.72 Hz and damping ratio $\zeta = 0.024$. Measured response corresponds to steady vibration at measured resonant frequency 3.97 Hz for direction y.

Tab. 2: Dynamic response to mechanical exciter – empty water tank

| Point and direction | Measured deflection (mm) at 3.97 Hz | Calculated deflection (mm) at 3.72 Hz for model b) |
|---|---|---|
| B1 – *y* | – 0.075 | – 0.096 |
| B2 – *y* | + 0.157 | + 0.137 |
| B3 – *y* | – 0.032 | – 0.007 |

### Comments to expected Seismic response

Considering usual standard approach the seismic response can be calculated through application of seismic response spectra. The practice in earthquake engineering and dynamics of structures in Slovakia is interconnected with the demands of valid National Standards STN 73 0036:1997 Seismic Actions on Structures and STN 73 2044:1983 Dynamic Tests of Structures. New demands are those of STN P ENV 1998. The execution of dynamic tests on existing structures drawn down necessary computations, dynamic analysis and assessment of expected seismic response (Juhásová, 1991).The obtained data and subsequent analyses give more precise basis for accomplishment of appropriate seismic resistance of tank structure. The full-scale measurement of structure vibrations is important both for empty and full tank. The received results should be compared with data from previous static and dynamic computations and assumptions used in the design.

### Conclusions

The structure of the water tower tank was subjected to the verification of its dynamic properties and dynamic resistance capacity before its full service operation. The original calculation results were compared to those obtained from dynamic calculations with and without consideration of water sloshing and test results. The detailing and resistance capacity of the most sensitive connections were checked and proved that the structure complies with new standards demands and conditions. Experiences obtained from this case study give also the indications of existing uncertainties and assessment variance in the design period comparing to actual dynamic properties and the expected structure performance in the case of "*design seismic effects*". It was confirmed, the experimental verification of dynamic properties and expected response to any accidental dynamic action contributes to the appropriate determination of the reliability and safety of civil engineering structures including towers and water tanks.

**Acknowledgement**

The paper was written with the support of *VEGA – Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Science.*

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