Investigation of Existing State and Assessment of Seismic Stability of Reinforced-Concrete Chimney

V. Micov, M. Vitanova & M. Stojmanovska
Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje, Republic of Macedonia

SUMMARY:

This paper shows the results from the analyses performed for the purpose of estimating the existing state and seismic stability of a reinforced-concrete chimney. The structure is 160m high with three different slopes and varying thickness of the cross section along its height. The procedure included experimental "in-situ" non destructive methods for determination of the quality of the built-in materials, as well as corresponding computational analysis. The mathematical model was verified with the results from the previously carried out experimental "in-situ" ambient vibration tests, namely, the obtained mode shapes and periods of natural vibrations, which are not presented and discussed in this paper.
Based on the results obtained from the analytical investigations, the seismic stability of the investigated chimney was assessed and recommendations were given for its possible repair and strengthening.

Keywords: Reinforced concrete chimney, assessment of seismic stability, "in-situ" measurements

1. INTRODUCTION

Tall reinforced concrete chimneys, with height ranging from 150 m to 300m, are used for transferring hot waste gasses produced from some industrial processes into the atmosphere and are considered as crucially important structure not only from the design point of view but also from financial one. Additionally investigation of their seismic safety is essential as they must be fully functional even after a very strong earthquake ground motion.

Herein results from the diagnosis of the existing condition of the "Negotino" power plant chimney and corresponding analytical investigation have been presented. The chimney is a reinforced concrete structure with height of 160m, clear span at the top of 5.60m and outer diameter at the bottom of 14.0m (Figure 1).

In order to obtain detailed information about the existing state of the chimney structure, osculation of the structure has been preformed with special focus on the zones where cracks are detected. Experimental "in situ" ambient vibration test were carried out identifying the mode shapes and periods of natural vibrations. Furthermore experimental "in-situ" non destructive methods for determination of the quality of the built-in materials have been completed.

Figure 1. Power plant “Negotino chimney

Thorough survey of the structure has been carried out and numerous micro-cracks in horizontal and vertical directions as well as mesh like cracks have been detected. Openings of the cracks are visible within the range of 0.1 mm to maximum of 1-2mm. Most damage was noticed at the 142-146 m height. Horizontal cracks that open and close under the wind action are noticed at 142 m and 143 m height and stretch on the ¾ of the diameter of that part of the chimney (Figure 2).

Figure 2. Horizontal cracks at level +142.00

As a result of atmospheric influences and temperature variations crushing and deterioration of the concrete has been noticed (Figure 3).

Figure 3. Crushing and deterioration of the concrete

At the lower part of the structure up to 130 m no significant damages have been detected.

2. DIAGNOSIS OF THE STATE OF THE CHIMNEY STRUCTURE

2.1. Determination of the quality of the build-in materials applying non-destructive methods

DIGI-SHMIDT digital concrete test hammer has been used for verifying the concrete strength and confirming previously obtained results from the test on cylinders taken from the body of the structure (Figure 4).

Test	Height [cm’]	Mass [g]	Density [kg/m^3]	F [cm^2]	Breaking force [KN]	Compression strength [MPa]
K-153	13	2080	2280	70.1	296	42.08
K-115	12.5	2340	2670	70.1	382	54.49
K120	9.8	1660	2416	70.1	360	51.35

DIGI-SHMIDT digital concrete test hammer offers non-destructive measure of the concrete compressive strength. The compressive strength fc is established by measuring the hardness (rebound value R) of the concrete surface and with the conversion curves. The measuring range is between 10 to 70 N/mm^2.

Following the defined procedure strength characteristics of the concrete were obtained at several measuring points, at two levels (at height of 5.0 m and base). Example of the graphic results that is instruments outputs at certain point are shown in Figure 5.

Applying the formula (PBAB 87) elasticity modulus needed for the analytical computations were calculated:

$$E_b = 9.25 \times \sqrt[3]{f_{bk} + 10} \qquad f_b(MPa) = MB \tag{2.1}$$

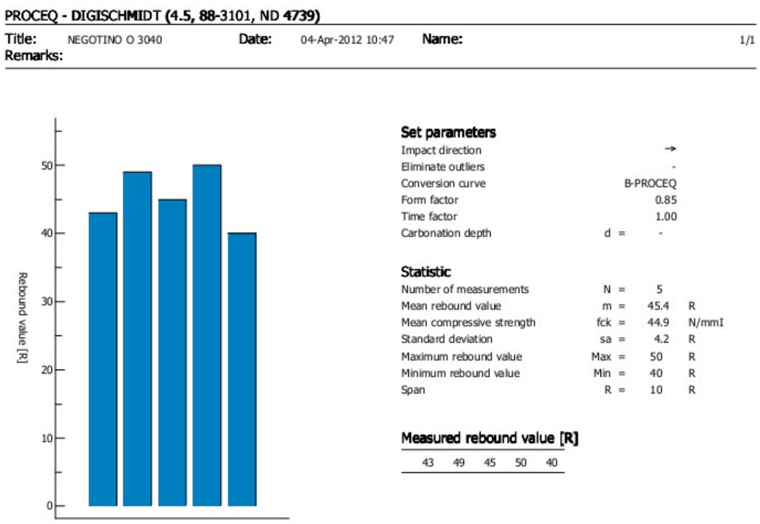

Figure 5. Instrument output of concrete strength

PROFOMETER 5+ was used for detection of the reinforcement location, their orientation and its protective layers. Measurements were taken at the height of 5.0 m. Measured results corresponded to the distribution of the reinforcement and protective layers from the final design of the power plant "Negotino" chimney. Figure 6 gives the graphic presentation of the built-in reinforcement at a defined measuring point.

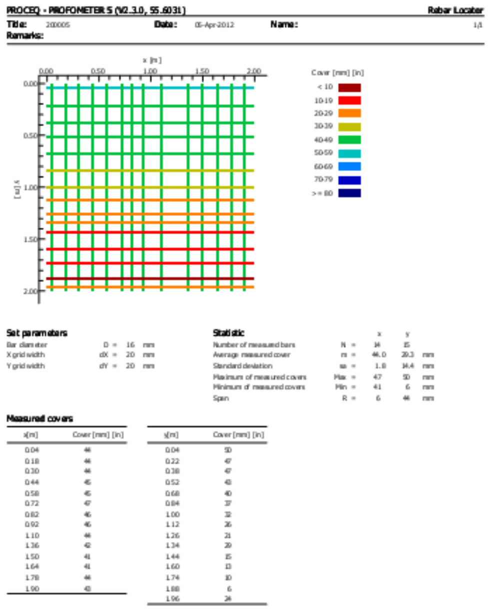

Figure 6. Instrument output of the built-in reinforcement

3. ANALYTIC MODELING OF THE CHIMNEY STRUCTURE

3.1. Numerical model of existing state of the structure

Modeling of the chimney was performed by use of the finite element method. The main body of the structure was modeled by 4 node shell elements. The linear elastic material model was used. The characteristics of the materials were adopted from the results of previous research, but the stiffness and deformation characteristics were taken from the main design. The displacements at the base of the chimney were considered fixed in all directions. No soil-structure interaction or base rotations were taken into account. A series of numerical analyses were conducted to simulate the behavior from the field test. After calibration of the model, static and dynamic analysis was carried out taking into account the seismicity of the region, the magnitude and characteristics of wind loads as well as loads due to difference between internal and external surface temperature. All the dynamic characteristics, static quantities and deformations were obtained.
The first three mode shapes of the numerical model of the existing structure are presented on Fig.7.

Discontinuity of the stiffness characteristics of the material of upper 40m of the chimney was considered. Because of the discontinuity (horizontal and vertical cracks), a significant incense of 25% occur only in the third mode of vibration. In this mode, the part of the chimney over the cracks behaved as a substructure. As a result of the extensive structural damage due to stronger wind action and sub-structural behaviour of this part of the structure, large displacements at the top of the structure are possible, threatening the overall stability of the structure. The stability of the structure is therefore undermined.

T_1=2.472 sec. (f_1=0.40 Hz) T_2=0.663 sec. (f_2=1.51 Hz) T_3=0.329sec.(f_3=3.03 Hz)

Figure 7. The first three mode shapes of the model of the existing structure

The results obtained from the numerical model pointed to values for maximum displacement due to permanent loads and wind amounting to x_p=23cm, and values of the tensile strength at critical sections amounting to σ_1=2.16MPa. Due to permanent loads and seismic effects, the displacement at the top of the structure was x_p=12.5cm, while the tensile stress at critical sections was σ_1=0.65MPa.
The comparison of natural frequencies obtained from the experimental and analytical analyses is shown in Table 3.1.1.

Table 3.1.1 Natural frequency obtained from analytical and experimental results

Natural frequency [Hz]	Experimental results (measured values)	Analytical results
f_1	0.39	0.40
f_2	1.37	1.51
f_3	3.12	3.03

3.2. Numerical model of the strengthened structure

In order to avoid sub-structural behaviour of the upper part of the chimney and protect its stability, a model of strengthened and repaired structure was proposed and analyzed. Strengthening elements in the upper part of the chimney were proposed and modelled. The complete static and dynamic analysis was done using nine load combinations including permanent loads, temperature, wind and seismic forces. The maximum displacements due to permanent loads and wind were x_p=22.1cm but the tensile strength at critical sections was σ_1=1.68MPa, which is larger than the allowed stress 2.4MPa. Through permanent loads and seismic effects, the displacement at the top of the structure was x_p=12.0cm, while the tensile stress at the critical section was σ_1=0.48MPa.

The obtained first three mode shapes for the strengthened structural model are shown in Fig.8
In the case of the strengthened structural model, the third period of vibration (in which the sub-structural effect was evident) was reduced significantly compared with the existing state model. The difference between the first and the second period of vibration was not so relevant. The used method of structural strengthening led to restoring the periods of vibrations in the designed one, before occurrence of cracks.

T_1=2.463sec (f_1=0.406Hz) T_2=0.625sec (f_2=1.600Hz) T_3=0.260sec (f_3=3.846Hz)

Figure 8. The first three mode shapes of the strengthened structural model

3.3. Comparison of the results

The periods of vibration for the designed, existing and strengthened states are given in Table 3.3.1.

Table 3.3.1. Period of vibration for the designed, existing and strengthened state

Period of vibration [sec]	Designed state	Existing state (with cracks)	Strengthened state
T_1	2.567	2.472	2.463
T_2	0.654	0.663	0.625
T_3	0.275	0.329	0.260
T_4	0.231	0.270	0.220

Table 3.3.2 and Table 3.3.3 present the compared maximal horizontal displacements x_p at the top of the structure and the maximum tensile stress σ_1 through combination of permanent load and wind effects and permanent load and seismic forces.

Table 3.3.2. Maximal horizontal displacements x_p at the top for the designed, existing and strengthened state

Maximal horizontal displacements x_p at the top due to different load combinations [cm]	Designed state	Existing state (with cracks)	Strengthened state
Permanent and wind load	24.4	23.0	22.1
Permanent load and seismic forces	12.7	12.5	12.0

Table 3.3.3. Tensile stress σ_1 at critical cross section for the designed, existing and strengthened state

Tensile stress σ_1 at the critical cross section due to different load combinations [MPa]	Designed state	Existing state (with cracks)	Strengthened state
Permanent and wind load	1.85	2.16	1.68
Permanent load and seismic forces	0.41	0.65	0.48

The results shown in Table 3.3.1, Table 3.3.2 and Table 3.3.3 indicate a significantly increased period of vibration T_3 and insignificantly increased displacements and tensile stresses at the critical cross sections of the existing structure in respect to the designed one. The strengthened structural model provides lower maximal displacement at the top of the structure, which is smaller than that of the designed structural model. The third period of vibration (where the damage is apparent) as well as the tensile strength and the maximal displacement are significantly lower than those of the existing damaged structural model.

CONCLUSION

Chimneys are special-type structures, which have different features than many other types of structures and are subjected to specific conditions during their serviceability period. Besides the peculiarities regarding the slender geometry, another important factor, which affects their behaviour, is the high level of temperature they are subjected to.
In accordance with the above mentioned considerations, investigation of the existing state and assessment of the stability of an existing 160m reinforced concrete chimney structure was carried out. Diagnosis of the existing state of the structure through osculation and instrumental measurements was performed. The results obtained from the "in-situ" measuring done by use of DIGI-SHMIDT instrument confirmed the results obtained from the test on cylinders taken from the body of the structure. The obtained value for the concrete strength was used for the numerical model. The performed analysis of the existing reinforced concrete chimney indicated that the upper part of the structure behaved as a sub-structure. In this part of the structure (at a height of 141m), horizontal and vertical cracks occurred. Based on all the performed analyses, a strengthened structural model was proposed. Complete static and dynamic analysis of this structure was done and the results showed that the proposed model ensured lower displacements and tensile stresses at the critical sections. In this way, the behaviour of the structure was almost the same as that at the designed level in reference to natural periods, displacements and stresses. The strengthening procedure is subject to further investigation.
All the results from the performed analyses are presented in IZIIS Report 2011-48.

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