THEORETICAL AND EXPERIMENTAL INVESTIGATION OF HIGH REINFORCED CONCRETE CHIMNEYS FOR MATHEMATICAL MODEL FORMULATION

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SUMMARY

In modern design and analysis of high reinforced concrete chimneys the following three basic problems should be resolved: determination of the mathematical model; definition of external forces (wind pressure and earthquake ground motion); and definition of safety criteria. The selection of the mathematical model is directly related to the structure and it represents its idealization for mathematical analysis of dynamic structural characteristics and analysis of the external force effects.Presented in the paper will be the theoretical investigations for mathematical model definition, including the analysis of soil-structure interaction, which is modelled applying elastic springs, that simulate rotation and translation of foundation in function of the foundation geometry and soil characteristics. The experimental investigations comprise dynamic characteristics study of already constructed high reinforced concrete chimneys using the ambient vibration method.

By means of analytical and experimental investigation synthesis, verification of methodology for definition of mathematical models of high reinforced concrete chimneys will be adopted, including also soil-structure interaction effects. This enables to confirm the safety level of this kind of structures subjected to strong earthquake ground motions, as well as wind actions.

INTRODUCTION

Recently, the strict environmental protection measures resulted in construction of reinforced concrete chimneys of larger height. During the last years the height of the chimneys, constructed in the world is more than 300 m with further tendency for increase in the height. Such a developement has made high reinforced concrete chimneys to be considered as structures of vital importance both from financial and design and structural analysis aspects. In the design of these structures the design engineers are faced with considerable problems due to outdated design code for their construction. The design regulations do not comply the contemporary demands even in countries with high technological developement. According to available world literature it can be concluded that there are only a few theoretical and experimental works on the dynamic behaviour under seismic effects, which certainly supports the opinion for the lack of adequate analysis methods for verification of the seismic stability of these structures.

The reinforced concrete chimneys of the "Negotino" steam power plant (1) (H = 160 m) and the "Bitola" steam power plant (2) (H = 250 m), which are the subject of theoretical and experimental studies presented in this paper have

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been designed and calculated applying modern seismic, dynamic analysis methods, defined as "design earthquakes" and "maximum credible earthquakes". The approach used for verification of the safety coefficients (3), (4) applies the method of ultimate states of the reinforced concrete ring sections, which has a more general consideration, compared to allowable stresses criteria since their defining criteria have more clear physical meaning.

The experimental dynamic investigation includes study of the dynamic characteristics of the two constructed chimneys applying the ambient vibration method. High sensitivity sensors attached to exterior side of the chimney at the base and at the steel platforms were used for recording the dynamic response. The series of records were processed by applying time function amplitude spectra. The Fourier analysis of the recorded dynamic response time histories enabled experimental determination of the dynamic characteristics, i.e., fundamental frequencies, mode shapes and critical damping coefficients. The main objective of the experimental study is to verify the method of mathematical model formulation and with experimental support of the theoretical analysis for determination of the safety level due to wind effect and earthquake ground motion. The obtained results can be, also, used for vulnerability assessment of the structure if subjected in future to strong earthquakes or severe hurricanes.

ANALYTICAL STUDY OF DYNAMIC CHARACTERISTICS

The following fundamental approaches have been used for theoretical determination of the dynamic characteristics: The chimneys are modelled as lumped mass systems; The model is linear; Beam finite element model with constant section proportions have been applied; Each discrete point of the model has two degrees of freedom (Translation in "x" direction and rotation with respect to "z" axis, Fig. 1);The stiffness matrix is calculated for the Young's modulus of elasticity, $E = 2.6 \cdot 10^7$ kN/m^2; The soil-structure interaction is modelled applying two elastic springs, which simulate rotation and translation of the foundation structure in function of the soil conditions and the geometry of the foundation structure.

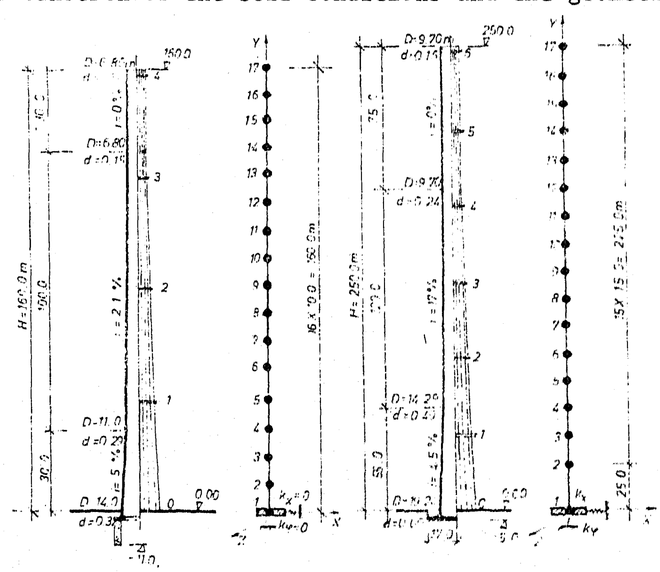


Fig. 1. Actual and idealized structures of two chimneys

The basic proportions of the structural elements of the two chimneys and their idealization are given in Fig. 1. The chimney, having height of H=160 m is founded on reinforced concrete ring-like foundation beam supported by eight walls,with diameter D=2.8 m, overlying on marl clay. The chimney having a height of H=250 m, is founded on reinforced concrete plate overlying on dense gravel with sand. Two models are applied for analytical study of the dynamic characteristics of the 250 m high chimney: 1. base fixed model and 2. rocking model. The elastic constants of Model 2 which simulate the soil-structure interaction are determined based on the geometry of the foundation plate and the soil mechanical characteristics (5).

EXPERIMENTAL STUDY OF DYNAMIC CHARACTERISTICS

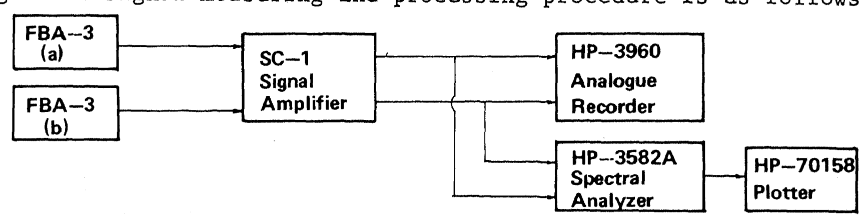
The time history record, obtained by shaking of the structure caused by an external excitation (wind force or any other local origin) contains the dynamic characteristics of the structures and the physical nature of the motion. By mathematical analysis of these time deterministic functions (signals), it is ppossible to determine the dynamic characteristics of the considered structure. For processing the deterministic function the harmonic method of analysis has been applied. It is based on the Fourier series and Fourier transform theory. Considering the given methods (since Fourier series represent Fourier transforms) the deterministic signals are divided into two types: periodic and nonperiodic. The Fourier series and the Fourier transform analysis is applied for the first and second type, respectively. Each periodic function, regardless the complexity of its mode shape, can be presented by a Fourier series. It is chaacterized by the sum of simple periodic harmonics with different amplitudes and phases, while the frequency of each of them is an integer multiplier of the fundamental frequency of the transformed function. The series of numbers, representing these multipliers and the series of the corresponding amplitudes and phases determine, completely, the complex function. It is its picture in the frequency domain.In this way, the time function is turned into frequency domain (amplitude and phase spectrum of the time function) from the time domain. The Fourier integral and transform is used for analysis of nonperiodic signals.

Equipment Used and Its Basic Characteristics

For dynamic study of the structures the following equipment have been employed: Force Balance Accelerometer FBS-3; Signal Conditioning SC-1; Instrumentation Tape Recorder HP-3960; Spectrum Analyzer Hp-3582A; and Plotter HP-70185. The employed FBA-3 accelerometers are of high sensitivity and are suitable for measuring frequencies of extraordinary low amplitudes and low frequencies (up to 50 Hz). Applying a low-frequency amplifier it is possible to measure ambient vibrations in the amplitude range of ± 1 x 10^{-5}g to 5 x 10^{-3}g. The Signal Conditioning SC-1 is used as a filter and amplifier of signals. It provides amplification of 200 to 100.000 times, while frequency filtering can be selected in the range of 1Hz to 120Hz, with simultaneous elimination of the DC components out of 0 - 0.03Hz. In this way, all long period components out of the received signals for analysis are eliminated during their processing. For further processing and storing of signals a four-channel analogue magnetic tape recorder HP-3960 has been applied. It has a reproduction system and a unit for calibration of input and output signals, which enables an adequate recording and reproduction of signals (amplitudes ± 1V - ± 10V and frequency of 0Hz - 2000Hz). For digital processing of signals a HP-3582A two-componental spectral analyzer has been used. During signal processing it is based on calculation of the direct Fourier transform, applying a highly effective algorithm of the fast Fourier transform. It has a manyfold application for the needs of digital processing of signals caused by different origins. For a given time-function (signals) the amplitude, frequency and power spectra can be calculated which represent a real picture of the signal in the frequency domain. For permanent storing of the time function and the calculated spectra a HP70158 plotter has been applied.

Applied Procedure and Obtained Results

The distribution of the measuring points was determined by the place of the steel platforms over the height of the structures. They, together with the point at the base, were selected as measuring points for dynamic studies. The measuring points are marked as (0), (1), (2), (3), etc. successively from the base to the top platform. This procedure was carried out applying simultaneously two FBA-3 accelerographs. To compare the sensitivity level of the two accelerographs dynamic calibration by simultaneous placing of the two FBA-3 accelerometers (a) and (b) was carried out at the beginning of each series of measuring. The block diagram of signal measuring and processing procedure is as follows:



Two series of measurements were carried out for each of the two structures. To obtain the vibration mode shape of the structure, the FBA-3$_{(a)}$ accelerometer retained itc calibration place, while the FBA-3$_{(b)}$ accelerometer was moved consecutively from one to another measuring point. Fig. 2 presents one segment t=12.5sec of the time history record at the measuring point (1) and the Fourier amplitude time history spectrum for the "Negotino" steam power plant. This was obtained by means of amplifying the HP-3582A Spectral Analyzer, and digitizing the 1024 points of the time history function. The time history record clearly shows the fundamental frequency characteristic of the structure.

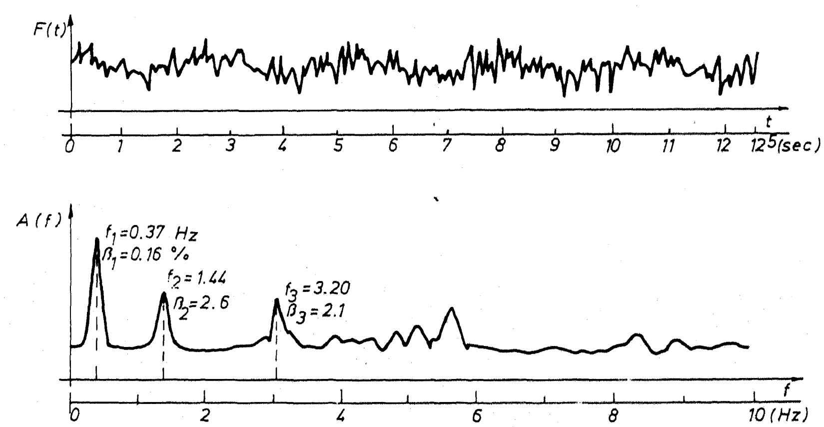


Fig. 2. Time history record and amplitude spectrum for chimney H=160 m

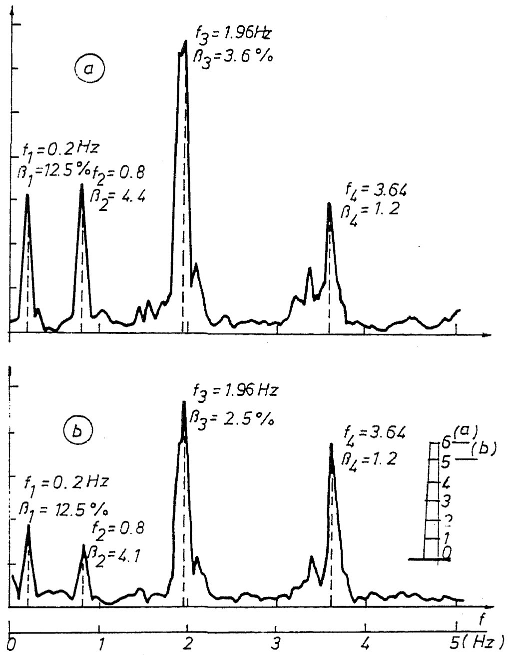


Fig. 3. **Mean amplitude spectra for measuring points 5 and 6 for chimney H = 250 m**

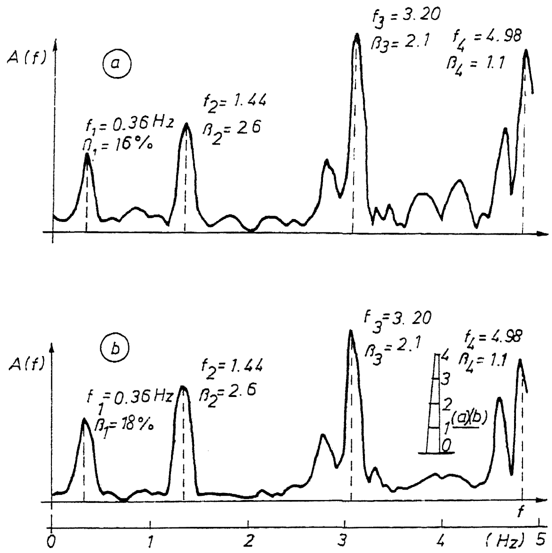


Fig. 4. **Mean amplitude spectra for measuring point 1 (calibration test) for chimney H = 160 m**

Type of rezults		Frequency (Hz)				
		f_1	f_2	f_3	f_4	f_5
Experimental rezults		0.20	0.80	1.96	3.64	–
Analytical rezults	Fixed model	0.20	0.81	1.98	3.68	6.25
	Rocking model	0.18	0.68	1.69	3.26	5.41

Table 1. Comperison between experimental and analytical frequencies for chimney 250 m high

Type of rezults	Frequency (Hz)			
	f_1	f_2	f_3	f_4
Experimental rezults	0.36	1.44	3.20	4.98
Analytical rezults	0.37	1.48	3.64	6.84

Table 2. Comperison between experimental and analytical frequencies for chimney 160 m high

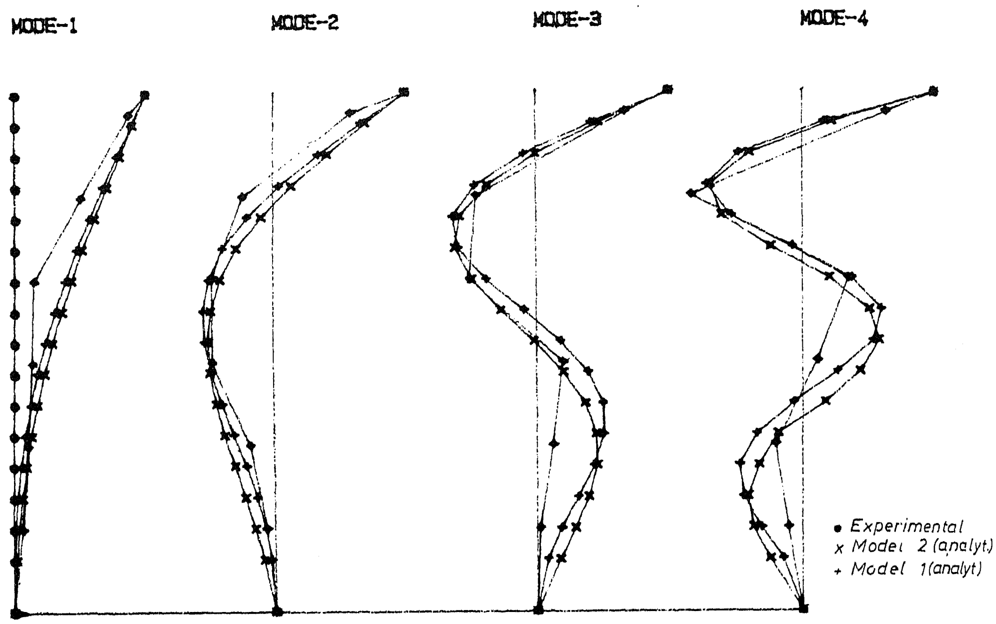


Fig. 5. **Comperison between experimental and analytical mode shapes for chimney 250 m high**

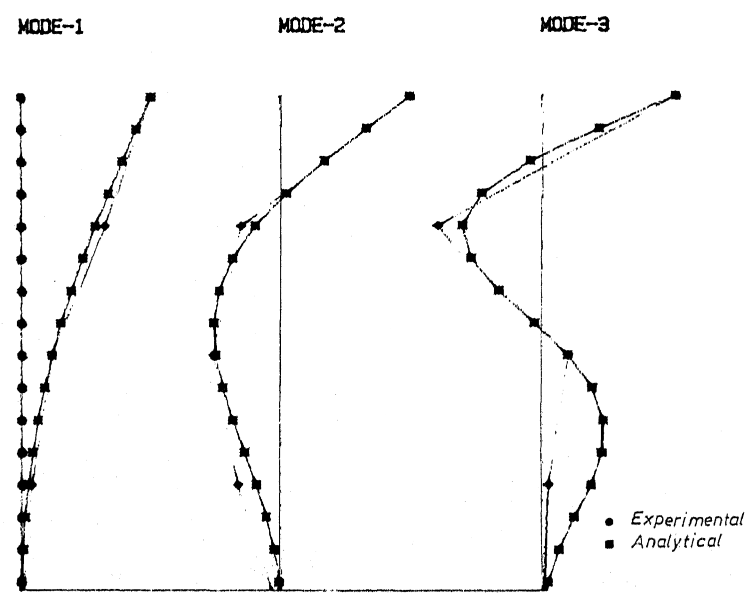


Fig. 6. **Comperison between experimental and analytical mode shapes for chimney 160 m high**

Due to limited space, presented in Figs. 3 and 4 are only the mean amplitude spectra for one measurement test of each chimney. The mean values are determined based on 15 time history records, each one of 12.5 sec.

CONCLUSIONS

The full-scale ambient vibration dynamic tests confirmed the basic assumptions used for the mathematical model formulation for theoretical determination of the dynamic characteristics of the two chimneys, which are the subject of the investigation. Full correlation between the analytical and experimental results are obtained for the fundamental periods and frequency mode shapes. Tables 1 and 2 and Figures 5 and 6 show the comparison between the experimental and analytical results in respect with the frequencies and the mode shapes for the first four, i.e., three analysed vibrations for the chimneys of 250 m and 160 m height, respectively.

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