Measurements and evaluation of ambient vibrations on monuments

Abstract

An efficient non destructive test is described for the determination of the dynamic characteristics, the structural damage and any discontinuities of the load carrying system of a monument. The same method may be applied in order to check repairs and strengthening of monuments.

The required instruments and an outline of the principle of the method, and of the application of the results is given.

1. Introduction

Ambient vibrations that are an inherent phenomenon of any structure built on the earth, may prove quite useful for obtaining information of various characteristics of the structure.

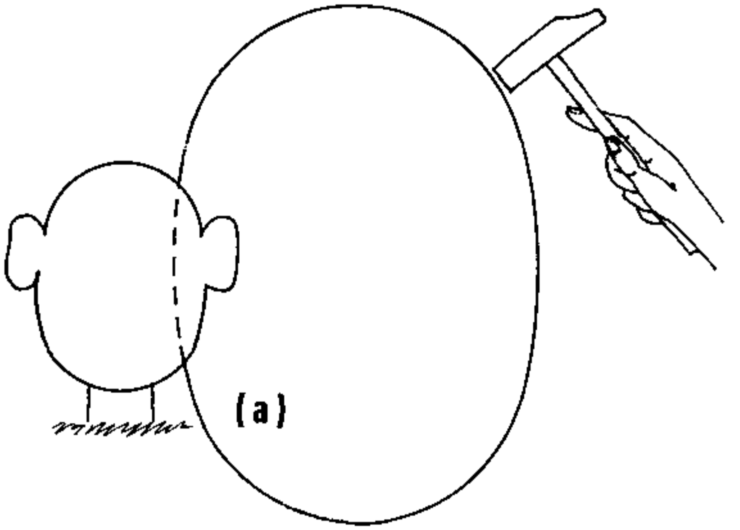

Fig. 1. Principle of the method. From the sound we hear, when our ear is in contact with the body (a), which is knocked by a hammer, we can estimate characteristics of the body.

A simplified example of this is given in the sketch of Fig. 1, where we sound-hit a body (a) in order to get information of its characteristics. The difference between this example and the subject under consideration, lies in two points : first, the body is not knocked by a hammer but it is excited by the air, by its inhabitants and its foundation ground, and second, we do not hear it with the ear, but we record, measure and evaluate its response with several, rather sofisticated, instruments.

If recordings and measurements are repeated from time to time, or after some damage, alterations, repairs or strengthening of the structure, quite interesting results may be obtained as far as these changes of the characteristics of the structure are concerned.

2. Scope

The scope of the method is to provide basic information on the following :

- The various dynamic characteristics of the whole structure as it stands now, including the response of its foundation soil ;
- The degree of soil-structure interaction ;
- The damage and discontinuities of the structure as a whole and/or of its members, due to an earthquake or an explosion or other violent excitations ;
- The overall response (displacements, accelerations etc.) of the structure due to either small ambient vibrations or stronger excitations, as for example with heavy traffic on the ground or under the ground, or low height flights of airplanes, strong winds etc. ;
- The degree of deterioration and the rate of deterioration with time. By repeating the measurements and comparing them from time to time we may estimate the rate of change of the various dynamic characteristics of the structure, which, in turn, gives estimates of the degree of the deterioration ;
- The degree of homogeneity of the various parts and members of the structure and its response ;
- The degree of effectiveness of various repairs and strengthening which might have been carried out on the structure ;
- The same may be applied in order to measure the change of the dynamic characteristics of the monument after the completion of repairs and strengthening,

as well as information useful in order to built the mathematical model of the structure and the verification of the computer program that evaluates its seismic response.

It must be emphasized here, that the method is advantageous for monuments, since, it is a non destructive one and provides information on the overall behaviour of the structure. The similarity between the seismic response and the one due to ambient vibrations is important, since the two responses under consideration are of the same nature.

3. Methodology

In Fig. 2 a basic outline of the methodology is schematically shown. By measuring the Excitation (E) on the foundation ground and the Response (R) of the structure we have to estimate its characteristics. There are basically two sets of methods : The manual and the automatic or semi-automatic methods. The difference between them lies in the accuracy. In some cases, when we have to compare methods, we must relate the efficiency of the method to its cost, but in the case of monuments cost is a secondary consideration. It is self - evident that the instruments we use in each case must be the appropriate ones. When the automatic or semi-automatic methods are followed, the number of measurement points is much higher than when manual methods are used. The suitable instruments and the whole process for the automatic or semi-automatic methods are much more costly, sophisticated, efficient and faster, than those for the manual methods. Both methods need experience in order to evaluate the results and draw pertinent conclusions.

It must be emphasized here, that we have to put the sensors on appropriate points of the structure, in order to measure the response of the

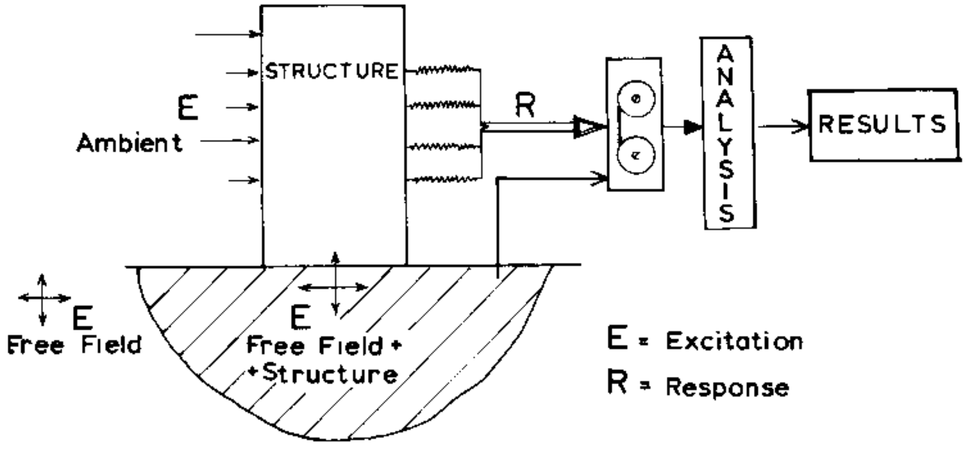

Fig. 2. Basic methodology. The response of the structure due to ambient excitation is recorded and analyzed.

whole structure and not that of some of its members, or of the supports of the sensors (of a stone on which we put the sensor etc.). In most cases it is necessary to construct a special support for the sensor which provides the motion of the point we want to study.

The location and direction of each instrument should be in accordance with the purpose for which we are carrying out the measurements and the peculiarities of each case. If, for example, we want to determine possible cracks in the corner C of a structure (see Fig. 3a), the pick-ups should be positioned in the direction shown. If the recordings of the pick-ups p_1 and p_2 show a difference in amplitude only, the crack is rather small. If the recordings show a difference in their frequency content also, then, the crack c-c must be larger.

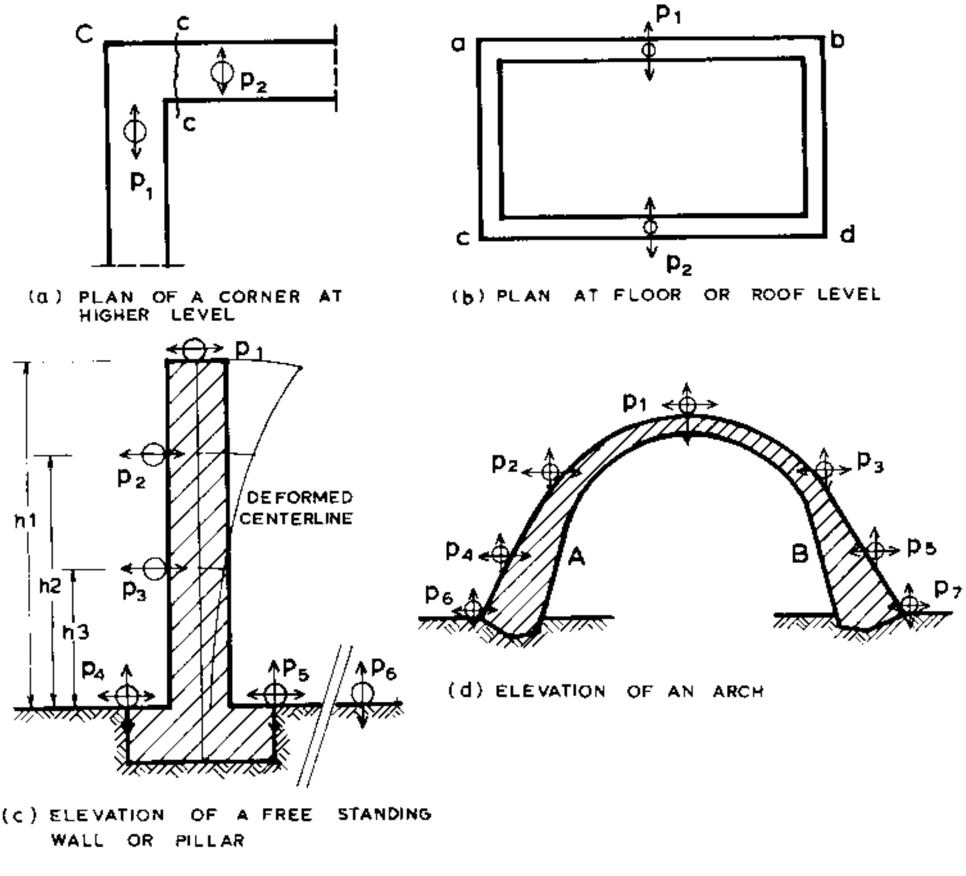

Fig. 3. Each pick-up should have the appropriate location and direction according to the case under consideration :
(a) Positioning of two pick-ups for determining possible crack c-c in the corner C ; (b) Determination of diaphragmatic function ; (c) Determination of the response against horizontal ground excitations and of the extent and effect of soil-structure interaction ; (d) Determination of the overall response and possible cracks of an arch.

The diaphragmatic performance of the floor or roof of a structure is very important for its earthquake response. The diaphragmatic performance results in equalizing the response of the two parallel walls a-b and c-d of a structure (see Fig. 3b). This may be checked with two pick-ups positioned as shown. If we have a phase difference between them, there is no diaphragmatic performance, and one has to take the appropriate decisions for the repair or strengthening of the structure.

In these two cases the detection of a small even crack c-c (Fig. 3a), or of the diaphragmatic function (Fig. 3b) can be achieved only due to the nature of this kind of vibrations of the structure which have a very small amplitude and excite the structure at all directions (two horizontal, one vertical, three rotations). If the vibrations were of larger amplitudes, then small cracks certainly could not be detected.

There are cases of studying the response of a free standing wall, or of a pillar against excitations from the ground, due to traffic or other relevant disturbances. In these cases we want to examine the relation between the horizontal response of the top of the structure and the motion of the foundation. The horizontal response of the top of the structure is the sum of the responses of the structure as a flexible one due to horizontal ground motion and that of a rigid body due to rocking of the foundation. By comparing the motions p_1, p_2 and p_3 (see Fig. 3c) to the horizontal components of p_4 and p_5 we may estimate the response of the structure due to horizontal ground motion. The difference between the motions p_4 and p_5 multiplied with the heights (h_1, h_2, h_3) gives the contribution of the rocking of the foundation to the horizontal motions p_1, p_2 and p_3 respectively. Very helpful is the determination of the position of the deformed centerline (which passes through the center of gravity of the cross sections). If there are cracks or other anomalies along the height, the deformed centerline will show discontinuities and there will appear :

a. difference in the phase and
b. difference in the frequency content of the motions p_1, p_2 and p_3. The positioning of the pick-ups p_2 and p_3 must be above and under the locations of possible cracks, damages, or any anomalies of the structure.

Due to the small amplitude and their global nature of the vibrations under consideration, the overall response of rigid and large structures (see Fig. 3d) may be evaluated. With the appropriate positioning of pick-ups along the height and length of the structure its structural and dynamic characteristics can be effectively evaluated. The difference in the response of side A to that of side B is a common subject of interest in examining the response of this kind of structures as it is, for example, an arch.

3.1. Manual Methods

The recorded signal is analyzed by hand. One method, which is well known as the « zero crossing method » after K. Kanai, described in Kanai and Tanaka (1961) is originally applied to the so called « microtremors »-small amplitude vibrations of the ground. According to the method, the duration of the measurement is 120 sec. One counts each « halfpseudoperiod » of the record as it is defined by the crossing of the zero line with the curve of the record, as well as the corresponding relevant maximum value of the record. The record usually is the velocity of the ground. The way by which the grouping of the number of the various halfpseudoperiods of the record is performed is of primary importance. The way of grouping depends on the accuracy and other parameters, closely related to the specific case. The range of periods between 0.01 sec and 3.0 sec is divided to about 45 smaller range-groups, not equally spaced. For example, from 0.01 sec to 0.2 sec we may have about 15 time intervals-groups, while from 0.2 sec to 1.0 sec about 20 and from 1.0 sec to 3.0 sec about 10 groups. This is the case when we have a stiff structure and stiff-rocky ground. In case of a flexible structure or a soft ground, the time intervals-groups are smaller at longer periods.

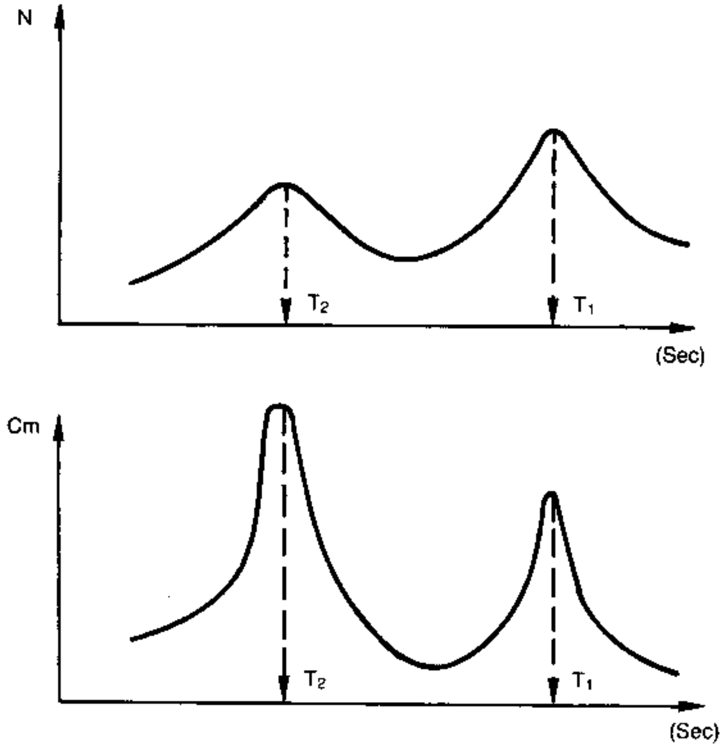

Fig. 4. Histograms of occurrence. Correspond to the « halfpseudoperiods » and the relevant maximum amplitudes.

The next step is to construct two histograms (see Fig. 4) for each record. One histogram corresponds to the halfpseudoperiods and the other to the amplitudes. The amplitudes (d) are calculated according to the very simple relation :

$$d = v/\omega \qquad (1)$$

where : v is the recorded velocity (cm/sec) and
ω is the respective circular velocity ($\omega = 2\pi/T$)

3.2. Automatic or Semi-automatic Methods

To this category are included the methods where the processing of the records is done automatically or semi-automatically.

A semi-automatic method is that described by Carydis (1974), by which the zero crossing method outlined in the previous paragraph 3.1., was programmed with the use of an electronic hybrid computer. The signal, recorded on an analog tape, is processed as far as the amplitudes of the record are concerned, with the use of the analog computer, while the number, the duration of grouping of halfpseudoperiods were evaluated with the use of both the logic and the digital part of the machine.

For the automatic procedure there are analog to digital converters which convert the analog signals to digital form, but there are also digital recorders which directly record the signals in digital form. Further, either general purpose digital computers with the appropriate software, or compact signal or fourier analyzers may be used. Using these machines we may calculate the following :

- Linear Fourier Spectrum of the Excitation, S_E (f)
- Linear Fourier Spectrum of the Response, S_R (f)
- Auto Power Spectrum of the Excitation S_{EE} (f) and
- Cross Power Spectrum of Response and Excitation S_{RE} (f).

What we need to know is the Transfer Function (in the literature usually found also as frequency Response, System Response, Compliance, Gain, etc.) of the structure, H(f). This is given as the ratio :

$$H(f) = S_R(f)/S_E(f) \qquad (2)$$

By multiplying both terms of the ratio of Eq. 2 with the complex conjugate of the excitation $S^*_E(f)$ we obtain :

$$H(f) = S_R(f)xS^*_E(f)/S_E(f)xS^*_E(f) = S_{RE}(f)/S_{EE}(f) \qquad (3)$$

If we do not calculate the ratio given by Eq. 3, then we have to be very careful in order to avoid biased results with the frequencies which are present in the excitation function. This means that if a machine, or other sources of noise are close enough during the time of measurements, in the response (R) of the structure the frequencies of the noise sources will be present. If we do not use Eq. (3) the excitation of the structure, must be a white noise (see Fig. 5).

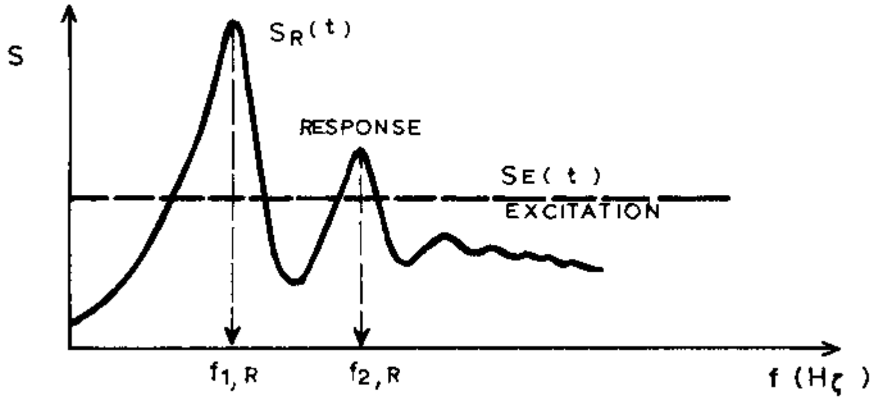

Fig. 5. The response (R) of the structure against its excitation (E). If the excitation of the structure has an uniform content of frequencies, the response of the structure is dominated by its natural modes of vibration which are equally excited.

3.3. Evaluation

Both of the methods will lead to the determination of the following quantities :

- The eigenfrequencies of the structure ω_1, ω_2, ..., ω_n
- The modal shapes of the structure $[\Phi_1]$, $[\Phi_2]$, ..., $[\Phi_n]$
- The modal damping ratios ζ_1, ζ_2, ..., ζ_n

where n is the number of degrees of freedom of the structure, or the number of degrees of freedom we can most accurately calculate. Particularly, for the damping ratio ζ, if we see more closely one of the resonant curves of Fig. 4 or 5 we may have the curve of Fig. 6. Using the « Half Power Bandwidth » concept, the damping ratio, which corresponds to the respective resonant mode (respective degree of freedom), is given by the relation :

$$\zeta = \Delta f/fo \tag{4}$$

From the above mentioned we may form :
the diagonal matrix of the eigenfrequencies :

$$[\omega^2] \tag{5}$$

the full matrix of the modal shapes :

$$[\Phi] \tag{6}$$

the diagonal matrix of viscous damping :

$$[2\zeta\omega] \tag{7}$$

On the other hand the diagonal mass matrix of the structure :

$$[m] \tag{8}$$

can be estimated by measuring each mass of the structure which is the most closely related to the respective degree of freedom.

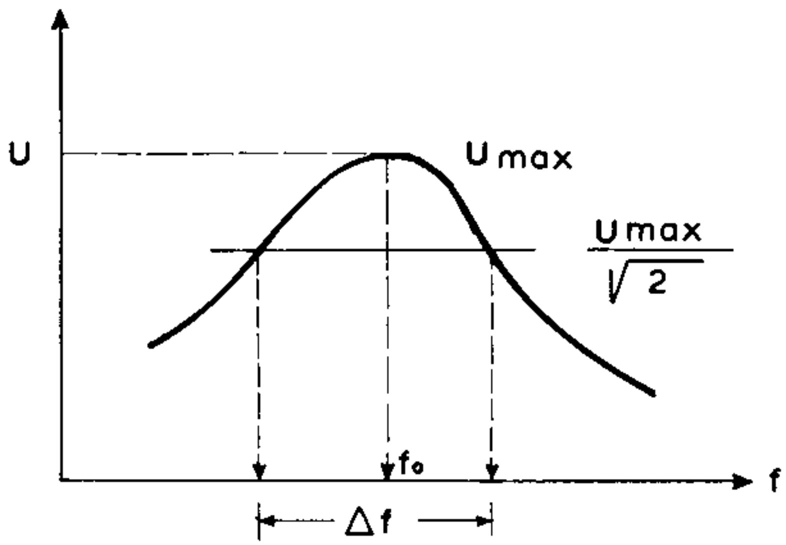

Fig. 6. Determination of damping with the use of Half Power Bandwidth method.

The following relations are well known :

$$[\Phi]^T\ [m]\ [\Phi] = [I] \text{ (unit diagonal)} \tag{9}$$

$$[\Phi]^T\ [K]\ [\Phi] = [\omega^2] \tag{10}$$

$$[\Phi]^T\ [C]\ [\Phi] = [2\zeta\omega] \tag{11}$$

where [K] and [C] are the stiffness and damping matrices respectively.
By appropriate multiplication of Eqs (9), (10) and (11) with $[\Phi]^{T-1}$ at left and $[\Phi]^{-1}$ at right, one may receive the quantities :

$$[K] = [m]\ [\Phi]\ [\omega^2]\ [\Phi]^{-1} \tag{12}$$

$$[C] = [m]\ [\Phi]\ [2\zeta\omega]\ [\Phi]^{-1} \tag{13}$$

The goal of the study is achieved by the determination of the matrices $[\omega^2]$, [K], [m], [Φ] and [C], and by comparing the matrices $[\omega^2]$, [Φ] and [C] either to those obtained during previous measurements of the same structure or to those resulted after application of pure analytical structural procedures.

4. Equipment

The selection of equipment besides the particular needs and the other parameters described in the various chapter, depends also to the availability of transportation. Usually the instrumentation for measuring and recording ambient vibrations consists of one to eight single axis pick-ups with a signal conditioner and a recording system. In very simple cases one-channel may be used, as is the one shown in Fig. 7a. The recording in this system is performed on paper tape and it is used only when we need to get a rough idea of the response, with a little manual work. In the most cases a system with four channels is used as the one shown in Fig. 7b. In all applications we have performed up to now, we have not used more than eight channels by employing two of the systems shown in Fig. 7b.

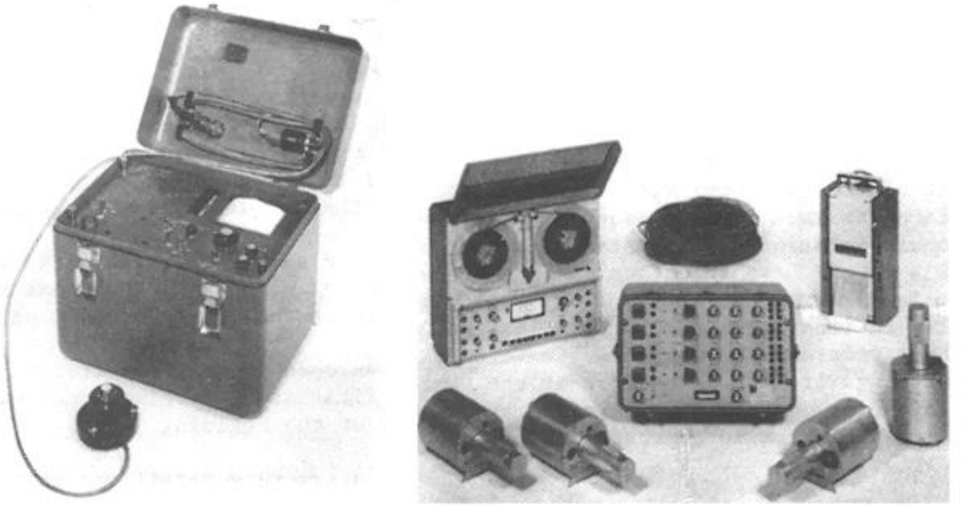

Fig. 7. Measuring and recording systems.
(a) The one-channel « Vibration Monitor VM-1 » ; (b) The four-channel « Vibration Survey System VSS-1 » by Kinemetrics. Courtesy of Kinemetrics.

The basic requirements of the pick-ups and of the signal conditioning system is :

a. the sensitivity, which must be as high as possible with a possibility of selecting large number of gains ;
b. the possibility for direct integration or differentiation of each signal ;
c. the possibility for direct summation and substraction of signals ;
d. the possibility for selecting any level of low pass filters. The instruments shown in Fig. 7 can record with accuracy accelerations of the order of 10^{-5} g (receiver 10^{-2} g and amplifier 10^{-3}).

The use of analog F.M. or A.M. data recorders on magnetic tapes is very helpful for the analysis of signals. There are modern digital recorders by which the analysis may be performed much easier without the necessity of converting the analog signals to digital form, as it is the case of the analog recorders. In some cases wireless communication from the pick-ups to the recording system may be employed.

5. Applications

In Fig. 8 an elevation of one of the Olympious Zeus temple(s) at the entrance of Athens is shown. In order to record and evaluate its response due

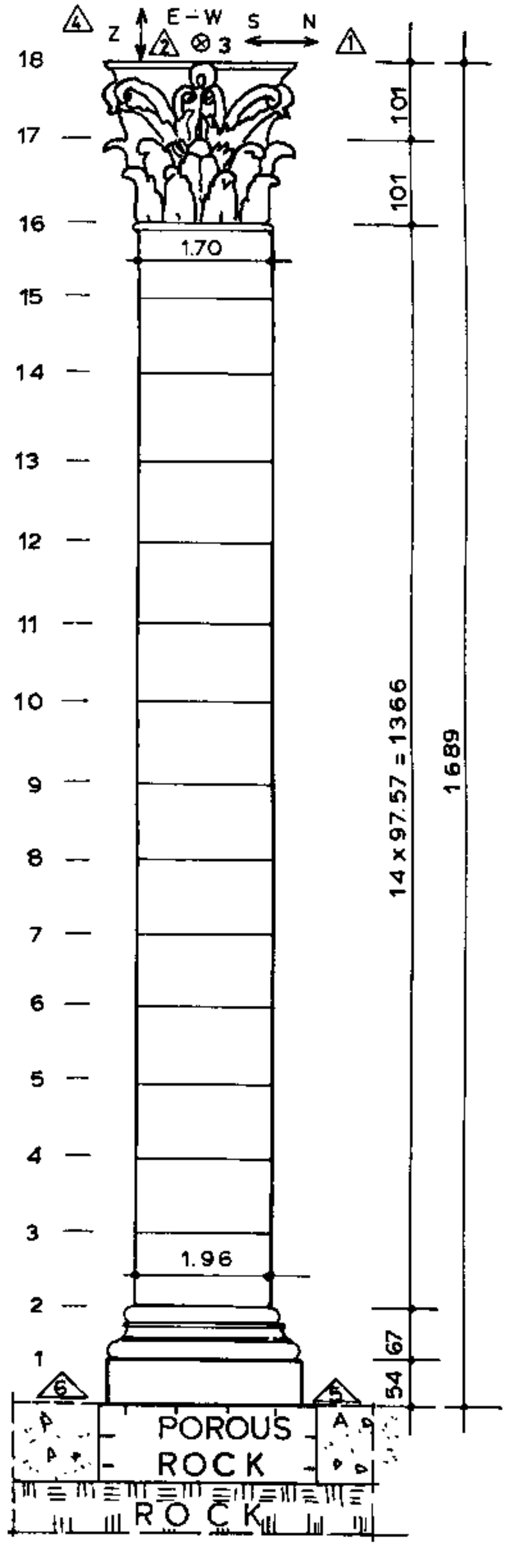

Fig. 8. One free standing pillar of the Olympious Zeus temple in Athens.

to wind and traffic excitations the measurements of ambient vibrations of the monument were carried out. The instruments were installed at various parts of each of the pillars. The recordings took place during strong winds and during the intentionally passing of heavy trucks on the nearby avenues (avenues surrounding ancient monuments is a common phenomenon !).

After the analysis, which was performed automatically, it was found that pollution and the ambient vibrations of the monument collaborate for its faster deterioration. The motion at the top of each pillar is much higher than the expected one.

The surface between adjacent vartebrae is not plane but curved with higher curvatures to the outside of the vartebrae. This was exaggerated at the upper part of the pillars. Due to the motion, the pollution enters inside the structure and deteriorates the material as the openings between adjacent pieces of the monument become larger and larger. This phenomenon was much reduced in the cases where connecting beams remain still at the top of the monument connecting some of the pillars.

It was interesting to discover that between the underlying rock and the foundation of the pillars a rather soft porous rock was inserted by the old builders. With the knowledge we have today of earthquake resisting structures we may attribute the positioning of the porous rock under the foundation, to an effort for isolating the superstructure from strong ground motions.

An other application of the method is performed by Mouzakis (1985) for the determination of various characteristics of the Arsakion Building in Athens. It took place during the works for renovation of this stone-masonry about 150 years old building in the center of Athens. The measurements answered quite successfully to the following questions :

- The existence or not of diaphragmatic function of the roof and floors
- The effect on the building of the nearby traffic
- The existence of cracks, manly in the corners of the building
- The amplification of the response with the height of the building.

An other application of the method refers to the evaluation of the response against wind and ground motions of the Parthenon and the Erechtheion monuments. The measurements take place every two to three years since 1974. Some of the records show a small difference with time. The corners as it is shown in Fig. 3a suffer from differential motions which finally lead to the widening of the cracks with time. The evaluation of the measurements is still under way and any further description of the findings here is beyond the scope of the present paper.

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