World Applied Sciences Journal 23 (11): 1448-1454, 2013
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2013.23.11.13161

Evaluation of Mechanical Safety of Building Structures Using Elastic Vibrations Varying in Wave Length

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Submitted: Jun 21, 2013; **Accepted:** Jul 19, 2013; **Published:** Jul 25, 2013

Abstract: The article considers the possibility of using acoustic methods for non-destructive testing of strength and composition of building structures. Screening of multiple structures or structures with large geometrical dimensions (long tunnels, large area roofs, etc.) at first stage of testing the directly defined acoustic parameters of materials of building structures shall suffice. However that is not enough to evaluate condition of building structures and make conclusions on their stability. In the calculations of bearing ability mechanical characteristics of the materials are applied: 1) elasticity modulus and 2) strength. This is especially true of materials for brickwork constructions and multilayer concrete structures. Major types of waves in building structures are volume waves (longitudinal and transverse waves) and channel waves (beam, lamellar, surface and bending). Essential advantage of bending waves is the possibility to evaluate materials of stone and brick works and multilayer concrete structures. The article provides theoretical justification of surface wave method and the results of its application for evaluation of technical condition and definition of remaining life of multilayer concrete structures. Recommendations concerning use of acoustic waves of various frequency ranges are provided in departmental regulatory literature and verified by independent examinations.

Key words: Acoustic methods · Non-destructive testing · Method of surface waves · Multi-layer reinforced concrete structures

INTRODUCTION

No specialists in the field of construction would argue about the fact, that with all possible unfavourable load combinations any building or structure, its foundation of building structures, internal engineering systems shall possess the correspondent strength and stability. In the Technical Regulations on safety of buildings and structures (Federal Law No. 384) it is also pointed out, that safety of buildings and structures is ensured by establishing the correspondent requirements of safety of design values of parameters of buildings and structures and quality throughout the life cycle of building or structure [1]. In other words, the buildings structures, as well as foundations of the building or structure shall possess the strength and stability to avoid hazards to life or health or people, property of individuals or legal persons, state or municipal property, etc. [2].

Additional to these regulations are the requirements stipulated by GOST R 53778 – 2010. (Buildings and structures. Rules for examination and monitoring of technical condition) [3]. They specify in the course of detailed instrumental testing of technical condition of the building or structure shall strictly define actual characteristics of materials of main bearing structures and their elements [4]. These standards follow the spirit of technical regulations established in the leading western countries [5].

Only in view of the above mentioned requirements one may speak of further research of such an important issue in construction industry, as testing methods of building structures material strength, definition and monitoring of measuring and testing base of specialized organizations.

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The experience of work done by the authors of the article in the field of evaluation of strength of materials of building structures has shown that even the most up to date methods, instruments and laboratory equipment are unable to provide accurate information, which would be the basis for further calculations of bearing capacity of operated objects [6-10]. This is especially true of materials for brickwork constructions and multilayer concrete structures. From here comes the actuality of this research, providing a certain solution for the laid down issue.

MATERIALS AND METHODS

Among the most widely spread methods of non-destructive control, which we practice in our work, integral methods of technical diagnosis using acoustic waves varying in length arising or excited in the controlled object shall be emphasized.

The main difference of seismic and acoustic waves from the ultrasonic waves is the vibration frequency and hence the wavelength. This difference, on one hand, impairs resolution ratio of the methods based on their use, however on the other hand it allows to decrease wave attenuation and thus to increase the spacing, as well as penetration depth with one-sided access to the structure.

The Main Part: As a rule, the following properties of acoustic waves are used:

Reflection from Surfaces Separating the Media Varying in Acoustic Properties: This is used to define geometrical parameters of tested object (length, thickness, etc.), finding and positioning of defects (caverns, foreign inclusions, cracks);

Change of Direction (Refraction) and Wave Propagation Velocity: This is used to detect and define position and parameters of defects (cavities, foreign inclusions, depth of cracks, non-compacted concrete zones, thickness of corroded concrete layer, etc.);

Depending on Acoustic Wave Propagation Velocities Function of Physical and Mechanical Parameters of the Material: Allows to determine material strength and its elasticity characteristics;

Frequency and Form of Own Oscillations of Structures and Buildings: This is used to evaluate boundary conditions and integral stiffness, as a rule, during monitoring of responsible objects. Screening of multiple structures or structures with large geometrical dimensions (long tunnels, large area roofs, etc.) at first stage of testing the directly defined acoustic parameters of materials of building structures shall suffice. Values of these parameters (propagation velocity or intensity of attenuation of excited waves) for various structures or areas of structures allow detecting loosened structures and their areas.

However that is not enough to evaluate condition of building structures and make conclusions on their stability. In the calculations of bearing ability mechanical characteristics of the materials are applied: 1) elasticity modulus and 2) strength.

To determine dynamic elasticity modulus E_d and modulus of shearing G_d from its acoustic parameters, use the following basic equations [11-12]

$$E_d \copyright \rho \, I V_p^2 \frac{(1+\mu_d) I (1-2\mu_d)}{1-\mu_d}, \text{ Pa} \quad (1)$$

$$G_d \copyright E_d / 2(1 J \geq_d) \copyright \rho V_s^2, \text{ Pa} \quad (2)$$

where ρ - material density, kg/m^3 ; V_p – velocity of longitudinal waves in the material, m/sec; V_s – velocity of transverse waves in the material, m/sec; μ_d - dynamic Poisson's ratio.

Because velocity of all waves is connected to velocity of longitudinal waves, for volume waves and surface waves in homogeneous half-space

$$V_X = f(V_p, \mu_d) \quad (3)$$

for channel waves

$$V_X = f(V_p, \mu_d, \lambda, A) \quad (4)$$

where A – geometrical parameters of the channel; λ - wave length, thus with certain Poisson's ratio evaluation of dynamic elasticity modulus as function of any wave velocity V_x represents no problem.

Relationship between strength of material and longitudinal wave velocity in it or elasticity modulus is empirically established and depends on many factors.

Most wide-spread materials in construction industry are brickwork and reinforced concrete. For brickwork strength calibration samples of stone and joints mortar is taken, their strength is calibrated on the press in compliance with the requirements of GOST 5802-86, GOST 8462-85, GOST 530-80, GOST 379-79 and brickwork strength is calculated from L. Onischik's formula [13]:

$$R_{brw} = A\,R_{st} \cdot \eta \cdot \left\{1 - \frac{a}{b + R_m/2R_{st}}\right\}, \quad \text{Pa} \tag{5}$$

[where A – structural coefficient; R_m, R_{st} – compressive strength limits, correspondent to building mortar and stone, MPa; a, b - coefficients (for brickwork a = 0.2, b = 0.3); η - compensation factor for brickwork on low grade mortars ($\eta < 1$ with $R_m < 0.04R_{st}$, in other cases $\eta = 1$)]
or V. Polyakov's formula

$$R_{brw} = A\,R_{st}\frac{0.35R_{st} + 3.25R_m}{1.35R_{st} + 3.25R_m}, \quad \text{Pa} \tag{6}$$

Structural coefficient is defined from the formulas

$$A = \frac{100+R_{st}}{100m+nR_{st}}, \qquad \text{kg/cm}^2 \tag{7}$$

where m = 1.25, n = 3 – for brickwork; m = 2.5, n = 8 – for rubblework, or for brickwork considering bending strength of brick $R_{br\,bd}$:

$$A = \frac{1.2}{1+R_{br}/3R_{br\,bd}}, \tag{8}$$

At that velocity of longitudinal wave is preliminarily evaluated at sampling points and after sample test the longitudinal wave velocity dependence of brickwork strength is drawn.

M.A. Aleshin [13, 14] suggested qualitative strength classification of brickwork in accordance with longitudinal wave distribution velocity in seismoacoustic frequency range (up to 10kHz), provided in Table 1.

In Table 1 the following notation is assumed: R_n – characteristic compressive strength of brickwork; V_p – longitudinal wave length in seismoacoustic frequency range.

Use Table 1 to evaluate brickwork strength R_{brw} with accuracy adequate for most practical tasks.

To evaluate concrete strength a calibration curve displaying dependence between longitudinal wave length (or any other wave) and strength. For this purpose wave propagation and strength at separate measuring points shall be determined by any method with calibration curves available:

Table 1: Qualitative Brickwork Strength Classification by Wave Lengths in Seismoacoustic Frequency Range

Brickwork Parameters	R_n, MPa	V_p, m/sec
Very strong	4 ÷ 4.5	> 3000
Strong	3 ÷ 4	2000 ÷ 3000
Reduced strength	2 ÷ 3	1500 ÷ 2000
Low strength	1.5 ÷ 2	1000 ÷ 1500
Weak	1 ÷ 1.5	500 ÷ 1000
Very weak	0.5 ÷ 1	~ 500

- Bore specimen tests;
- Detachment with chipping;
- Chipping of structure's fin;
- Creep;
- Ultrasonic.

It must be borne in mind, that bore specimen testing, detachment with chipping and chipping methods refer to calibration methods and are recommended for use while plotting calibration curves for other methods.

Calibration curve plotting methods for concrete strength ultrasonic evaluation method are stipulated by GOST 17624-87 [4, 15]. Same principles may also be applied for methods based on application of waves in acoustic frequency range.

When calibration curves for ultrasonic methods are drawn, they may be used directly with regard to the fact, that velocity of correspondent types of waves in seismoacoustic frequency range is normally 3÷5% lower than ultrasound velocity.

Major types of waves in building structures are volume waves (longitudinal and transverse waves) and channel waves (beam, plate, surface and bending).

Elasticity theory provides the following relationships between velocities of these waves [11-15]:

$$\frac{V_s}{V_p} = \sqrt{\frac{1-2\mu}{2(1-\mu)}}, \tag{9}$$

$$\frac{V_R}{V_p} = \sqrt{\frac{1-2\mu}{2(1-\mu)}} \cdot \frac{0.87+1.12\mu}{\mu+1}, \tag{10}$$

$$\frac{V_R}{V_s} = \frac{0.87+1.12\mu}{\mu+1}, \tag{11}$$

$$\frac{V_d}{V_p} = \sqrt{(\mu + 1)\frac{1-2\mu}{1-\mu}}, \tag{12}$$

$$\frac{V_{lam}}{V_p} = \sqrt{\frac{1-2\mu}{(1-\mu)^2}}, \tag{13}$$

where V_p – longitudinal wave velocity; V_s – transverse wave velocity; V_R - Rayleigh wave velocity; V_d – rod wave velocity; V_{lam} – lamellar wave velocity; μ - Poisson's ratio.

It must be borne in mind, that channel waves (bar and lamellar) are subject to above given formulas only at low frequencies, at wave lengths essentially exceeding the maximum cross-sectional dimension – for bar waves and slab thickness – for lamellar waves. At high frequencies they are transformed into longitudinal or Rayleigh wave correspondingly. Dependence diagrams for relationships (9-13) are provided in Fig. 1.

Of special interest is the use of bending waves. These waves feature strong dispersion (wave length dependence of wave velocity). Dispersion curve form is in turn determined by thickness of the structure and character of through-the-thickness acoustic parameter variation in the material. Considering low attenuation of such waves, the possibility arises to use them for strength evaluation not only for concrete, but for brickwork material and other types of bearing structures, e.g. rubble stone footings, stone walls, arches and vaults [12-15].

The possibility to use bending waves for evaluation of strength of building structure materials arises due to availability of theoretical solution for dispersion curve for bending waves in homogeneous slab, expressed as dependence between unitless parameters V_{bd} / V_R and λ / H:

$$\frac{\sqrt{1-\frac{V_{bd}^2(0.87+1.12\mu)^2}{V_R^2(1+\mu)^2}}\sqrt{1-\frac{V_{bd}^2(0.87+1.12\mu)^2(1-2\mu)}{2V_R^2(1+\mu)^2(1-\mu)}}}{\left(1-\frac{V_{bd}^2(0.87+1.12\mu)^2}{2V_R^2(1+\mu)^2}\right)^2} \copyright \frac{th\left(\frac{H}{\lambda} I\pi\sqrt{1-\frac{V_{bd}^2(0.87+1.12\mu)^2(1-2\mu)}{2V_R^2(1+\mu)^2(1-\mu)}}\right)}{th\left(\frac{H}{\lambda} I\pi\sqrt{1-\frac{V_{bd}^2(0.87+1.12\mu)^2}{V_R^2(1+\mu)^2}}\right)}, \quad (14)$$

where H – slab thickness; λ - bending wave length; V_{bd} – bending wave phase velocity.

This transcendental equation was solved resulting in two values λ/ H and V_{bd} / V_R, for Poisson's ratio from 0.1 to 0.4, which are used for theoretical evaluation of dispersion curves with specified values of V_R, H and μ. Dispersion curves for homogeneous slab for various values of Poisson's ratio are provided in Fig. 2 (a – section λ / H from 0 to 30, b – to 10) [16].

Bending waves method was implemented in structures based in Moscow and St. Petersburg [17-20]. Main advantage of bending waves method, as expected, is the possibility of evaluating material of stone and brickwork and multilayer concrete structures, for instance slabs on soil foundation.

See Fig. 3–5 for results of bending waves usage for diagnosis of condition of extraboundary volume of metro tunnels.s

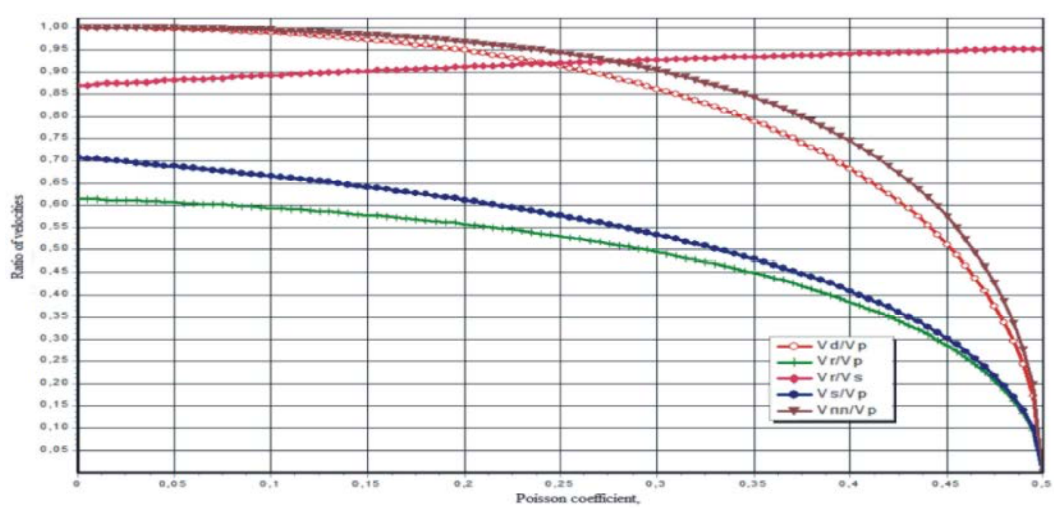
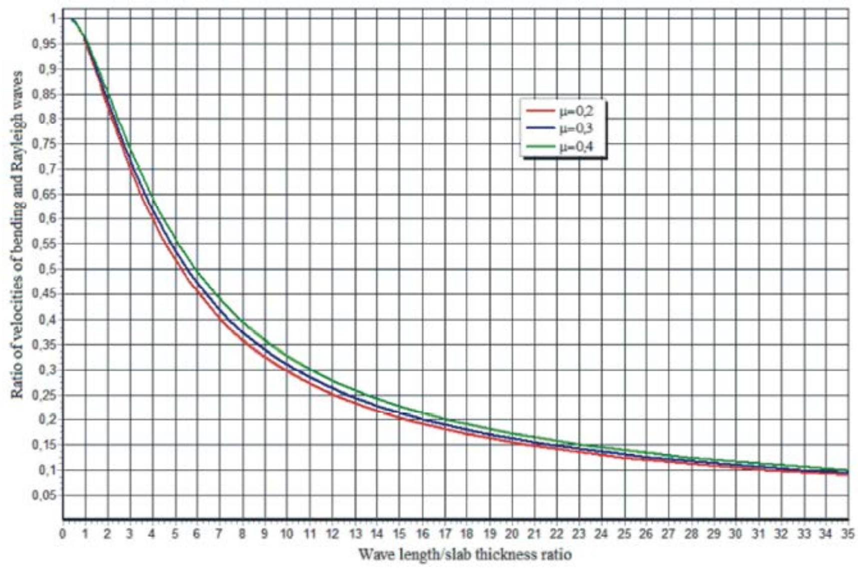
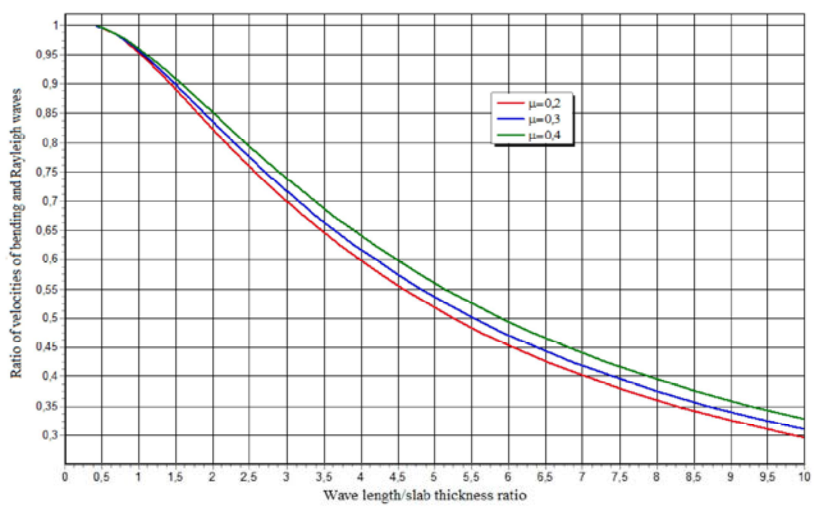


Fig. 1: The ratio of elastic waves in concrete



a)



b)

Fig. 2: Dispersion curves for various values of Poisson's ratio

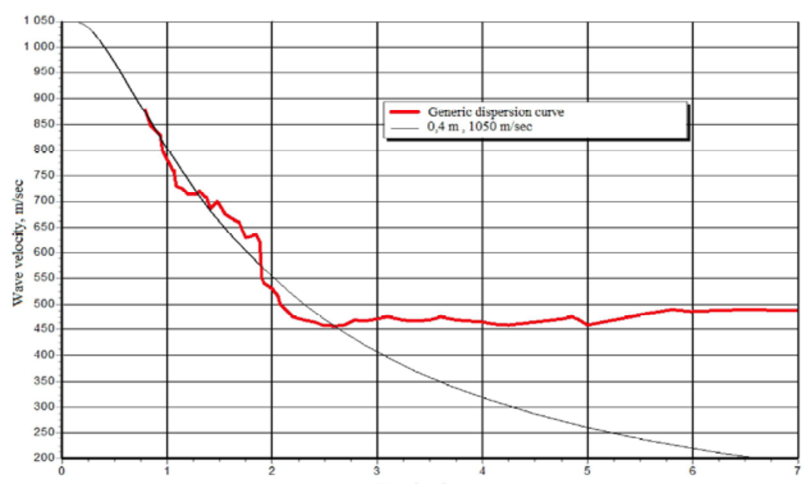


Fig. 3: Generic dispersion curve

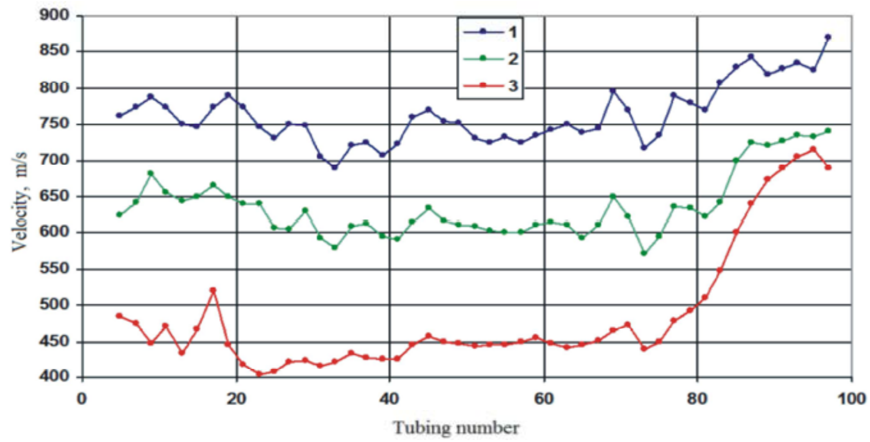


Fig. 4: Surface wave velocity fluctuation through tunnel length

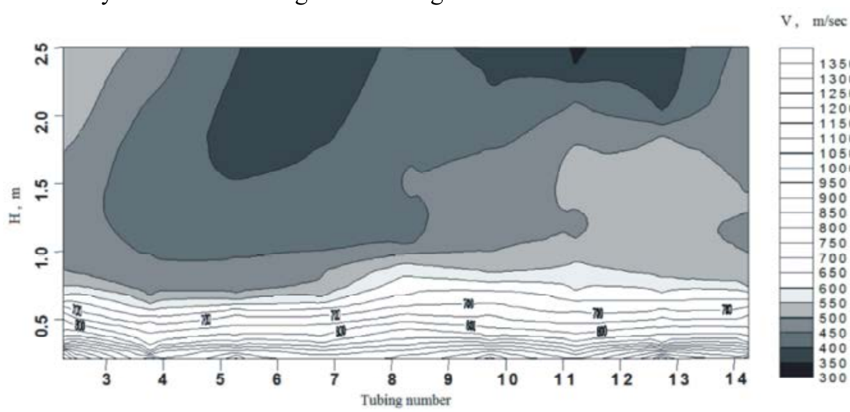


Fig. 5: Diagram of contours of surface wave velocity in extraboundary volume

CONCLUSIONS

Analysis of characteristic oscillations of structures (or the whole building) is used for integral evaluation of their condition for column covers and bearing walls, as well as for locating and identifying large defects in concrete or stone work. Imitation of simultaneous impact in various points of the structure is achieved as follows:

- With the same arrangement of sensors impact is created in all points, where this appears necessary in order to separate the required oscillation modes;
- Use a computer for each measurement point in compliance with the wave superposition principle to create combined implementations, representing a sum (with consideration for sign) of implementations from various points of impact on the structure;
- The combined implementations created are processed similar to any other implementations to make dispersion curves or locus diagrams for velocity of correspondent oscillation mode.

This method is used for diagnosis of structures, where material strength causes concern as a result of deterministic evaluations with acclaimed methods. At that the 'structural strength' is determined, which from the viewpoint of evaluation of bearing capacity in this particular case represents the major subject for study.

The above suggested approach has been used repeatedly for mass explorations of buildings and structures, monitoring of technical conditions of critical facilities, for the research and practical purposes.

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