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THE ASSESSMENT OF THE DYNAMIC RESPONSE TO SEISMIC EXCITATION FOR CONSTRUCTIONS EQUIPPED WITH BASE ISOLATION SYSTEMS ACCORDING TO THE NEWTON-VOIGT-KELVIN MODEL

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Abstract: *The paper presents the results of the researches carried out for constructions base isolation technical solutions using rheological dissipative elastic devices modelled as a viscous-elastic compound system. In this context, there are analysed the conditions for the achievement of an equivalent viscous-elastic connection, based on the coupling of elastic and viscous devices in a Newton-Voigt-Kelvin structure. On this basis, the dynamic analysis highlights the level of the dynamic response by the significant amplitudes of the instantaneous displacements to the dominant spectral frequency of the seismic excitation. In the end, there are presented the parametric variation curves which allow the assessment of the dynamic isolation level and the efficiency of the viscous–elastic link, used as a base isolation system for construction (buildings, bridges, viaducts) located in seismic prone areas.*

Key words: *antiseismic isolation, dynamic response, rheological models, Newton-Voigt-Kelvin*

1. INTRODUCTION

The advanced technologies evolution in the field of advanced industry of special devices designed for elastomeric elastic systems, dissipative fluid systems, or shock-absorbing systems has led to the substantiation of new concepts regarding the composition of seismic systems isolation systems for constructions.

Thus, the physical, mechanical, elastic and/or dissipative characteristics grouped in parametric value classes are provided by a large, constructive and functional variety of anti-seismic devices, elastomeric and dissipative with viscous fluid. Under these conditions, the design solutions for base insulation systems can be determined based on the favorable combination of anti-seismic devices, in such a manner that the calculus model to allow a significant and rapid engineering assessment.

Nowadays, there are multiple and varied concerns for the identification of specific categories of efficient viscous-elastic systems for the constructions base isolating to seismic actions. As a result of the researches carried out and the validation of suitable solutions, the present paper presents, in the synthesis, a construction dynamic model, based on an isolation system which contains several and various anti-seismic devices.

On this basis, the isolation system can be represented as a Newton-Voigt-Kelvin equivalent rheological model. For the execution of the system, the fundamental spectral component of the spectral composition of the in action system was adopted. Thus, the calculus model takes into account a rigid with the construction mass, with the Newton-Voigt-Kelvin equivalent link, and with inertial excitation as a result of the transport movement of the ground under the construction foundation, in a horizontal acceleration field according to the fundamental mode $a = \omega^2 X_0 \sin\omega t$, where: X_0 is the horizontal displacement amplitude and ω is the circular frequency of the seismic movement, with the period $T = \omega / 2\pi$.

Based on the adopted calculus model, there were defined the instantaneous displacements characteristics expressed by amplitude, which can be used in the assessment of the dynamic isolation degree.

2. DYNAMIC RESPONSE IN RELATIVE INSTANTANEOUS DISPLACEMENTS

The Newton-Voigt-Kelvin linear dynamic model with composed viscous link V - (E / V) is represented in Figure 1 where: m - construction mass, *k* - equivalent rigidity of the elastomeric devices in displacement on horizontal direction, *c* - equivalent viscosity of anti-seismic fluidic devices, *M* - viscosity multiplier of fluidic devices *(Mc)* in serial connection with group *(c/k)*. The ground seismic transport motion in the direction OX is noted by x_o (X_0) which defines the instantaneous coordinate of the mobile mark O having the amplitude *X* and the motion law $x_o(t) = X_0 \sin\omega t$, for the fundamental component $\omega = 2\pi / T$ of the spectral composition.

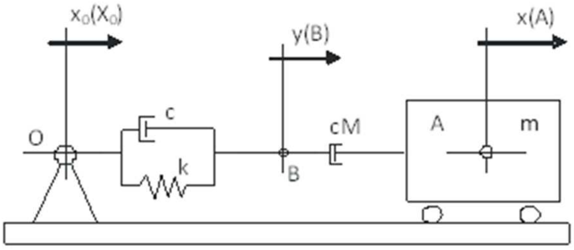

Fig.1 Dynamic model with viscous-elastic link V- (E/V)

The absolute movement of the point A in relation with the fixed mark O_1X is given by the instantaneous displacement *x(t)* with the amplitude *A*, the absolute instantaneous displacement of the link point B of the rheological system V-(E/V) is *y(t)* with the amplitude *B* .

The motion differential equations, in complex forms can be written as follows:

$$\begin{cases} m \cdot \ddot{\tilde{x}} - Mc\,(\dot{\tilde{y}} - \dot{\tilde{x}}) = 0 \\ c\,(\dot{\tilde{x}}_0 - \dot{\tilde{y}}) + k\,(\tilde{x}_0 - \tilde{y}) - Mc\,(\dot{\tilde{y}} - \dot{\tilde{x}}) = 0 \end{cases} \quad (1)$$

in care avem:

$$\tilde{x}_0 = X_0 e^{j\omega t};\ \tilde{x} = \tilde{A} e^{j\omega t}, cu\ \tilde{A} = A e^{j\theta_2};$$
$$\tilde{y} = \tilde{B} e^{j\omega t}, cu\ \tilde{B} = B e^{j\theta_1};$$

where:

$$\tilde{x}_0 = X_0 e^{j\omega t};\ \tilde{x} = \tilde{A} e^{j\omega t},\ with\ \tilde{A} = A e^{j\theta_2};\ ;$$
$$\tilde{y} = \tilde{B} e^{j\omega t}, with\ \tilde{B} = B e^{j\theta_1}$$

Solving the system (1) by using the complex measures $\tilde{x}_0$, $\tilde{x}$, $\tilde{y}$, $\dot{\tilde{x}}_0$, $\dot{\tilde{x}}$, $\dot{\tilde{y}}$ and $\ddot{\tilde{x}}$, the amplitudes A and B are obtained, expressed as:

$$A(c,\omega) = X_0 \sqrt{\frac{(c^2k^2 + c^4\omega^2)\cdot M^2}{\omega^2\,(c^2M + km)^2 + c^2[kM - m\omega^2\,(1+M)]^2}} \quad (2)$$

$$B(c,\omega) = X_0 \sqrt{\frac{(c^2\omega^2 M + mk\omega^2)^2 \cdot c^2\omega^2 (kM - m\omega^2)^2}{(c^2\omega^2\,M + mk\omega^2)^2 + c^2\omega^2\,[kM - m\omega^2\,(1+M)]^2}} \quad (3)$$

Figure 2 presents the variation curves of the instantaneous displacement amplitude x=Asin($\omega t-\theta_2$).

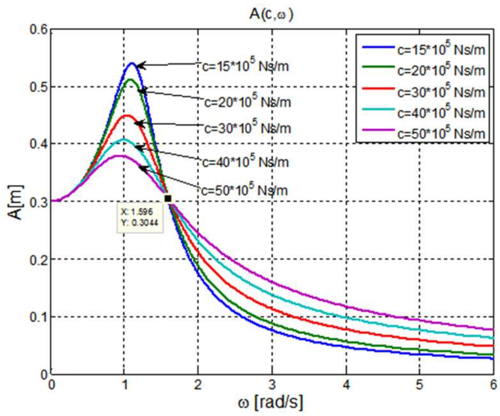

Fig. 2. The variation curves of the amplitude *A* in relation with the current variable *ω* and the discrete variable *c*

Figure 3 presents the variation curves of the amplitude of the instantaneous displacement y=Bsin($\omega t-\theta_1$).

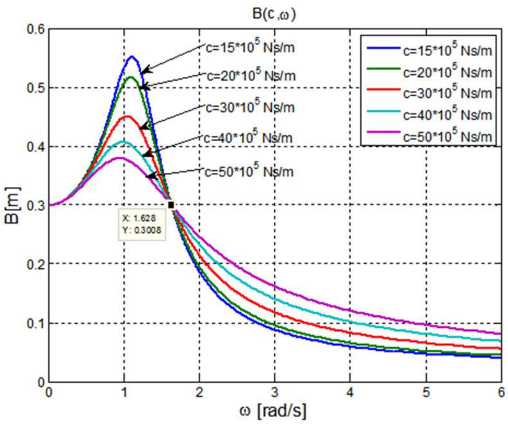

Fig. 3. The variation curves of the amplitude *B* in relation with the current variable *ω* and the discrete variable *c*

The dephasings θ1 and θ2 of the instantaneous displacements y and x in relation with the instantaneous displacement x_o are expressed by the relations:

$$tg\theta_1 = \frac{c\omega\delta - k\gamma}{c\omega\gamma + k\delta} \quad (4)$$

$$tg\theta_2 = \frac{\delta\gamma - \varepsilon\gamma}{\gamma^2 + \delta\varepsilon} \quad (5)$$

where

$$\begin{cases} \delta = c\omega[kM - m\omega^2(1+M)] \\ \gamma = c^2\omega^2 M + mk\omega^2 \\ \varepsilon = c\omega(kM - m\omega^2) \end{cases} \tag{6}$$

so that with the formula (5) the dephasings θ_1 and θ_2 can be determined in relation with the pulse ω variation.

3. THE INSTANTANEOUS DEFORMA - TION OF THE COMPOSED VISCOUS-ELASTIC SYSTEM V–(E/V)

In dynamic regime, on the composed system direction of deformation, there can be distinguished two the significant deformation:

- instantaneous deformation, $v_1 = v_1(t)$, of the Voigt-Kelvin viscous-elastic system, denoted (E/V);
- instantaneous deformation $v_2 = v_2(t)$ of the Newton viscous system, denoted *(V).*

The maximum values or the V_1 and V_2 amplitudes of the instantaneous deformations $v_1(t)$ and $v_2(t)$, are required in order to determine the force in the composed viscous-elastic link and the energy which is dissipated in the analyzed viscous system, on portions and/or on the whole.

3.1 The viscous-elastic system instantaneous deformation (E/V); Voigt-Kelvin model

Considering the instantaneous displacements $\tilde{x}_0$, and $\tilde{y}$ in the complex formulation, the instantaneous deformation can be determined as $\tilde{v}_1 = \tilde{V}_1 e^{j\omega t}$ with $\tilde{V}_1 = V_1 e^{j\theta_1}$, so that $\tilde{v}_1 = \tilde{x}_0 - \tilde{y}$, resulting:

$$\tilde{V}_1 = X_0 - \tilde{B} \tag{7}$$

where the expression of $\tilde{B}$ is introduced, and it is obtained:

$$\tilde{V}_1 = \frac{X_0}{\gamma^2 + \delta^2}(\delta - \varepsilon)(\delta - j\gamma) \tag{8}$$

with the amplitude V_1 and the dephasing φ_1

$$V_1 = \frac{X_0}{\sqrt{\gamma^2 + \delta^2}}(\delta - \varepsilon) = \frac{X_0}{\sqrt{S}}(\delta - \varepsilon)$$
$$tg\varphi_1 = \frac{\gamma}{\delta} \tag{9}$$

The amplitude V_1 of the system's deformation (E/V) can be written as follows, also:

$$V_1(c,\omega) = X_0 \frac{mc\omega^2 M}{\sqrt{\omega^2\,(c^2M + mk)^2 + c^2[kM - m\omega^2\,(1+M)]^2}} \tag{10}$$

and the dephasing φ_1 can be expressed as:

$$\varphi_1 = arctg\frac{c^2\omega^2 M + mk\omega^2}{c\omega[kM - m\omega^2\,(1+M)]} \tag{11}$$

Figure no. 4 presents the variation curves of the maximum deformation V_1 *(c,ω)* depending on the current variable *ω* and the discreet variation of the viscous damping *c*.

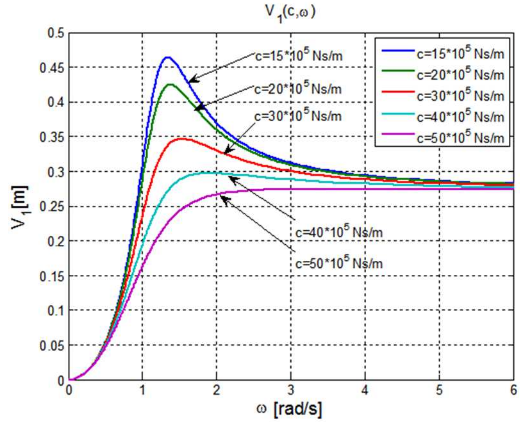

Fig. 4 The variation curves of the maximum deformation V_1 in relation to the continuous variation of *ω* and the discrete variation of *c*

3.2 The viscous- system (V) instantaneous deformation; Newton model

For the linear vascular system with the constant *cM*, where *M* is a real and positive multiplier, the instantaneous deformation is $v_2(t)$, and in the instantaneous complex representation $\tilde{v}_2 = \tilde{V}_2 e^{j\omega t}$ with $\tilde{V}_2 = V_2 e^{j\theta_2}$. Depending on the instant displacements x(t) and y(t), complex formulated, the expression is as follows:

$\tilde{v}_2 = \tilde{y} - \tilde{x}$,or $\tilde{V}_2 = \tilde{B} - \tilde{A}$, finally obtaining:

$$V_2(c,\omega) = \frac{X_0}{S}(R + jI) \tag{12}$$

where:

$$\begin{cases} R = R(c,\omega) = \gamma(\gamma - \alpha M) + \delta(\varepsilon + \beta M) \\ I = I(c,\omega) = -\gamma(\varepsilon + \beta M) + \delta(\gamma + \alpha M) \\ S = S(c,\omega) = \gamma^2 + \delta^2 \\ \alpha = -c^2\omega^2 \\ \beta = c\omega k \end{cases} \tag{13}$$

From the formula (12) the amplitude $V_2(c,\omega)$ and the dephasing φ_2 are resulting, as follows:

$$V_2(c,\omega) = \frac{X_0}{S}\sqrt{R^2 + I^2} \tag{14}$$

$$\varphi_2 = arctg\frac{S}{R} \tag{15}$$

Figure no. 5 presents the curves family for $V_2(c,\omega)$ depending on the current variable ω and the discrete variation of the viscous harmonization c.

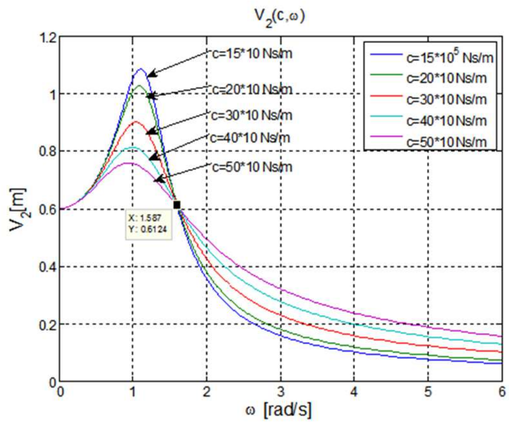

Fig. 5 The variation curves of V_2 depending on ω and the parameter c.

4. THE DYNAMIC ISOLATION PARAMETERS

The force Q_0 from the V-(E/V) system link can be determined based on the maximum viscous deformation V_2, as follows:

$$Q_0 = Q_0(c,\omega) = c\omega M V_2(c,\omega) \tag{16}$$

represented in Figure no. 6.

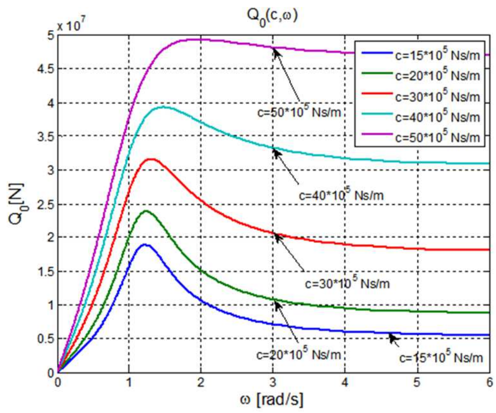

Fig. 6 The variation curves of force Q_0 depending on ω and c

The transmissibility T of the motion from the excitation source with the displacement $x_o = x_o(t)$ to the mass m with the displacement $x = x(t)$, can be expressed as:

$$T = T(c,\omega) = \frac{1}{X_0} A(c,\omega) \tag{17}$$

represented in Figure no. 7.

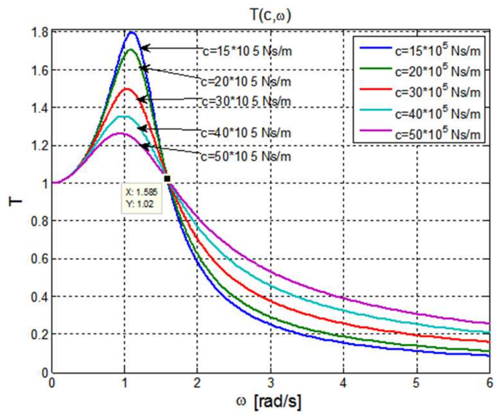

Fig. 7 The variation curves of the transmissibility T depending on ω and c

5. THE DISSIPATED ENERGY

The total dissipated energy in the two dumpers with constant c, and respectively cM is the sum of the dissipated energies in each linear viscous dumper. The formula is as follows:

$$W_d = W_{d1} + W_{d2} \tag{18}$$

where:

$$W_{d1} = \pi c \omega V_1^2, \quad \text{or} \quad W_{d1} = \pi c \omega \frac{X_0^2}{S}(\delta - \varepsilon)^2 \tag{19}$$

and:

$$W_{d2} = \pi c M \omega V_2^2, \text{ or} \quad W_{d2} = \pi c \omega \frac{X_0^2}{S^2}(R^2 + I^2) M \tag{20}$$

The total dissipated energy W_d resulting as:

$$W_d = \pi c \omega \frac{X_0^2}{S}\left[(\delta - \varepsilon)^2 + \frac{1}{S}(R^2 + I^2)M\right] \tag{21}$$

and being represented in Figure no. 8.

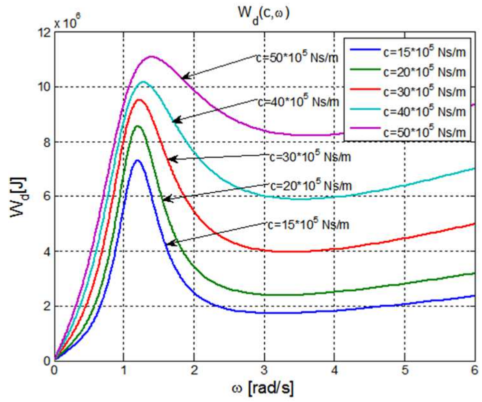

Fig. 8 The variation curves of the dissipated energy depending on the pulsation ω and the harmonization c

6. CONCLUSIONS

The dynamic isolation constructions at the base in order to reduce the transmission of the seismic movements excitation force is an essential component of the research in the field of civil engineering. Thus, as a result of the introduction of a large variety of anti-seismic devices with high performances, today there can be designed anti-seismic systems based on the most favorable combinations in the form of composed rheological models.

In this case, combinations of anti-seismic devices with predominantly viscous, elastic or viscous-elastic properties are possible which ultimately provide the required system parameters (stiffness, damping) for dynamic isolation optimal design. On this basis, in this paper there were tackled the anti-seismic systems using the favorable and necessary connection of the anti-seismic devices, series or parallel, which ensure the rigidity and the equivalent damping on the seismic movement excitation direction..

Thus, it was designed a viscous-elastic anti-seismic system type V-(E/V) in the form of the Newton-Voigt-Kelvin model. The results of the study can be summarized as follows:

a. the dynamic excitation is adapted for the fundamental spectral component of the March 1977 earthquake in Romania;

b. the construction isolated at the base has the following parameters: mass m = 3Mkg; the equivalent horizontal linear rigidity of the viscous-elastic base isolation link k = 4.8M N / m; equivalent linear viscous damping, given by the discrete values of five possible variants c = (1,5 ; 2 ; 3 ; 4 ; 5) MN·s/m; the dynamic excitation for the fundamental component of the seismic spectrum corresponds to T= 2s and a =3m/s^2;

c. the dynamic response of the construction to the given excitation is expressed by the instantaneous displacement $x(t) = A\sin(\omega t+\theta_2)$, with the variation of amplitude $A(c,\omega)$ representation depending on the continuous pulse ω variation and on the equivalent viscous damping c, with discreet variation;

d. the instantaneous deformation of the two viscous-elastic (E/V) and viscous (V) systems grouped in series is determined as $v_1= V_1 \sin(\omega t+\varphi_1)$ and respectively $v_2= V_2 \sin(\omega t+\varphi_2)$, where the amplitudes $V_1(c,\omega)$ and $V_2(c,\omega)$ are represented in the form of families of representative curves;

e. the dynamic isolation parameters are expressed both by the maximum transmitted force Q_o and the movement transmissibility T. Both measures are represented by families of curve depending to the excitation pulse ω and the viscous damping c;

f. the dissipated energy in the hydraulic dampers with constant c and respectively cM is expressed in analytical form and graphically represented by the families of curves parameterized by the discrete values of c, at the continuous variation of ω, mentioning that M is a real and positive multiplication parameter.

Taking into account the above statements, it is considered that the analytical approach of the dynamic behavior of a construction having its base isolated against seismic actions is a necessary and significant stage for the overall assessment of a technical solution in this domain. As a result, the established analytical relations can be used in the calculations for the analysis and dimensioning of the base insulation systems.

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Evaluarea raspunsului dinamic la excitatii seismice pentru constructii echipate cu sisteme de izolare a bazei dupa modelul Newton-Voigt-Kelvin

Rezumat: Lucrarea prezintă rezultatele cercetărilor efectuate pentru soluţiile de izolare a bazei a construcţiilor realizate cu dispozitive elastice disipative reologice modelate ca un sistem compozit vâscos-elastic. În acest context, sunt analizate condiţiile de realizare a unei conexiuni elastice vâscoase echivalente, bazate pe cuplarea dispozitivelor elastice şi vâscoase într-o structură Newton – Voigt - Kelvin. Pe această bază, analiza dinamică evidenţiază nivelul răspunsului dinamic prin amplitudinile semnificative ale deplasărilor instantanee la frecvenţa spectrală dominantă a excitaţiei seismice. În final, sunt prezentate curbele parametrice de variaţie care permit evaluarea nivelului de izolare dinamică şi a eficienţei legăturii vâsco-elastice utilizate ca sistem de izolare a bazelor de construcţie (clădiri, poduri, viaducte) situate în zonele predispuse la seism.

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