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Influence of Some Basic Parameters on the Earthquake-Induced Motion of an Open High-Pressure Pipeline

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In a previous vork of the author [1] the problem of the dynamic interaction between an open high-pressure pipeline and the moving liquid inside it during seismic loading has been solved. A thorough kinematical analysis has been performed in which the basic idea is a two-stage application of the Coriolis's theorem. Thus, the partial differential equation is obtained which governs the earthquake-induced motion of an arbitrary pipeline span:

$$(1)\qquad EI\frac{\partial^4 v}{\partial x^4}+c_sI\frac{\partial^5 v}{\partial x^4\partial t}+m_\Sigma\frac{\partial^2 v}{\partial t^2}+2m_lu\frac{\partial^2 v}{\partial x\partial t}+m_lu^2\frac{\partial^2 v}{\partial x^2}$$
$$+(B_0+A_0x)\frac{\partial^2 v}{\partial x^2}+2A_0\frac{\partial v}{\partial x}+c\frac{\partial v}{\partial t}=\frac{1.584}{L}\left(\frac{B_0}{L}-A_0\right)\delta(t)$$
$$+\frac{4.752}{L^2}A_0x\delta(t)-m_\Sigma[\varphi_1(x)\ddot{\delta}(t)+\varphi_2(x)\ddot{\delta}(t-\beta)].$$

Here EI is the bending stiffness; m_l and m_Σ are the liquid mass and the total mass per unit length, respectively; c, c_s are the coefficients of external and internal viscous damping, respectively; u is the liquid flow velocity; v — the unknown additional displacement due to the dynamic character of the loading; $\varphi_{1,2}(x)$ are the shapes of deflections due to a unit value of the displacement at each of the supports; x — running abscissa from the end of the arbitrary span considered. The origin of the coordinate system is fixed at the left support of the span considered (so the abscissa increases in the liquid flow direction). $\ddot{\delta}(t)$ and $\delta(t)$ are the real acceleration and displacement time-histories, which involve the actual seismic input; β is the time interval which is needed by the seismic wave for covering the distance L between both adjacent supports of the span. And the following expressions are denoted with A_0, C_0 and B_0, respectively:

$$(2)\qquad A_0=\frac{G_p\sin\alpha}{L}+\frac{2\pi R\gamma_l u^2}{C_1^2}$$

$$(3)\qquad C_0=G_p(i-1)\sin\alpha+(G_p+G_l)(i-1)\mu\cos\alpha+\frac{\pi}{4}(D_2^2-D_1^2)\gamma_lH_1$$
$$+\frac{2\pi R\gamma_l Lu^2}{C_1^2}(i-1)+\pi D_2l_f\gamma_lH_1\mu'$$

(4) $$C_0-\pi R^2\gamma_l H_i=B_0.$$

The following notations are assumed: G_p, resp. G_l — weight of the pipe, resp. of the liquid inside it (in our case — water), per unit length; D_1, D_2 — internal and external diameter of the pipe, respectively; γ_1 — the weight of unit water volume; α — slope of the pipeline to the horizon; μ is the coefficient of friction between pipe and supports; i — number of the span considered (counting down the hill); H_1 — static pressure at upper compensator [m]; H_i — static pressure for the span considered [m]; l_f, μ' — length of the frictional part and coefficient of friction at upper compensator, respectively; C_1 — velocity factor (after Manning).

Eq. (1) has been deduced in the coordinate system shown in Fig. 1. The layout of the pipeline span is shown there, and the third axis of the space coordinate system is directed to the reader.

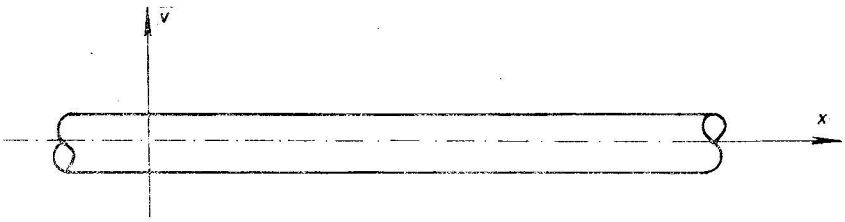

Fig. 1

The interaction between the pipe and the moving liquid inside it is taken into account in Eq. (1). The axial loading on the pipeline and the loading due to the internal water pressure have been taken into account as well. A horizontal seismic input is considered which is transmitted to the pipeline through the base blocks located in equal distances from each other. It is assumed that the seismic wave propagation coincides with the pipe axis (and thus also with the water flow direction) which yields maximum loading. The vertical longitudinal section of the pipeline is shown in Fig. 2.

In [1] an approximate solution of Eq. (1) is given in the form:

(5) $$v^*=f_1(t)\sin\frac{\pi x}{L}+f_2(t)\sin\frac{2\pi x}{L}\cdot$$

Further, for the unknown functions $f_1(t)$ and $f_2(t)$, the set of ordinary second order linear differential equations has been obtained:

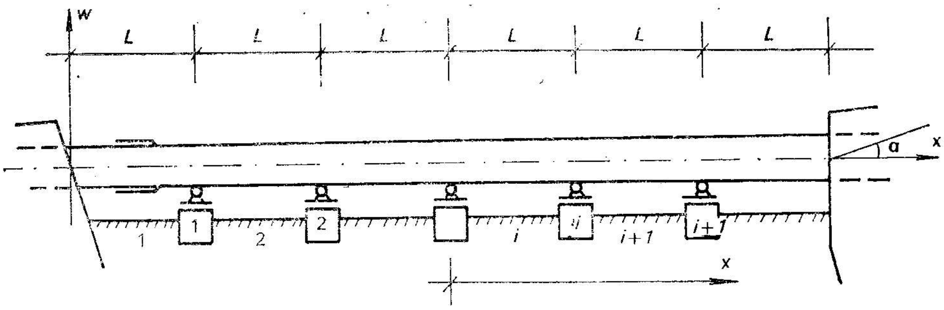

Fig. 2

(6) $$\begin{cases}\ddot{f}_1+2\zeta\omega_1\dot{f}_1-\bar{c}\dot{f}_2+\bar{d}_1f_1+\bar{t}_1f_2=\bar{r}_1\delta(t)+\bar{s}_1[\ddot{\delta}(t)+\ddot{\delta}(t-\beta)]\\ \ddot{f}_2+2\zeta\omega_2\dot{f}_2+\bar{c}\dot{f}_1+\bar{d}_2f_2+\bar{t}_2f_1=\bar{r}_2\delta(t)+\bar{s}_2[\ddot{\delta}(t)-\ddot{\delta}(t-\beta)].\end{cases}$$

Here: $\zeta=0.01$ is the damping value after [2];

$$\bar{c}=\frac{16}{3}\frac{m_l}{m_\Sigma}\frac{u}{L};\quad \bar{s}_1=-0.73348;\quad \bar{s}_2=-0.3654;$$

$$\bar{d}_1=\frac{1}{m_\Sigma}\left[EI\left(\frac{\pi}{L}\right)^4-m_l u^2\left(\frac{\pi}{L}\right)^2+\frac{2A_0\pi}{L}-B_0\left(\frac{\pi}{L}\right)^2-\frac{A_0\pi^2}{2L}\right];$$

$$\bar{d}_2=\frac{1}{m_\Sigma}\left[EI\left(\frac{2\pi}{L}\right)^4-m_l u^2\left(\frac{2\pi}{L}\right)^2+\frac{4A_0\pi}{L}-B_0\left(\frac{2\pi}{L}\right)^2-\frac{2A_0\pi^2}{L}\right];$$

$$\bar{r}_1=\frac{2}{\pi m_\Sigma L}\left(1.584A_0+3.168\frac{B_0}{L}\right);\quad \bar{r}_2=-\frac{4.752A_0}{\pi L m_\Sigma};$$

$$\bar{t}_1=7.111\frac{A_0}{m_\Sigma L};\quad \bar{t}_2=1.778\frac{A_0}{m_\Sigma L}. \tag{7}$$

The set of equations (6) is solved numerically.

The aim of this paper is to trace the influence of some key parameters on the solution of the set (6), i. e. on the response of the pipeline span considered under seismic loading. This investigation has been performed with the data of a real working water power station pressure pipeline. We used the seismic input data of the following earthquakes [3]:

1. The N-S component of the Niš, 18th May 1980 Earthquake — the part from sixth till sixteenth second;
2. The N-S component of the Priština, 18th May 1980 Earthquake — the part from seventh till seventeenth second;
3. The W-E component of the Brzece, 23d May 1980 Earthquake — the first six seconds.

The data from the acceleration and displacement records was increased 10 timeh because these three earthquakes are not very strong. So the PGA of the input earts

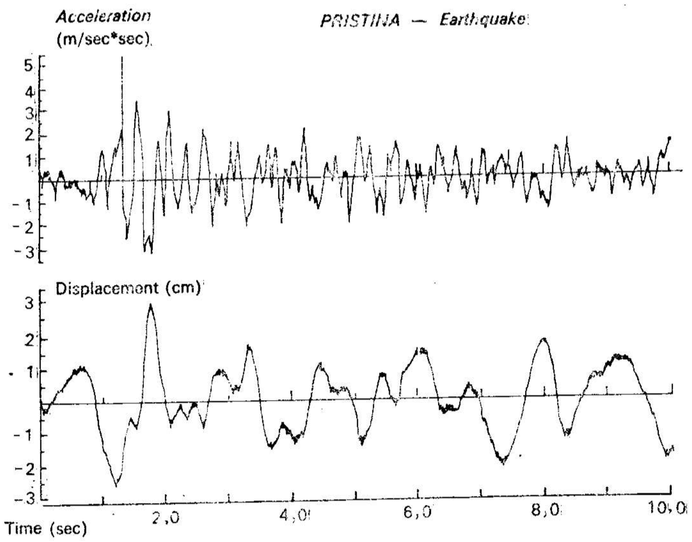

Fig. 3

quakes are Priština: 33.8% g; Niš: 38.3% g; Brzece: 108.0% g, Figs 3-5. A velocity $a=2000$ m/s of the seismic wave propagation is assumed. This value holds for rocky ground. The numerical solution for different parameter values has been performed with accuracy 10^{-6}. The results of this study are given in Table 1. When the variation of some parameter is investigated, the other ones, which do not depend on its variation, take their basic values shown at the top of the Table. The maxima of the functions $|f_1(t)|$ and $|f_2(t)|$ for the time intervals considered are given in the Table.

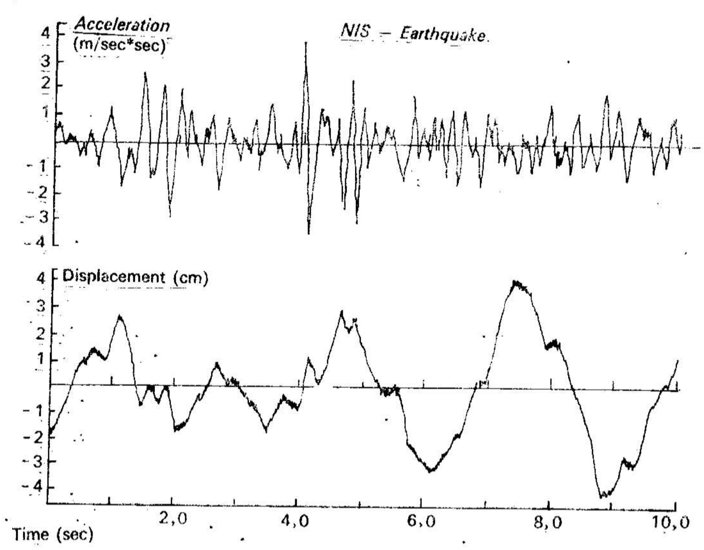

Fig. 4

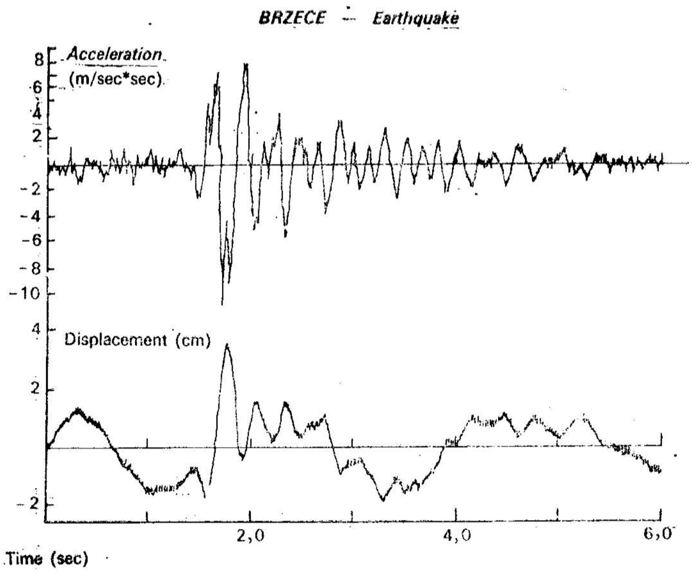

Fig. 5

Let us now analyze these results more thoroughly.

Because of the quick convergence of the solution (5) we shall pay more attention to the variation of the $|f_1(t)|$ maximum. And this maximum determines actually the maximum value of the solution at any cross section of the span for the time interval considered.

Table 1

Basic values of the parameters: $Q=6.5$ m³/sec; $UI=16$; ALFA$=12°$; $D1=1.3$ m; $DD=22$ mm; L$=8.0$ m; $HUK=370.85$ m; $H1=345.9$ m. IMPORTANT: The absolute maxima of the functions $f_1(t)$ and $f_2(t)$ are given in the table in centimeters

Q [m³/sec]		3.5	4.5	5.5	6.5	7.5
Priština	F1	2.4668	2.4669	2.4669	2.4670	2.4671
	F2	0.0046	0.0048	0.0049	0.0050	0.0051
Niš	F1	2.3088	2.3088	2.3088	2.3088	2.3088
	F2	0.0059	0.0059	0.0060	0.0060	0.0060
Brzece	F1	7.4615	7.4616	7.4618	7.4620	7.4623
	F2	0.0125	0.0128	0.0131	0.0134	0.0138
L (m)		6.0	7.0	8.0	9.0	10.0
HUK (m)		364.60	367.75	370.85	373.95	377.10
BETA (sec)		0.003	0.0035	0.004	0.0045	0.005
Priština	$F1$	0.5889	0.7784	2.4670	4.8839	4.3899
	$F2$	0.0003	0.0044	0.0050	0.0109	0.0159
Niš	$F1$	0.7469	1.4542	2.3088	2.6195	3.7179
	$F2$	0.0003	0.0026	0.0060	0.0101	0.0182
Brzece	$F1$	1.5719	1.3753	7.4621	4.7384	6.5834
	$F2$	0.0007	0.0084	0.0134	0.0250	0.0422
ALFA (deg)		8	10	12	14	16
$H1$ (m)		357.20	351.50	345.90	340.32	334.80
HUK (m)		373.90	372.35	370.85	369.35	367.88
Priština	$F1$	2.4677	2.4674	2.4670	2.4667	2.4664
	$F2$	0.0050	0.0050	0.0050	0.0050	0.0050
Niš	$F1$	2.3093	2.3091	2.3088	2.3085	2.3082
	$F2$	0.0060	0.0060	0.0060	0.0060	0.0060
Brzece	$F1$	7.4614	7.4617	7.4621	7.4624	7.4627
	$F2$	0.0134	0.0134	0.0134	0.0134	0.0134
HUK (m)		350.90	359.20	366.85	370.85	377.50
$H1$ (m)		325.95	334.25	341.90	345.90	352.55
Priština	$F1$	2.4683	2.4678	2.4673	2.4670	2.4666
	$F2$	0.0050	0.0050	0.0050	0.0050	0.0050
Niš	$F1$	2.3082	2.3085	2.3087	2.3088	2.3090
	$F2$	0.0060	0.0060	0.0060	0.0060	0.0060
Brzece	$F1$	7.4676	7.4653	7.4632	7.4621	7.4602
	$F2$	0.0134	0.0134	0.0134	0.0134	0.0134
HUK (m)		350.90	359.20	366.85	370.85	377.50
UI		4	9	13	16	20
Priština	$F1$	2.4651	2.4659	2.4663	2.4670	2.4677
	$F2$	0.0050	0.0050	0.0050	0.0050	0.0050
Niš	$F1$	2.3065	2.3074	2.3081	2.3088	2.3096
	$F2$	0.0060	0.0060	0.0060	0.0060	0.0060
Brzece	$F1$	7.4668	7.4648	7.4629	7.4621	7.4605
	$F2$	0.0134	0.0134	0.0134	0.0134	0.0134

Table 1 — Continued

*D*1 (m)		1.3	1.3	1.4	1.5	1.6
Priština	*F*1	2.4226	2.4670	2.1194	1.7525	1.8039
	*F*2	0.0114	0.0050	0.0015	0.0016	0.0038
Niš	*F*1	1.9706	2.3088	1.9086	1.7647	2.0741
	*F*2	0.0065	0.0060	0.0013	0.0024	0.0046
Brzece	*F*1	6.8134	7.4621	4.4944	4.4537	4.2907
	*F*2	0.0219	0.0134	0.0032	0.0037	0.0108
DD (m)		19	20	21	22	23
Priština	*F*1	2.4141	2.3594	2.4805	2.4670	2.4719
	*F*2	0.0111	0.0091	0.0051	0.0050	0.0040
Niš	*F*1	1.9628	2.1411	2.1656	2.3088	2.8958
	*F*2	0.0065	0.0064	0.0055	0.0060	0.0053
Brzece	*F*1	6.8375	7.1632	6.9640	7.4621	6.7733
	*F*2	0.0218	0.0200	0.0144	0.0134	0.0066

We can see that the water discharge Q has a very small influence (through the flow velocity u) on the $|f_1(t)|$ maximum. And the character of this relation depends on the earthquake: it can be an increasing or decreasing function.

When the influence of the span length L is traced, a distance of 176.0 m between the main concrete supports is accepted (so the mumber of spans is 22 for the basic span length value 8.0m). A pressure of 380.0 m at the end of this distance is assumed. So with a slope to the horizon $\alpha(ALFA)=12^0$ the pressure at the upper compensator is $H_1(H1)=345.9$ m. The span with number $i(UI)=16$ is considered. It is clear that the water pressure for this span H_i (HUK) will also vary with the variation of L. The variation of the time interval $\beta(BETA)$ for the different values of L is also taken

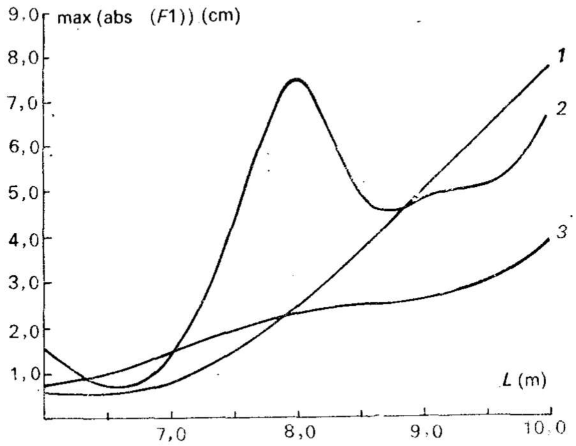

Fig. 6

into account (for $L=8.0$ m $BETA=0.004$ sec). We can see that the influence of L is big, Fig. 6. Curve 1 corresponds to the Priština-earthquake, curve 3 — to the Niš-earthquake and curve 2 — to the Brzece-earthquake. It is clear that the earthquake type is of heavy importance for the $|f_1(t)|$ maximum. For the earthquake of a "single-shock" type (Brzece) there is a high maximum ($L=8.0$ m) after the minimum ($L=6.5$ m). The curves are drawn by means of a natural cubic spline procedure.

Another parameter is the slope angle *ALFA*. When pressure at the end of the distance between the main supports is fixed (380.0 m), the pressures at the upper compensator *H*1 and at the span considered *HUK* will vary with the variation of *ALFA*. We can see that the influence of the slope is small, and the earthquake type determines the relation again. The $|f_1(t)|$ maximum is an increasing function only for the Brzece-earthquake.

Further two cases of variation of the span pressure *HUK* are investigated. It the first one it is connected with the corresponding variation of the pressure at the compensator *H*1, and in the second one — with the variation of the span number *UI*. From both cases studied it is clear that the influence of *HUK* is small as well. The relation of the $|f_1(t)|$ maximum vs. *HUK* is determined from the earthquake: it can be increasing or decreasing.

The $|f_1(t)|$ maximum depends stronger on the internal pipe diameter D_1 (*D*1), Fig. 7. The relation for the Brzece-earthquake has an interesting character with extreme values.

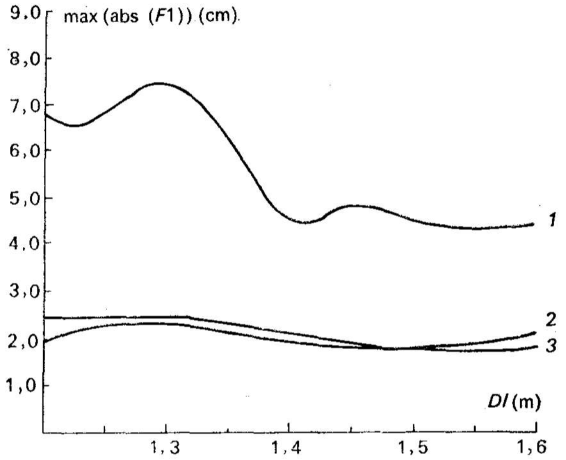

Fig. 7 Curve *1* — Brzece; curve *3* — Priština

The influence of the pipe thickness *DD* is shown in Fig. 8. Here the extreme values for the relation illustrated with the curve 3 (Brzece) are not so clearly expressed.

A general conclusion which can be drawn from the parameter study performed here above is that only few of the parameters have significant influence on the maxima of $|f_1(t)|$ and $|f_2(t)|$. These are the span length (*L*), the pipe diameter (*D*1) and the pipe thickness (*DD*). The influence of the other parameters is small. An important result is also that the earthquake type and intensity are very important for the $|f_1(t)|$ and $|f_2(t)|$ maximum values. These values are quite higher for the Brzece-earthquake which has the greatest PGA. Besides, the three above mentioned quantities have clear maxima for the abscissa under this input. Obviously, it is important that this earthquake is of the "single-shock" type. And it is known [4] that motions of such type occur only at short distances from the epicenter, only on firm ground and only for shallow earthquakes. This result is important for the philosophy of the Earthquake Resistant Design for a given site with fixed geological conditions. Of course, this is only true for the interval in which this parameter study has been performed. The parameter values chosen are close to the real ones but they do not exhaust the possible variety for this kind of structures.

The next task, as seen by the author, is to continue the parameter study of the problem with the data of real structures whose parameters are off the range of the ones used in this paper.

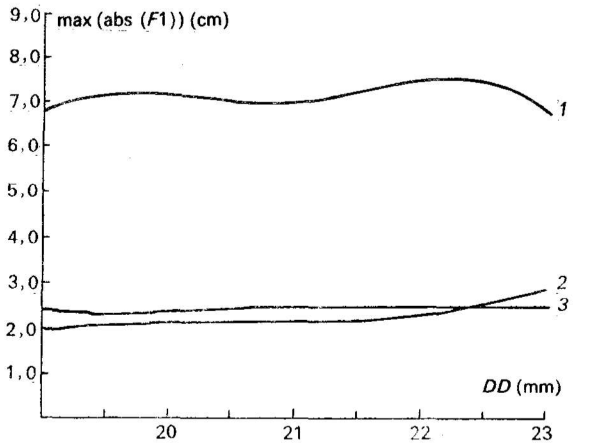

Fig. 8. Curve *1* — Brzece; curve *3* — Prištima

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