EARTHQUAKE-INDUCED VIBRATIONS OF A BURIED PIPELINE INCLUDING FLUID-STRUCTURE INTERACTION – PARAMETRIC STUDY

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ABSTRACT. In the present work, an extensive parametric study is performed of the seismic response of a buried fluid-conveying pressure pipeline to a transverse earthquake excitation represented by a kinematic time-history record. The transverse vibration model of the buried pipe is developed as an Euler-Bernoulli beam on elastic Winkler foundation. The boundary and initial conditions are considered with respect to the applied mechanical model of the structural system including fluid – structure interaction. The constant velocity flow of the inviscid fluid in the pipe is approximated as a plug flow. The parametric study is performed using the previously written by the author computer program in the MatLab environment – “SIVBuPP”. The influence of different parameters is traced such as pipe diameter, surrounding soil characteristics, velocity of the flowing water. This allows us to give insights into the relative effect of these parameters on the dynamic response of a buried fluid-conveying pressure pipeline to a transverse earthquake excitation. The obtained results are analyzed and graphically illustrated. Finally, some conclusions are drawn with respect to the seismic design of buried penstocks in hydropower systems.

KEY WORDS: buried pipe, seismic excitation, fluid-structure interaction, parametric study

1. Introduction

In the present work, an attempt is made to trace the influence of different parameters on the earthquake-induced response of a buried pipeline conveying water with a constant flow velocity. This performed analysis represents an inherent phase in the process of a sophisticated and long-standing research of this problem. After extensive review of the existing and available theoretical studies, codes and guidelines for practical applications, a theoretical model and computational procedure for the horizontal transversal earthquake-induced vibrations hydropower pressure penstocks including fluid–structure interaction was developed [2,4]. The theoretical model of the problem consisted in the formulation of the governing partial differential equation of motion of the mechanical model of the considered structural system. Further, the numerical solution of this governing equation was elaborated [3,4]. A fully implicit scheme of the Finite difference method (FDM) was implemented due to its unconditional stability as explained in some more detail further below.
A special approach was created and implemented for finding and justifying of an appropriate computational step over the space (length) coordinate resulting in particular recommendations for practical use [1]. The parametric studies preformed based on the results from the latter study and presented further below enabled better insight into the relative influence of some key system parameters on the dynamic response of a buried fluid-conveying pressure pipeline to a transverse earthquake excitation.

2. Mathematical model
An Euler-Bernoulli beam on elastic Winkler foundation was analyzed in the transverse vibration model of buried pipeline conveying an inviscid fluid with a constant velocity, U. The fluid flow was approximated as a plug flow. The clamped support conditions were applied as boundary conditions of the elaborated model. The Finite Difference Method (FDM) was applied for the solution of the problem of the earthquake-induced vibrations of a buried penstock [2,3] whose governing equation of motion was developed in the form (1):

\[
EJ \frac{\partial^4 u(x,t)}{\partial x^4} + MU \frac{\partial^2 u(x,t)}{\partial x^2} + 2MU \frac{\partial^3 u(x,t)}{\partial x \partial t} + (M + m) \frac{\partial^2 u(x,t)}{\partial t^2} + C \frac{\partial u(x,t)}{\partial t} + Ku(x,t) = C \frac{\partial u_e(x,t)}{\partial t} + Ku_e(x,t)
\]

After a detailed study of various schemes, the fully implicit scheme was implemented because of its unconditional stability and some other advantages. The application of this scheme for numerical solution of the problem governed by the fourth-order differential equation (1) was enabled by some additional mathematics. By means of the MATLAB language and computational environment, a computer program SIVBuPP was written by the author to allow the implementation of the proposed numerical procedure for practical applications, [4].

3. Mechanical model properties
The varied parameters of the investigated steel pressure penstock with respect to applied real values are as follows [5]:
- Inside diameter, \(D_{in}\): 0.49, 1.00, 1.998 and 3.21 m
- Pipe wall thickness, \(t\): 0.005, 0.01, 0.016 and 0.02 m
- Modulus of elasticity, \(E\): 2.1 \times 10^{11} \text{ N/m}^2
- Mass density, \(\rho_{st}\): 7850 \text{ kg/m}^3

Since the structural model of the buried penstock was assumed to correspond to the type implemented in hydropower systems, the conveying fluid is water. The input data for the flowing water is as follows:
- Flow velocity, \(U\): 2.50, 5.00, 7.50 and 10.00 m/s
- Mass density, \(\rho_{w}\): 1000 \text{ kg/m}^3

In the parametric study, three different types of surrounding soil, according to [6], were considered. The types of the soil with the corresponding parameters are shown in Table 1.
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Table 1. Input parameters related to the soil and corresponding stiffness and damping

<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>Angle of an internal friction, ( \varphi ), [7]</th>
<th>Mass Density, ( \rho_s ), kg/m(^3) [7]</th>
<th>Shear Wave Velocity, ( V_s ), m/s [6]</th>
<th>Unstrained Shear Strength, ( c ), kN/m(^2) [6]</th>
<th>Diameter, ( D_{soil} ), m</th>
<th>Soil Spring Stiffness, ( K ), kN/m(^3) [8]</th>
<th>Soil Damping Coefficient, ( C ), kN·s/m(^2) [9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type B: Very loose</td>
<td>35</td>
<td>2100</td>
<td>500</td>
<td>250</td>
<td>0.49</td>
<td>1041.70</td>
<td>2148.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>1946.74</td>
<td>3937.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.998</td>
<td>3645.83</td>
<td>7290.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.21</td>
<td>5807.42</td>
<td>11206.91</td>
</tr>
<tr>
<td>Type C: Dense Soil</td>
<td>30</td>
<td>1800</td>
<td>300</td>
<td>100</td>
<td>0.49</td>
<td>450.99</td>
<td>1104.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>848.20</td>
<td>2025.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.998</td>
<td>1615.94</td>
<td>3749.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.21</td>
<td>2623.90</td>
<td>5763.56</td>
</tr>
<tr>
<td>Type D: Medium to</td>
<td>25</td>
<td>1600</td>
<td>180</td>
<td>70</td>
<td>0.49</td>
<td>303.31</td>
<td>589.18</td>
</tr>
<tr>
<td>Dense to Cohesive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>574.53</td>
<td>1080.00</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.998</td>
<td>1094.08</td>
<td>1999.60</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.21</td>
<td>1770.58</td>
<td>3073.90</td>
</tr>
</tbody>
</table>

The Winkler spring stiffness, \( K \), and damping, \( C \), of the equivalent spring–dashpot system, introduced for representing the support conditions of the mechanical model, were obtained by the computational procedures given in [8,9]. The values of the coefficients, \( K \) and \( C \), were calculated for the above cited diameters, types of soils and burial depth \( H = 1.50 \) m.

The Kobe 1996 earthquake component with \( \text{PGD} = 0.096 \) m and \( \text{PGV} = 0.276 \) m/s in horizontal direction was used for the analysis. The displacement and velocity time histories of this record are presented on Figure 1 and Figure 2.

![Figure 1. Displacement time history of Kobe earthquake in Japan, 1996 [10]](image-url)
The parametric study is performed using the computer program in the MatLab environment – “SIVBuPP”. According to the obtained results in the study [1], the step length, $\Delta x$, of the spatial mesh coordinate was assumed to be equal to the half of the pipe diameter for each of the studied cases. The time step of the computational FDM mesh was determined by the time step of the input seismic records, being in this case $t = 0.01$ s.

4. Numerical results

4.1 Pipeline length in the model

For evaluating of the influence of the pipe length on its dynamic response, a number of computational runs with different lengths of the considered penstock reach were made. The appearance of a displacement wave reflected from the boundary opposite to the one where the propagating excitation was applied, was observed. In the case of harmonic input wave with a specific, relatively low predominant frequency and zero damping, the pipeline response is highly influenced. In this case, the length of the pipeline had a significant influence. The overlap between the displacements due to the incident and the reflected waves was observed, and the resulting transversal pipe displacements in the middle part of the pipeline reach were relatively large due to this superposition.

In the case of an input signal with relatively high predominant frequency or such one representing the frequency content of a real earthquake, the above mention effects of large displacements in the middle part were not observed. In this case, the influence of the pipe length was not so essential. Therefore, since the studied buried pressure pipeline was considered to represent a hydropower penstock with an usual maximum length between the anchor blocks between 100 m and 200 m, the 100 m long model of the penstock with fixed clamped end conditions was further used for the parametric research.

Figure 2. Velocity time history of Kobe earthquake in Japan, 1996 [10]
4.2. Soil stiffness and pipe diameter

Figure 3 shows the influence of the soil stiffness on the relative lateral displacement of the pipeline. It can be seen that increasing of the soil stiffness reduced these pipe displacements. The results showed further that reducing of the pipe diameter generally lead to increasing of the response displacements, Figure 4. The observed phenomenon in the present analysis could be explained by the fact that the calculated values of soil stiffness and damping [8,9] increase with increasing of the pipe diameter (Table 1). Of course, the pipe mass follows the same trend, i.e. it increases with the pipe diameters.

However, the analysis of the dynamic response of a buried empty pipe, performed in [11], showed some different results. Namely, the response of the pipe in lateral direction increased with increasing of the pipe diameter. It was also observed that any increase of the pipe diameter also induced an increase of both the soil lateral spring stiffness and the mass of the pipeline, and the influence of the latter was more distinct than the former one.

It should be emphasized here that the influence of the pipe diameter on the dynamic response of the pipeline cannot be clearly and uniquely assessed. The computational procedures [8,9] for determining both parameters K (soil lateral spring stiffness) and C (damping) of the spring-dashpot model of the assumed pipe-soil mechanical system with perfect contact at the interface make use of diameter-based relations. Hence, the resulting values for K and C are diameter-dependant, as is also the mass of the pipeline per unit length. Yet some clear trend of decreasing response displacements with increasing pipe diameter could be identified from the results presented in Figure 4.

Figure 3. Effect of soil stiffness on the pipeline response
4.3. Mass of the pipe with stagnant water

Figure 5 shows the effect of the stagnant water inside the pipeline on its maximum lateral displacement. It can be seen that by increasing of the system mass due to added water inside, the dynamic interaction between the pipe and the surrounding soil also increased, thus leading to a larger response in terms of displacement. The same effect was observed for the other soil types, too. However, the order and intensity of these changes are negligibly small, Figure 5. In this connection, the results similarly reported in [11] are fully confirmed.

4.4. Velocity of the flowing water

Figure 6 shows the influence of the water flow velocity on the dynamic response of the pipeline.

One could observe that increasing of the water flow velocity slightly amplified the pipe lateral response. The pipe response displacement increased with increment of the velocity of 10 m/s. The usual water flow velocity in hydropower pipelines is in the range of a few meters per seconds, limited from both sides by the
requirements for avoiding particle sedimentation in the pipeline and abrasion of the internal pipe wall. Hence, for such facilities, the influence of flow velocity changes on the pipeline response may be neglected.

Another question of crucial importance has to be addressed here as well. On the one hand, we observed the influence of stagnant water presence in the pipe on its response. On the other hand, we traced the influence of the water flow velocity inside the pipe. These both factors proved to be negligible for the dynamic pipeline response in terms of displacements. Now, the general question remains, whether the flow movement of the water inside the pipe influences its earthquake-induced dynamic response at all. This question is justified by the use of the mechanical model studied here specially developed to account also for the dynamic fluid-structure interaction between the vibrating pipe and the moving water inside it during seismic excitation. The answer is given again by the results shown in Figure 6 since the particular case of stagnant water (i.e. flow velocity = 0 m/s) is presented there, too. The magnitude of the resulting pipe response displacements clearly shows that the presence of flow velocity inside the hydropower penstock does not substantially influence its earthquake-induced response. Thus, the influence of the stationary water flow and of the resulting earthquake-induced fluid-structure interaction on the horizontal lateral pipeline response in terms of displacements may be neglected.

4.5. Soil Damping

Figure 7 shows the effect of soil damping on the dynamic response of the pipeline. This effect was studied for five different values of soil damping obtained for the corresponding seismic wave velocity for soft soil according to [6]. Further, as mentioned above, the soil damping values $C$ (represented by the dashpots in the mechanical model) were calculated by the procedures according to [8,9]. The obtained results are shown in Figure 7.
Figure 7. Effect of the soil damping on pipeline response

A similar relation between the peak response displacement of the pipe and the soil damping was also observed for dense and very dense soil type as well as for the other pipe diameters. As the results indicated, increasing of the soil damping lead in general to decreasing of the pipe displacements.

5. Conclusions

The performed parametric study of the seismic response of a buried water-conveying pressure pipeline to a transverse earthquake excitation confirmed the suggestion that the resulting dynamic interaction between surrounding soil, buried pipeline and flowing water is a very complex phenomenon influenced by a significant number of parameters with quite different contribution.

However, some conclusions can be summarized as follows:

- Increasing of the soil lateral springs stiffness reduces the dynamic interaction between the buried pipe and the surrounding soil in terms of lower pipe displacements;
- The influence of the pipe diameter on the dynamic response of the pipe cannot be unambiguously identified since the values of the soil stiffness and damping in the mechanical model are in a direct relation to both the pipe diameter and the mass of the pipe, in addition to the particular set of local soil conditions [8,9];
- Increasing of the mass of the pipe – water system due to the presence of stagnant water inside leads to larger displacement of the pipeline compared to the response of an empty pipe, however, the magnitude is negligible;
- Any change of the water flow velocity in the possible range of realistic values may be neglected in its influence on the dynamic penstock response.
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- The presence of water flow with constant velocity inside the pipe has a negligible influence on the earthquake-induced lateral pipeline response, too;
- The dynamic response of the buried pipeline is considerably reduced with increasing of the soil damping.

REFERENCES


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