16. D-A-CH Tagung Erdbebeningenieurwesen & Baudynamik (D-A-CH 2019)
26. und 27. September 2019
Universität Innsbruck

SEISMIC PIPE-SOIL-STRUCTURE-INTERACTION IN URBAN AREAS

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ABSTRACT
The aim of this paper is to investigate the influence of a massive rigid structure on a relatively soft soil profile crossed by a pipeline, under seismic excitation. The neighboring structure may cause differential displacements/rotations along the pipeline due to local ‘disturbances’ and potentially induce damage. For the exploration of the problem, the thin-layer method coupled with finite elements is employed in the realm of linear elastodynamic theory. Numerical analysis focuses on the interaction between a massive structure and a lightweight pipeline running nearby. A parametric analysis is conducted to determine the factors which may affect the response of the pipe. The dynamic behavior of the system is analyzed in both frequency and time domain. The effect of the structure on the pipeline is investigated in terms of transfer functions (amplification ratios), ratios of maximum spectral accelerations and relative displacements. Results for pipe – soil – structure interaction are compared against corresponding results where only the pipe is present. It is shown that a pipeline close to a structure with fundamental period close to that of the soil deposit can be considerably affected.

Keywords: *Pipeline-soil-structure-interaction, Thin-layer method, Transfer-functions*

1. INTRODUCTION

In recent years, the rapid growth of urban areas has resulted in increasing demand of energy and of a broader distribution network, with natural gas pipelines being an important part of this infrastructure. Transmission pipelines may extend to industry zones and often across highly populated areas. To reduce the potential risk of incidents, pipelines are being routed along existing highways or near other utility infrastructure. However, this practice might not always be appropriate, as the adjacent massive structures may affect locally the response of the pipeline during a seismic event, and the ensuing displacements may cause loss of serviceability of the pipeline. The same holds for networks of pipelines and production lines running within an industrial area. Though this may be a significant problem, it has attracted minor research interest.

This work deals with the dynamic pipe-soil-structure interaction problem. Although the seismic response of a buried pipeline tends to follow that of the surrounding soil, and the pipeline is not expected to have any appreciable effect on the dynamic response of a neighboring structure, the opposite problem (i.e., impact of structure on the pipeline) may be non-negligible. Previous research on Structure-Soil-

Structure-Interaction (SSSI) problem and the absence of any provisions/recommendations in design codes as to a "safe distance" between pipelines and adjacent structures have provided the motivation for the present study.

2. PROBLEM DEFINITION

2.1. Problem Description

The problem under consideration is depicted in Figure 1. The dynamic interaction between a massive rigid structure and a soft, lightweight buried pipeline is numerically explored by means of the elastodynamic method. To this end, it is assumed no change in the static stress field close to the pipeline, due to excavation for constructing the foundation of the adjacent structure. For instance, bored pile walls installed around the foundation produce less disruption to the adjacent soil due to absence of vibration. Thus, the excavation has low impact on the stress field of the neighboring buried pipeline. This practice is commonly used for the foundation of structures on soft soil, especially when the structures are close to other structures. The simulation aspects of the problem and the assumptions in the analysis are described in the ensuing. Note that, apart from the dynamic interaction between pipe and nearby structure, which is examined herein, there might also be some influence to the seismic response of the pipe because of the differential stress field between the soil region with an overlying structure and that in free-field conditions for the case of strong excitations and potentially inelastic soil response.

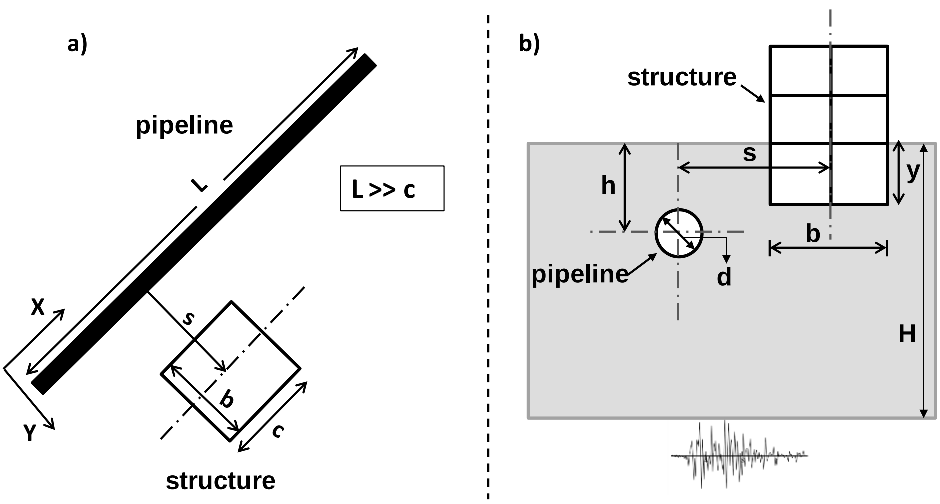

Figure 1: Problem description.

2.2. Dimensional Analysis

Due to the large number of parameters involved, dimensional analysis of the problem under consideration is deemed necessary to obtain a set of governing parameters. The problem involves eleven major dimensional independent parameters ($M = 11$): diameter, d, length, L, and embedment depth, h, of pipeline, distance between structure and pipeline, s, embedment depth of structure, y, geometry of foundation of structure, b and c, fundamental natural period of the soil deposit, T_1, fundamental natural period of structure, T_{str}, excitation period, T, and predominant period of the transient excitation motion, T_c. Parameters such as the stiffness of soil and depth to bedrock are not explored, since interaction effects are significant in case of soft soils, and in this study a very soft soil profile has been selected.

In light of the two fundamental dimensions associated with the variables at hand (length [L] and time [T]; $N = 2$), application of Buckingham's theorem [1] yields nine dimensionless ratios ($M - N = 9$) controlling the solution of the problem. These dimensionless groups were selected to be L/d, s/d, h/d, y/d, b/d, b/c, T_1/T_{str}, T_c/T_{str}, T/T_1. A parametric study is performed to identify the influence of the aforementioned parameters on the interaction effects between the two structures. Note that from the above ratios, L/d was fixed at 30 and remains constant in the analyses. Table 1 summarizes the cases studied.

Table 1. Cases studied for the interaction between structure and pipeline.

Case	*Dimensionless parameters*						*Case*	*Dimensionless parameters*					
	b/d	*c/b*	*s/d*	*h/d*	*y/d*	T_1/T_{str}		*b/d*	*c/b*	*s/d*	*h/d*	*y/d*	T_1/T_{str}
1	13	1	11	7	7	1	7	7	1	11	7	7	0.6
2	13	1	11	0	0	1	8	7	1	7	7	7	0.6
3	7	1	7	7	7	1.5	9	7	2.5	11	7	7	2.1
4	7	1	11	7	7	1.5	10	7	2.5	11	7	7	1
5	7	1	17	7	7	1.5	11	17	0.4	22	7	7	2.4
6	7	1	11	7	7	1	12	17	0.4	22	7	7	1

3. NUMERICAL INVESTIGATION

3.1. Method of Analysis

3.1.1. Thin-Layer Method

For the investigation of the problem, the thin-layer method (implemented in the computer code BAUBOW [2]) coupled with finite elements (SAPC [3]) is employed in the realm of linear elastodynamic theory. The thin-layer method was developed by Waas in the early 1970's [4] and refers to displacement solutions in a viscoelastic isotropic or transversely isotropic medium triggered by static or dynamic ring loads acting in it. Discretizing the medium into a number of thin (real or fictitious) horizontal layers extending to infinity, solving the wave equations analytically with respect to the horizontal variables and applying the pertinent boundary conditions yields the stiffness matrix of the soil-foundation system in a semi-analytic finite-element sense. The top surface of medium is free of stresses while the bottom is bonded to a rigid base. In the vertical direction, material properties may vary with depth. Using cylindrical coordinates, ring loads of the form $p(\omega) = \tilde{p}\, cos(n\theta)\, e^{\,i\omega t}$ or $p(\omega) = \tilde{p}\, sin(n\theta)\, e^{\,i\omega t}$, with ω being the cyclic excitation frequency, θ the azimuth of the load vector and n an arbitrary value, may act in the radial, tangential or vertical direction (Figure 2a). The displacement solutions for ring loads of the above form are expressed in terms of solutions to an associated eigenvalue problem. For the formulation of the eigenvalue problem, the displacement field in the medium (as well as the load, stress and strain fields) are expanded in Fourier series in cylindrical coordinates, with the radial, tangential and vertical displacements being functions of *r* and *z*. Therefore, all relevant equations become uncoupled.

The homogeneous boundary value problem for motion in the medium, considering no stresses at the surface and zero displacement at the bottom, can be written in terms of displacements. The solution to the problem incorporates Hankel functions of the unknown wave number *k*. Due to the complexity of the analytical solution of the problem, the finite element method is used to obtain an approximate solution. The medium is discretized into a finite number of thin elements in the vertical direction and the problem reduces to a set of algebraic eigenvalue equations for generalized Rayleigh and Love waves, with the wave numbers k_R and k_L as the eigenvalues. Selecting the appropriate eigenvalues (or wave patterns, according to the direction of energy flow) and applying certain orthogonality relations, the matrices of Rayleigh and Love wave numbers are obtained. Then, the displacement solution is used for determining the displacements due to ring loads applied at the layer boundaries along the interface $r = r_0$, as shown in Figure 2b. With the displacement solutions, a frequency-dependent flexibility matrix, which relates forces and displacements at a number of rings in soil, can be derived. The dynamic stiffness matrix, $\mathbf{K_m}(\omega)$ (with *m* referring to the number of soil layers), is obtained by inversion.

3.1.2. *Computation of Transfer Functions (FEM)*

The response of the 3-dimensional superstructure (one or multiple) to harmonic motion is computed by means of SAPC [3], taking into account the flexibility matrix derived in the first step by applying the thin-layer method. $\mathbf{K_m}(\omega)$ is added to the dynamic stiffness matrix of the structure at the corresponding foundation degrees of freedom to obtain the global stiffness matrix, which is used for dynamic analyses in the frequency domain. The harmonic motion may be defined at the base of the structure, or at any layer in the soil. The transfer functions of acceleration or displacement are computed for any node of the structure. Computed impedances or transfer functions implicitly contain the propagation of body and surface waves into the soil, without interference due to reflections on artificial model boundaries.

3.1.3. Fourier Transform

From the acceleration time-histories the Fourier spectra are obtained by means of Fast Fourier Transform (FFT). By multiplying transfer functions with Fourier spectra and then transforming back into the time domain, one obtains the time-histories of the individual nodes.

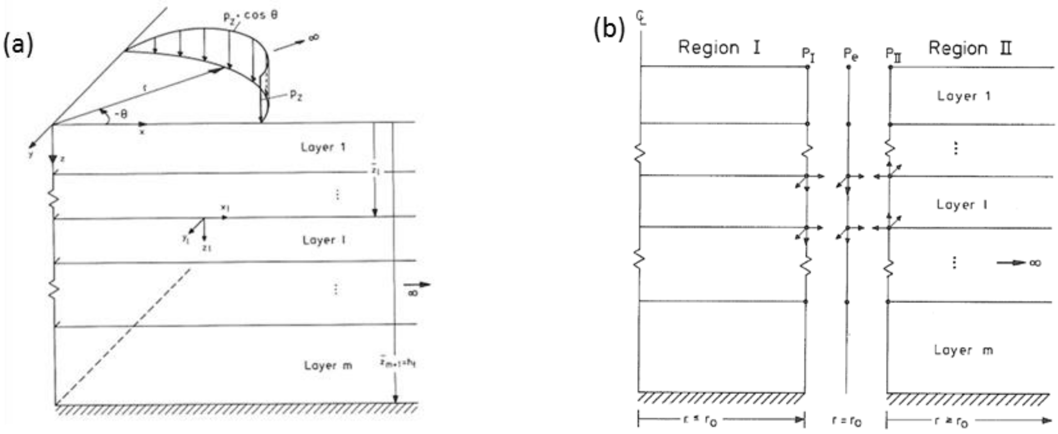

Figure 2: (a) A horizontally infinite medium with a ring load in cylindrical coordinate system, (b) Subdivision of medium into region I and II (after Waas et al [5]).

3.2. Soil Profile

For the exploration of the problem, a soft soil profile consisting of clay is considered. The variation of shear modulus with depth is illustrated in Figure 3a. The bedrock is located 27.5 m below the ground surface. The amplification ratio of soil profile based on BAUBOW analysis is depicted in Figure 3b. It is shown that the fundamental natural frequency of the soil deposit is about 3.3 Hz (or T_1 = 0.3 s) and the second natural frequency is about 7 Hz. The computed fundamental natural frequency seems reasonable and it is verified by using simple hand calculations. The mean value of shear wave propagation velocity up to a depth of 27.5 m is $V_{s,\ mean}$ = 323 m/s. Hence, the fundamental natural frequency is $V_{s,\ mean}$ / (4H) = 323/(4×27.5) = 2.94 Hz, which is close to the computed value. Evidently, the second natural frequency of soil deposit seems to be the resonance of the very soft soil stratum up to about 6.5 m (with V_s < 100 m/s). Up to 6.5 m, the mean value of shear wave propagation velocity is about 192 m/s and the corresponding frequency is 192/(4×6.5) = 7.4 Hz.

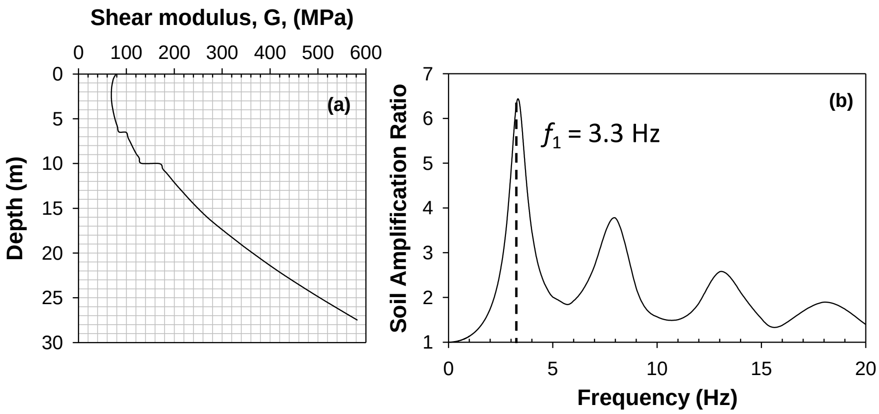

Figure 3: (a) Variation of soil shear modulus with depth. (b) Soil amplification ratio with reference to bedrock.

3.3. Foundation Model

In this analysis, the pipeline is considered flexible ($L/d = 30$). The pipeline is simulated as a strip flexible foundation with dimensions 9m x 0.3m (Figure 4). The length of square elements used in discretization of the pipeline is 0.15 m. The middle nodes represent the axis of pipeline. Displacements at the center of each approximate ring element are computed and the flexibility matrix of the pipeline is obtained. For this first step of analysis (computing the flexibility matrix), both pipeline and the foundation of the adjacent structure are considered flexible.

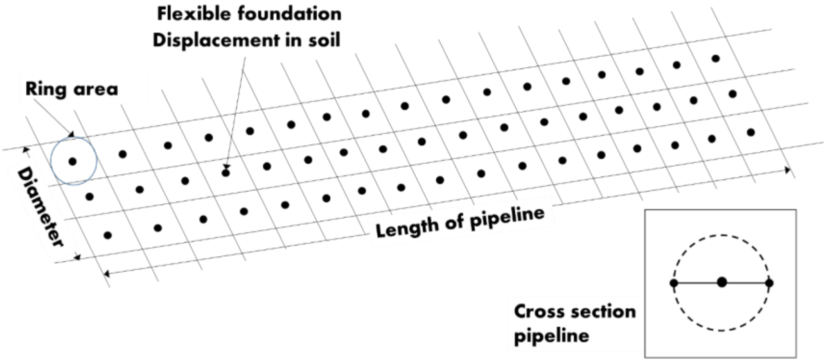

Figure 4: Simulation of pipeline as a strip flexible foundation.

3.4. FEM Model

For the FEM modeling of the pipeline, flexible beam elements along its axis and rigid beam elements vertical to its axis are used. The pipeline is considered continuous with no constraints at the ends. However, for determining the stiffness of the flexible beam elements, it is assumed that the pipeline has simple restraints at both ends. With reference to the adjacent structure, rigid beams connect the nodes at the foundation in order to create a rigid slab. The superstructure is assumed rigid and is modeled as a stick model. The geometrical and vibrational characteristics of the structure vary according to the parametric investigation.

3.5. Seismic Input

Three actual recorded seismic ground motions, Friuli 1976, Rinaldi 1994 and Takatori 1999, with different predominant mean periods (T_c) were employed, considering that they are applied at bedrock, which is located at – 27.5 m from ground surface. The vertical accelerograms have been scaled to peak vertical acceleration (PVA) = 0.28g and the horizontal to peak horizontal acceleration (PHA) = 0.36g. Figure 5 shows the 5%-damped response spectra of input motions.

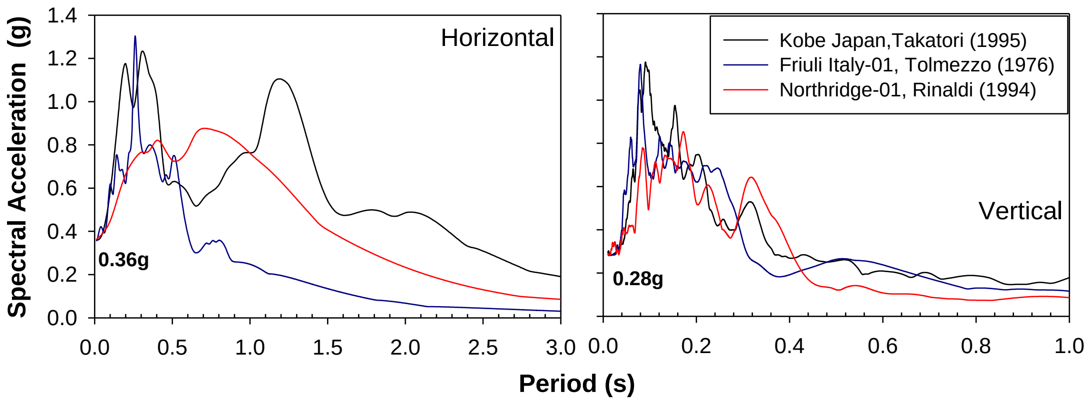

Figure 5: 5%-damped response spectra of input motions.

4. RESULTS

4.1. Transfer Functions

Figure 6 displays a typical variation of transfer functions along the pipeline with and without the presence of the adjacent structure under harmonic excitation. For a better interpretation of the results, transfer functions are depicted as a function of the dimensionless excitation period (T/T_1). Evidently, the influence is local and the maximum effect is observed along the *Y* axis in the middle node. Figures 7 and 8 depict results only for the middle node of pipeline. The dimensionless distance, *s/d*, between pipeline and neighboring structure seems to play a significant role in the dynamic response of the pipeline. Evidently, as *s/d* increases the impact of the structure decreases, as shown in Figure 7. It has also been found that the maximum effect on the pipeline is observed when resonance occurs between structure and soil deposit, i.e., $T_{str} = T_1$ (Figure 8).

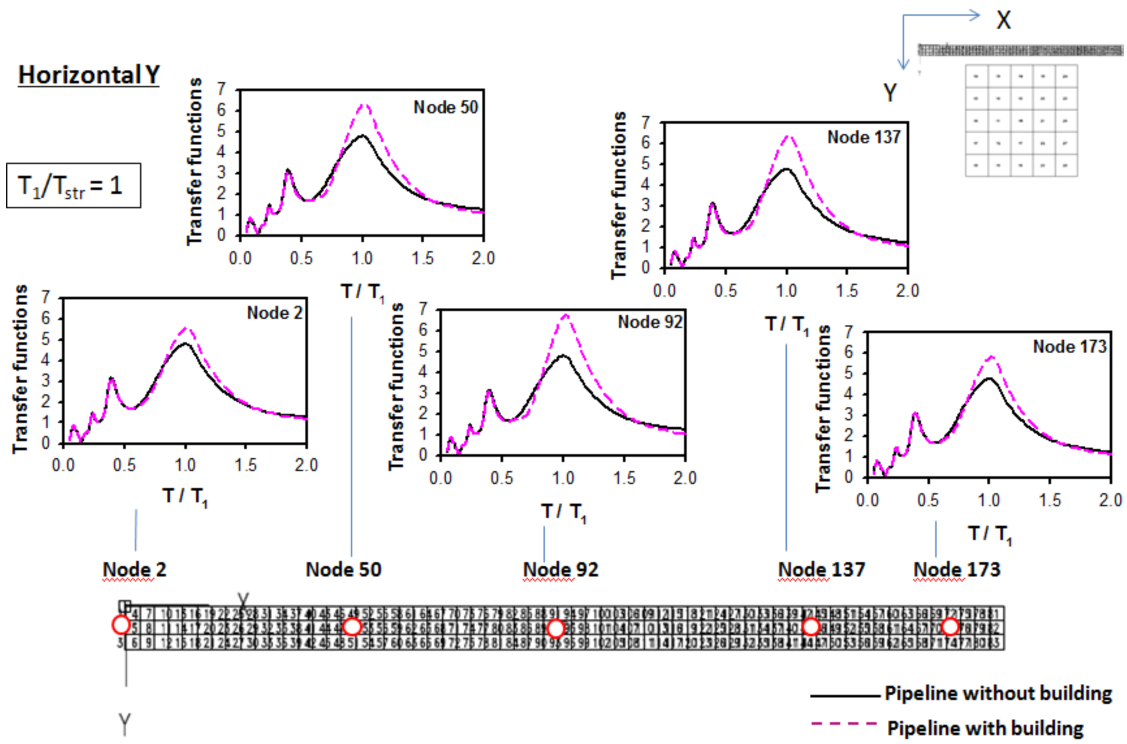

Figure 6: Transfer functions along the pipeline with and without the influence of the neighboring structure (T_1/T_{str}=1), where *T* is the harmonic excitation period, T_{str} is the fundamental period of structure and T_1 is the first mode period of the soil profile.

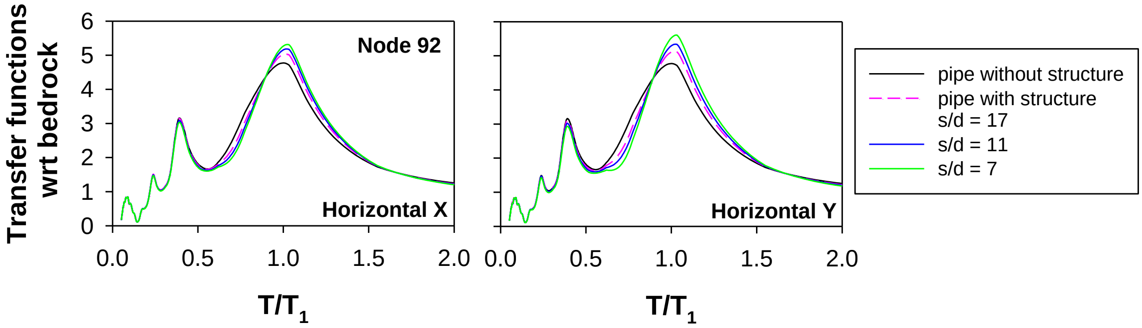

Figure 7: Transfer functions of the middle node (92) with and without the influence of the neighboring structure for X and Y oscillation modes; effect of *s/d* ratio.

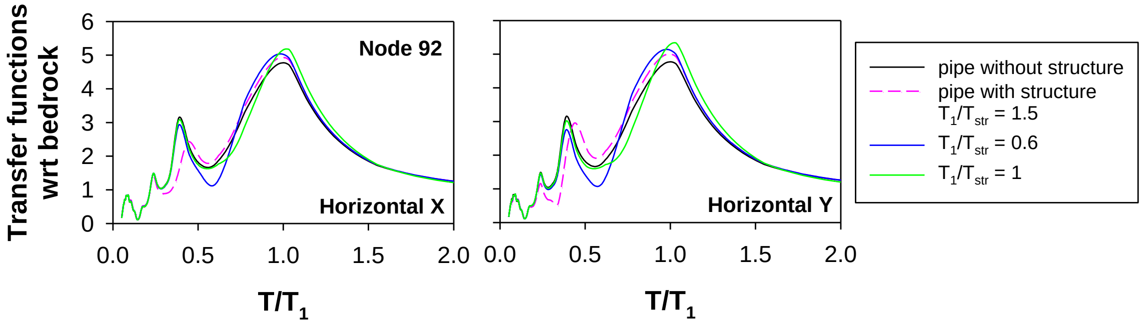

Figure 8: Transfer functions of the middle node (92) with and without the influence of the neighboring structure for X and Y oscillation modes; effect of T_1/T_{str} ratio.

4.2. Maximum Spectral Acceleration

Figure 9 presents results for the ratio of maximum spectral acceleration for the three time-histories. $S(\tilde{A})$ denotes the maximum spectral acceleration of the middle node (92) of pipeline considering the influence of the adjacent structure and $S(A)$ is the corresponding value without the structure. It is seen that in some cases the maximum spectral acceleration of pipeline increases with the presence of the adjacent structure, in other cases decreases or remains invariable. In most of the cases studied the horizontal acceleration of a pipeline close to the structure increases. Evidently, the increase is greater in the *Y* direction. The maximum increase in spectral acceleration of the pipeline is observed in case 6 for the Friuli record and is about 14%. Cases 6, 10 and 12, with T_1/T_{str} = 1, seem to be affected the most. In case 2, though the T_1/T_{str} equals 1, a considerable decrease in acceleration is observed. This can be attributed to the fact that both pipeline and structure are at the surface (y/d = 0). Evidently, the increase is more pronounced in case of Friuli record (T_c/T_{str} = 1). For a given T_1/T_{str} ratio, the increase in s/d ratio seems to reduce the influence of the adjacent structure (cases 3, 4 and 5). With reference to the vertical direction, a significant decrease in maximum spectral acceleration of pipeline is observed in most cases.

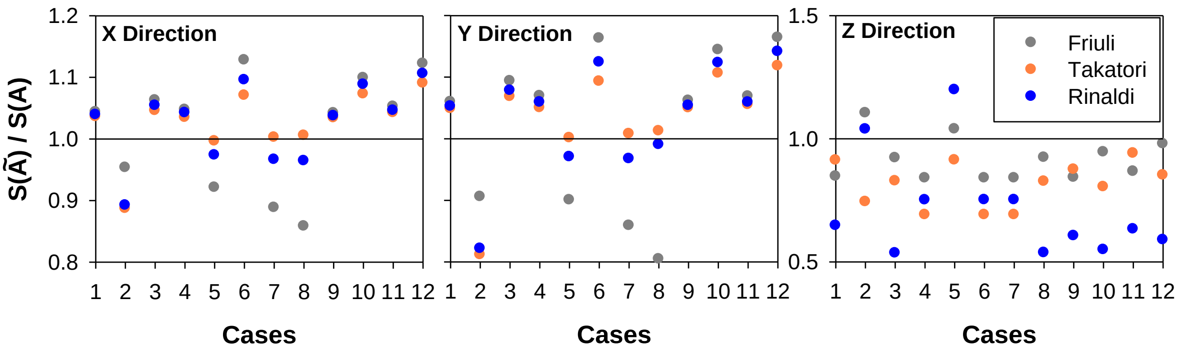

Figure 9: Ratio of maximum spectral acceleration in X, Y and Z Direction.

4.3. Maximum Displacement

The influence of the dynamic behavior of a structure on a neighboring pipeline was investigated in terms of relative displacements. For each node of the pipeline model, the transfer functions of displacement in the principal directions are computed from those of acceleration, and the displacement time-histories are obtained. The maximum relative displacement of the pipeline (node 92) upon the effect of structure is compared against the corresponding value without the structure. Changes in maximum relative displacement of pipeline, for all 12 case studies, with respect to Friuli record are presented in Table 2. It is observed that the influence on the relative displacements of pipeline is insignificant (about 2% ~ 3%), however in case of resonance between structure and soil this may increase to 10%. In the vertical direction, results demonstrate that the structure has a minor effect on the maximum vertical displacement of the pipeline (not shown).

Table 2. Change in maximum relative displacement of pipeline in case of Friuli record.

Difference in maximum relative displacement (%)					
Cases	Direction		Cases	Direction	
	X	Y		X	Y
1	3	3	7	2	3
2	-3	-6	8	2	4
3	3	4	9	2	4
4	2	3	10	4	6
5	1	2	11	3	4
6	7	10	12	-6	-6

5. CONCLUSIONS

The main conclusions of the parametric study are:

- A rigid heavy structure close to a pipeline may have positive, negative or no remarkable effect on the seismic response of the pipeline.
- The influence of the structure on the dynamic response of the pipeline naturally decreases with dimensionless distance, with the critical distance being $s/d \cong 20$.
- A significant increase in horizontal maximum spectral acceleration (up to 14%) and a corresponding relative displacement (up to 10%) of the pipeline is observed when the fundamental period of the nearby structure is close to that of the soil deposit, i.e., $T_1/T_{str} \cong 1$.
- The following parameters seem to be crucial for the dynamic response of the pipeline:
  - s/d (distance between structure and pipeline to pipeline diameter)
  - T_1/T_{str} (fundamental natural period of the soil deposit to fundamental natural period of structure)
  - T_c/T_{str} (predominant period of excitation motion to fundamental natural period of structure)
- Parameters h/d, y/d, b/d and b/c seem to have second-order influence on the response.
- Although the impact of the structure on the maximum vertical spectral acceleration of the pipeline seems to be important, the impact in terms of relative displacements seems to be trivial.

ACKNOWLEDGEMENTS

This work was supported by the Horizon 2020 Program of the European Commission under the MSCA-RISE-2015-691213-EXCHANGE-Risk grant (Experimental and Computational Hybrid Assessment of NG Pipelines Exposed to Seismic Hazard, www.exchange-risk.eu). This support is gratefully acknowledged. The authors would like to acknowledge the help of Dr. Hans-Georg Hartmann in using the BAUBOW software.

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