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EXPERIMENTAL EVALUATION OF DYNAMIC BEHAVIOR OF PIPELINE SYSTEMS OF THERMAL POWER PLANTS EXPOSED TO SEISMIC LOADS

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Abstract: This paper deals with the experimental results obtained by *in situ* and model testing of a segment of the pipeline system of a thermal power plant. The field testing has been performed by using the forced and ambient vibration method. The model testing has been performed by means of a shaking table. The model was designed and constructed to the scale of 1/3 and tested on the seismic shaking table in the IZIIS' laboratory. The adopted modeling concept was an adequate model with artificial mass simulation, using the same material as that of the prototype. The spring hangings, as well as the special rolling support, have also been simulated. The model was subjected to random, harmonic and earthquake motion in horizontal, vertical and biaxial directions. The results show that the support springs can accept displacements in both the horizontal and the vertical direction in the elastic range of deformation, while the stop point base support is sensitive to the intensity of earthquake motion and isrequired to be limited to the horizontal and vertical directions.

EXPERIMENTAL EVALUATION OF DYNAMIC BEHAVIOUR OF PIPELINE SYSTEMS OF THERMAL POWER PLANTS EXPOSED TO SEISMIC LOADS

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This paper deals with the experimental results obtained by in situ and model testing of a segment of the pipeline system of a thermal power plant. The field testing has been performed by application of the forced and ambient vibration method. The model testing has been performed by means of a shaking table. The model was designed and constructed to the scale of 1/3 and tested on the seismic shaking table in the IZIIS' laboratory. The adopted modeling concept was: an adequate model with artificial mass simulation, using the same material as that of the prototype. The spring hangings, as well as the special rolling support have also been simulated. The model was subjected to random, harmonic and earthquake motion in horizontal, vertical and biaxial direction. The results show that the support springs can accept displacements in both horizontal and vertical direction in the elastic range of deformation, while the stop point base support is sensitive to intensity of earthquake motion and it is required to be limited in horizontal and vertical direction.

Keywords: Vibration; response curve; shaking table; spring hangings; pipe-line; seismic behaviour.

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1. Introduction

Pipeline systems play an important role in the proper functioning of the integral electricity production system of thermal power plants. To increase the life time and safety factor of pipeline systems, it is necessary to investigate the characteristics of the system including the restraining conditions (spring hangings and supports) under dynamic and seismic loads. Until now, the investigations of dynamic behavior of pipeline systems of TPP (thermal power plants) have been based on the analytical approach, using the refined finite element concept. Very few investigations have been performed by experimental testing, including in situ testing of dynamic characteristics of such systems by means of the ambient and forced vibration method, see Ref. 1and 2, as well as laboratory testing by means of a shaking table, see Ref. 3, 4 and 5. The objective of the investigations presented in this paper was to evaluate the seismic stability of pipeline systems as well as their behavior in resonant working conditions by performing full scale and model testing. This study is related particulary to seismic stability of an existing thermal power plant "Oslomej" located near Kichevo at western part of Macedonia. This region is seismically very active. During the exploration period of 20 years several earthquakes with moderate intensity had happened. This is the main reason of study performed recently and presented in this paper. The most vulnerable part of the power plant is pipeline system, which has not been designed seismically. For that purpose, a model was designed to the scale of 1/3 in correlation with existing pipeline system by simulating its dynamic properties, material characteristics as well as supporting conditions. The model was subjected to random, harmonic and earthquake motion in horizontal, vertical and biaxial direction with various intensity equal and/or higher than the expected ones.

2. Full Scale Dynamic Testing of Pipeline System

Full scale dynamic testing of a pipeline segment proportioned ∅ 457x16mm was carried out under pressure p=3.044 MPa and temperature t=540 ˚C, within length of 135m and height of 40.0 m. Along the pipeline there are 12 spring gibbets (hanging devices) with variable restoring force; 6 spring gibbets with constant restoring force; 4 rigid gibbets, one leading and one stopping point per branch. Presented on Fig. 1 is the spatial layout of the pipeline with explanation of the measured levels. To define the dynamic characteristics of the pipeline segment, forced and ambient vibration tests were carried out.

2.1. *Ambient vibration test*

The ambient vibrations of the pipeline were measured in working conditions and in conditions of non operation of the turbo-generator. For ambient vibration measurements the equipment consisting of Ranger seismometers (a), signal conditioning system (b), Fourier Spectrum Analyzer (c) and small x-y plotter (d), presented on Fig. 2 was used.

The seismometers were installed at the measuring points shown on Fig. 3. The signals from the seismometers were amplified and filtered and then transmitted to the spectrum analyzer. By Fourier transform, the dominant frequencies of vibration were defined and the typical FAS - Fourier amplitude spectra are presented in Figs. 4 and 5.

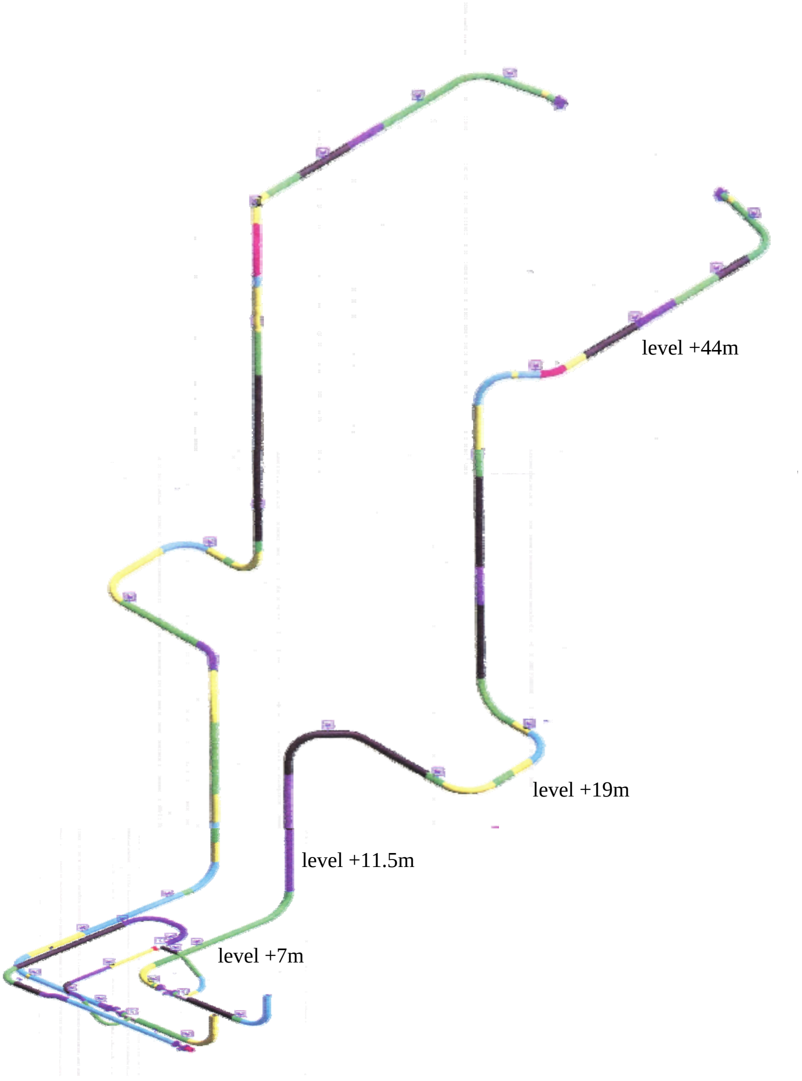


Fig. 1. Spatial presentation of the pipeline

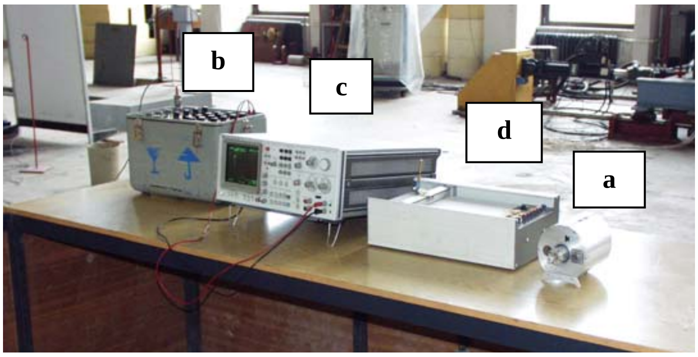


Fig. 2. Equipment for ambient vibration measurements

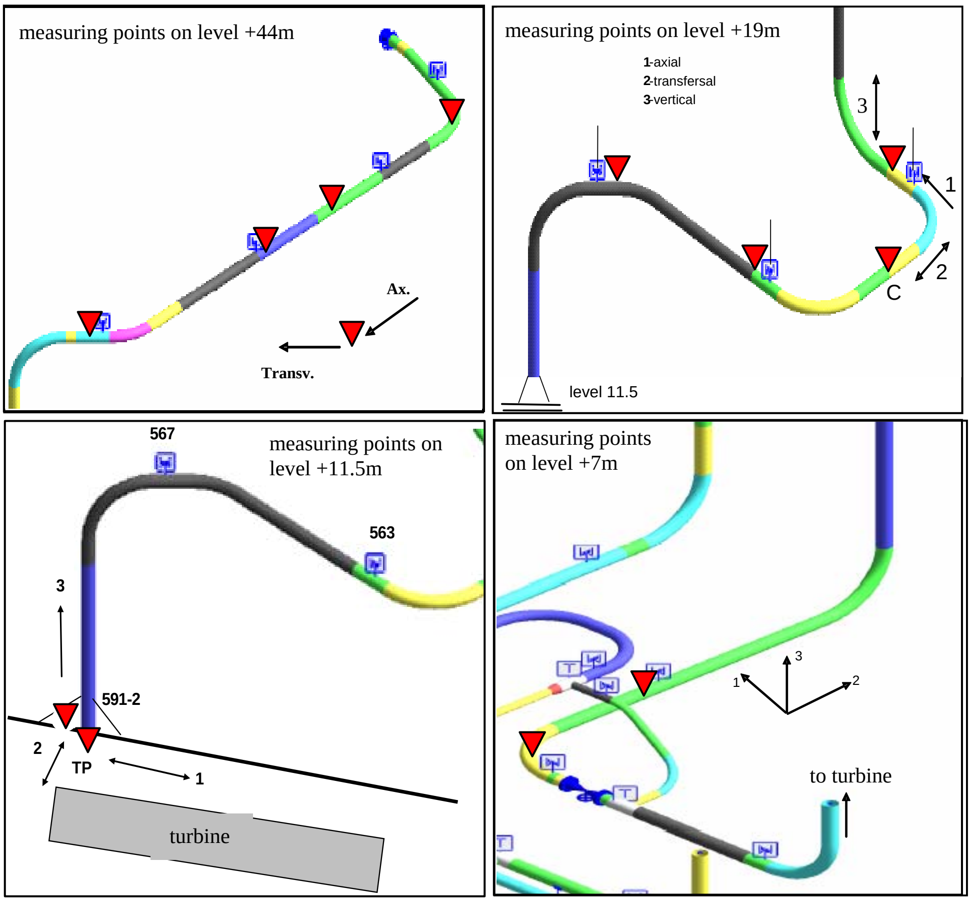


Fig. 3. Measuring points on the steam boiler building and the pipeline branch

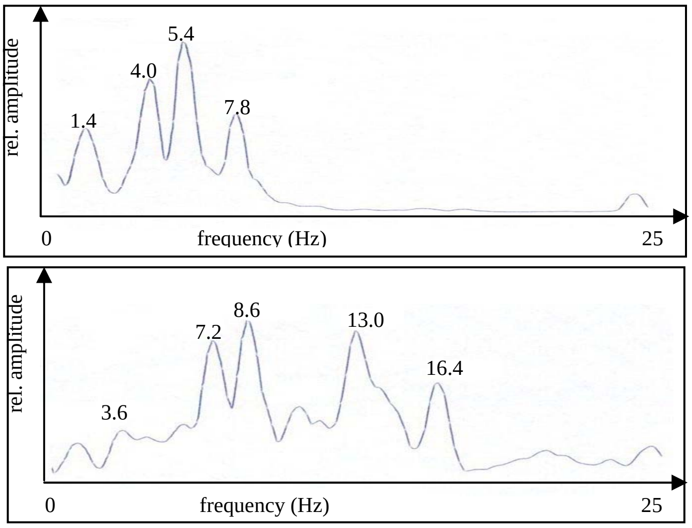


Fig. 4. Fourier amplitude spectra in transversal and vertical directions of the pipeline at referent point 563

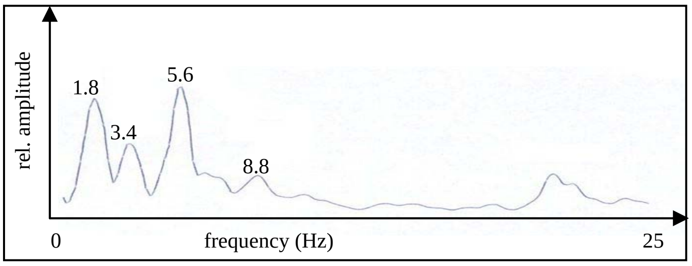


Fig. 5. Fourier amplitude spectrum in axial direction of the pipeline at referent point 563

2.2. *Forced Vibration Test*

Forced vibration test was carried out by means of an electro-dynamic exciter of harmonic force. It was installed on a steel panel, especially made for that purpose, and attached to the pipeline in its middle part, between gibbets 563 and 565 (Figure 6). During the tests, the pipeline was excited in axial, transversal and vertical direction. Obtained frequency response curves are presented in Figs. 7 and 8, while in Table 1 presented are the dominant frequencies obtained by both applied methods - ambient and forced vibration tests.

Fig. 6. Position of the shaker on the pipeline

Table 1 Dominant frequencies obtained by ambient and forced vibration tests

Dominant frequencies (Hz)					
Ambient vibrations			Forced vibrations		
direction x-x	direction y-y	direction z-z	direction x-x	direction y-y	direction z-z
1.8	1.4	7.2	1.7	1.4	7.4
3.4	4.0	8.6	2.7	3.2	
5.6	5.2	13.0	3.5	5.0	
8.8	7.8		6.4	7.4	

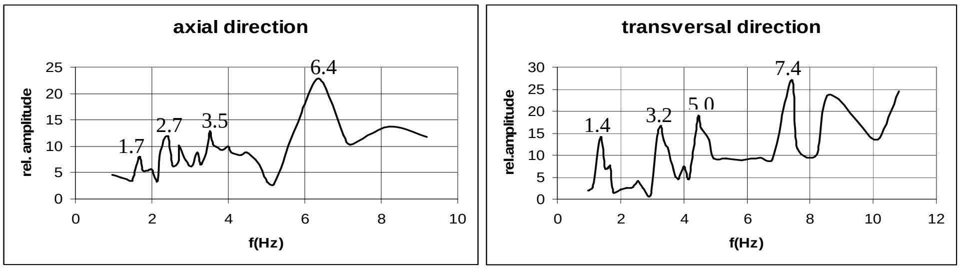


Fig. 7. Resonant frequency curve in axial and transversal direction of the pipeline at point 563

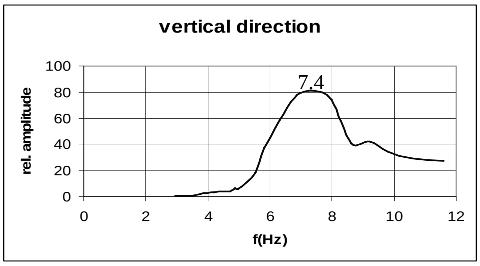


Fig. 8. Resonant frequency curve in vertical direction of the pipeline at point 563

3. Laboratory Shaking Table Testing of Model to a Scale of 1/3

3.1. *Scaling factors for model design*

The reduced scale model of the pipeline segment was designed according to the similitude requirements and modeling principles. An adequate model with artificial mass simulation was used. Table 2 shows the scaling factors model - prototype. To simulate the supporting structure of the pipeline, a steel frame was designed and constructed with a natural frequency corresponding to that of the real structure – the boiler plant in compliance with the similitude requirements. The natural frequency of the steel structure at the site (original structure) has been defined by ambient vibration method. According to the scaling factor 1/3, the stiffness of the model frame has been calculated, as well as the frequency of the frame model has been defined and steel model has been designed. After fixing the frame on a table, the frequency was checked and adjusted to the required one by rearanging the bracings of the frame (see Fig. 11). Considering that the pipe was made of steel, which is the same material as that of the prototype structure, additional mass was added, i.e., the pipe was filled with sand along its entire length. The fulfillment of the similitude requirements regarding the prototype and the model enabled that all the shaking table test results defining models behavior under dynamic and seismic action be fully representative for the real - prototype structure. The most influencing scaling factors are: the factor of time as well as the factor of frequency. This is important to represent realistic response of the pipeline system to expected seismic input. In order to simplify the model tests, the influence of the temperature was not considered which doesn't affect the simulation of seismic behavior, but only the static stress conditions which are not a point of interest of this study.

Table 2. Scaling factors model - prototype.

Parameter	Required scaling factor	Achieved scaling factor
Length, displacement (l_r)	1/3	1/3
Time (t_r)	$(1/3)^{1/2}$	$(1/3)^{1/2}$
Frequency (f_r)	$(1/3)^{-1/2}$	$(1/3)^{-1/3}$
Mass density (ρ_r)	1	1
Inertial force (F_r)	$(1/3)^2$	$(1/3)^2$
Young's modulus (E_r)	1	1
Strain (ε_r)	1	1
Stress (σ_r)	1	1
Acceleration (a_r)	1	1
Additional mass	$(1/3)^2$	$(1/3)^2$
E/σ ratio	1	1
Stiffness (k_r)	1/3	1/3

3.2. *Geometrical characteristics*

The spatial pipeline model was constructed to the length scale of 1:3, representing a characteristic real part of the prototype structure, shown on Fig. 9. This is a typical spatial configuration of pipelines at thermal power plants, having very few supporting points comparing to their dimensions.

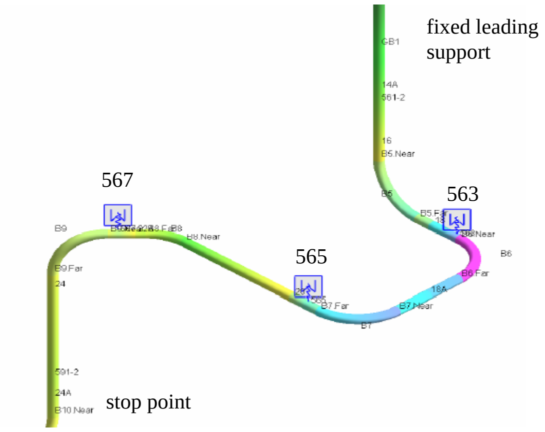


Fig. 9. The selected part of the prototype pipeline structure

The diameter of the pipe was 152 mm and the thickness was 5.3mm, while its total length was 13.3m. The model consisted of two vertical and three horizontal parts, along with two vertical and three horizontal curvatures among them, as presented on Figs. 10 and 11. The bottom part of the pipe was fixed to a steel plate that rested on two steel balls, thus composing a specific rolling support. (the so called stop-point, a). These balls enable free horizontal motion of the pipeline and uplifting in vertical direction. The pipe-line was connected to a steel frame structure at four points: one fixed leading support at the top (b) and three spring hangers placed at the beginning of the horizontal curvatures (c, d, e). This frame structure represented the boiler-plant, which is the supporting structure for the pipeline system in actual conditions. The columns of the frame were fixed to the shaking table by bolts.

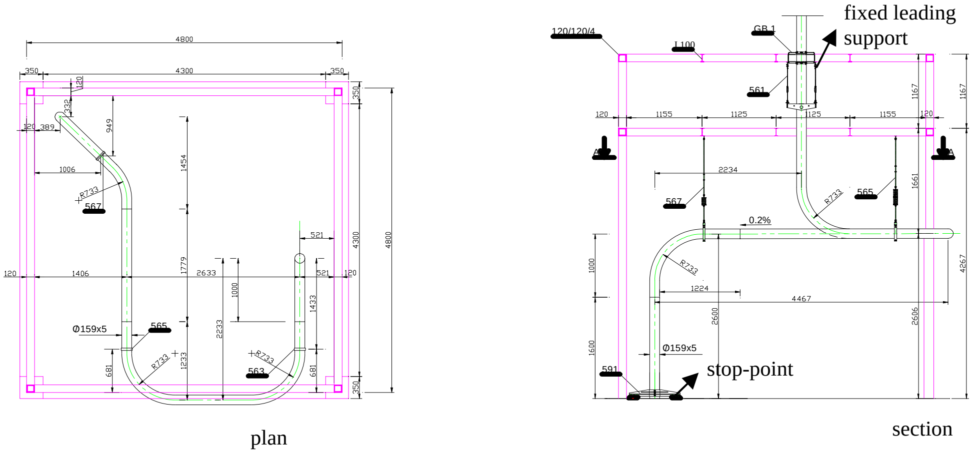


Fig. 10. Plan and vertical section of the model of the pipeline system

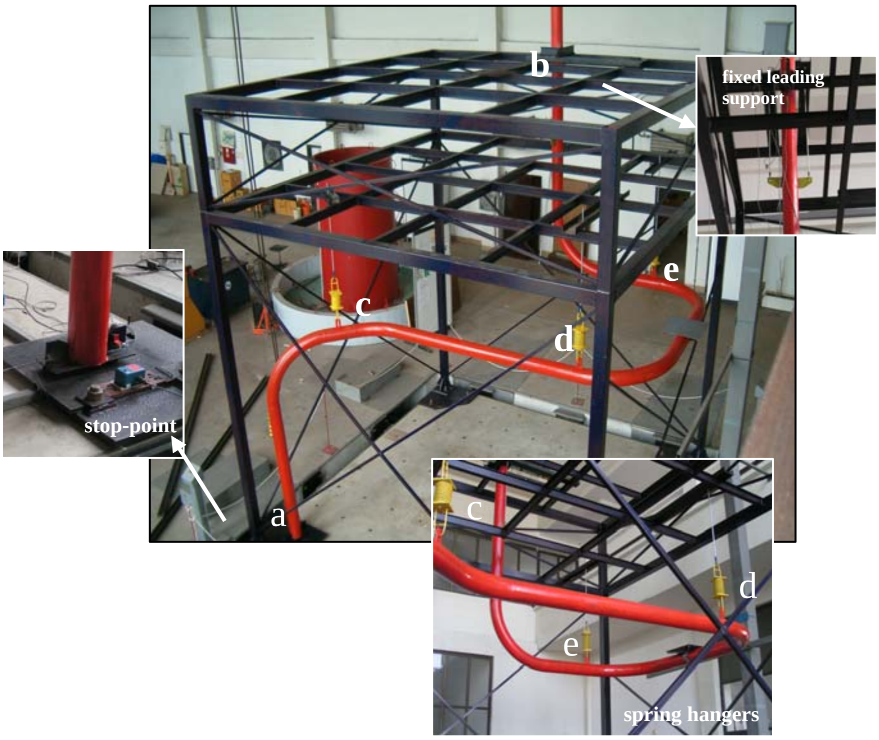


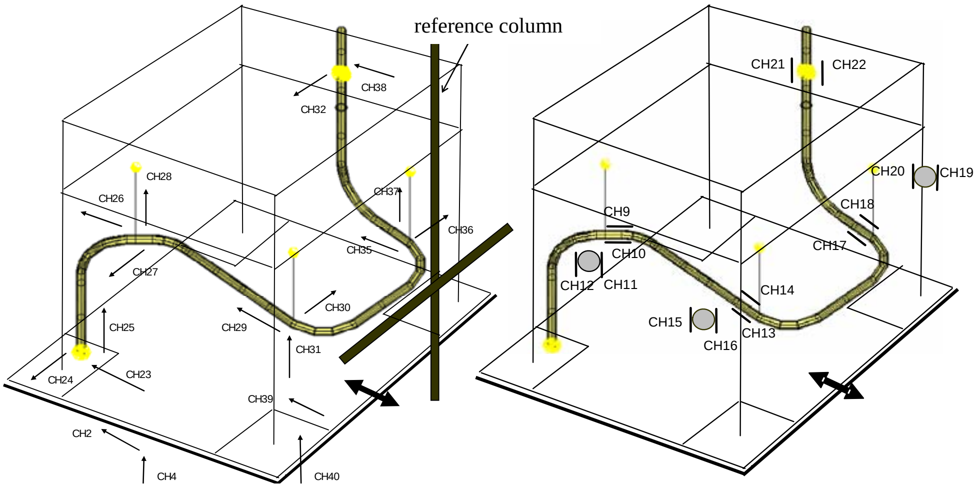
Fig. 11. Model of the pipeline system fixed to the IZIIS shaking table

3.3. *Test set-up*

Dynamic testing of the model was performed on the two-componential seismic shaking table in the Laboratory of the Institute of Earthquake Engineering and Engineering Seismology in Skopje. The shaking table represents a pre-stressed RC plate proportioned 5x5m in plan, with possibilities to generate different types of dynamic excitations, including seismic inputs, with max intensity of up to 1.5g in horizontal and 1.0g in vertical direction, separately or simultaneously. The max. mass of the model to be tested on the shaking table is limited to 40t.

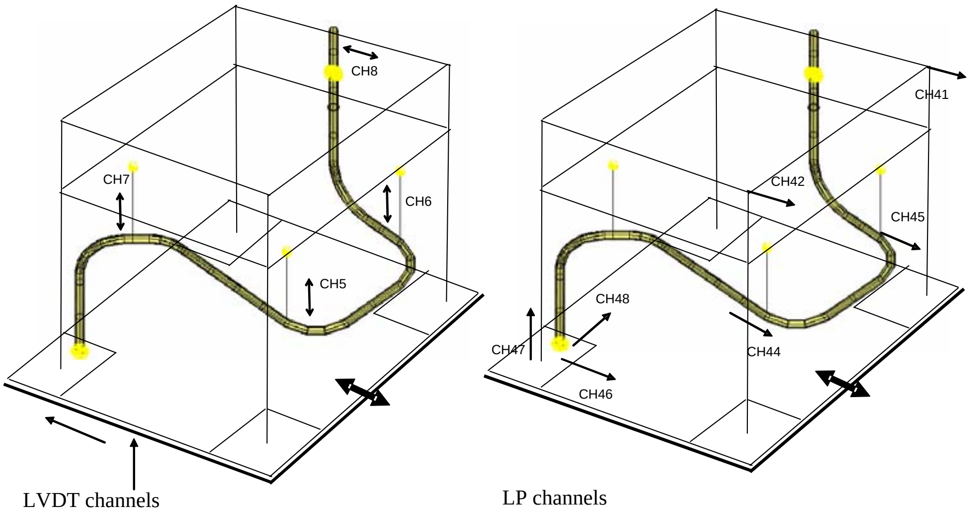
3.4. *Instrumentation of the model*

According to the objectives of the investigation, the model was instrumented with different sensors for measuring the response parameters of interest. 18 accelerometers, 14 SG-s (strain gauges), 4 LVDT-s (linear variable differential transducers) and 7 LP-s (linear potentiometers) were placed at different points for measuring the accelerations, strains, relative and absolute displacements (a total of 48 channels). Presented in Fig. 12 are the positions of the accelerometers, strain gauges, LVDT-s and LP-s.



Acceleration channels

Strain-gauge channels



LVDT channels

LP channels

Fig. 12. Disposition of instruments at measuring points and assignment of channels

3.5. *Data acquisition system*

The data were collected by a 64 channel high-speed data acquisition system, which transforms the analogue signals into digital. Special data processing software was used to plot the time history and Fourier amplitude spectra of response for any recorded points and physical values (acceleration, displacement, and strain).

3.6. *Test results*

3.6.1. *Dynamic characteristics*

The natural frequencies of the steel frame and the pipeline in horizontal and vertical direction were obtained applying ambient and forced vibration testing methods. Random excitation in the frequency range of up to 50 Hz was also applied to determine the natural frequencies and mode shapes based on acquisition of acceleration records. The FAS obtained at characteristic points of the pipeline are presented on Fig. 13. The natural frequencies of the model and those of the prototype are comparatively presented in Table 3. The data obtained by forced and ambient vibration tests of the model are useful to define dynamic characteristics of the model but they are not enough to investigate seismic response of the model under stronger dynamic conditions in non-linear range. That’s why shaking table tests have been performed.

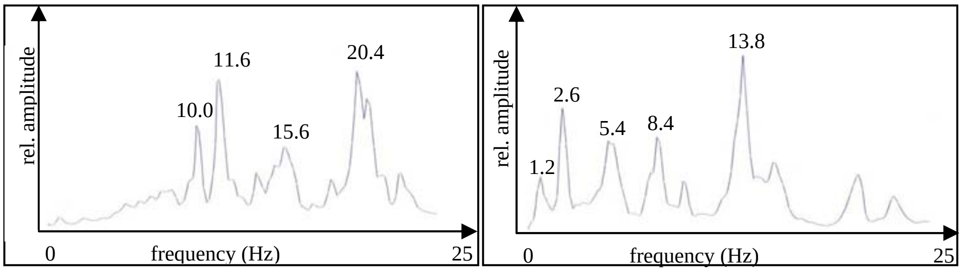


Fig. 13. FAS for CH31, vertical component (left) and FAS for CH29, horizontal component (right)

Table 3. Comparison between natural frequencies of the model and those of the prototype.

CH 31- vertical component, f (Hz)			CH29-horizontal component, f (Hz)		
Model	Model/($3^{1/2}$)	Prototype	Model	Model/($3^{1/2}$)	Prototype
11.6	6.70	7.2	2.6	1.5	1.4
15.6	9.0	8.6	5.4	3.1	3.2
20.4	11.8	13.0	8.4	4.9	5.0
			13.8	7.97	7.4

3.6.2. *Seismic Response of the Model*

In the second phase of the experimental programme, the model was tested on the seismic shaking table under a series of seismic excitations applied with different intensities of input acceleration. Taking into account the objective of the testing - the behaviour and the stability of the model exposed to near and far field earthquakes, four earthquakes were selected as representative:

- El Centro earthquake
- Petrovac (Montenegro) earthquake
- Mexico earthquake
- Bregin earthquake

For simulation purposes, the time histories of excitation were scaled by a factor of $(1_r)^{1/2}=(1/3)^{1/2.}=0.577$
A total of 21 tests were performed under different intensities, presented in Table 4.

Table 4. Seismic tests performed on the model

Test no	Earthquake	Direction	Input acc. (g)	Effects
1.	El Centro	Horizontal	0.15	Moderate vibration
2	Petrovac	Horizontal	0.15	Moderate vibration
3	Mexico	Horizontal	0.04	Without any special effects
4	Mexico	Horizontal	0.08	Without any special effects
5	Bregin	Horizontal	0.6	Without any special effects
6	Petrovac	Vertical	0.05	Without any special effects
7	Petrovac	Vertical	0.13	Without any special effects
8	Petrovac	Simultaneous	0.15H 0.13V	Without any special effects
9	El Centro	Horizontal	0.24	Without any special effects
10	Petrovac	Horizontal	0.3	Moderate vibration
11	Mexico	Horizontal	0.21	Intensive vibrations, spherical steel balls displaced from bed at the stop point
12	Bregin	Horizontal	1.0	Without any special effects
13	Petrovac	Simultaneous	0.3H 0.22V	Quite intensive vibrations
14	El Centro	Horizontal	0.3	Intensive but stable vibrations
15	Petrovac	Horizontal	0.4	Quite intensive vibrations, good effects
16	Petrovac	Simultaneous	0.43H 0.26V	Quite intensive vibrations, spherical steel balls displaced from bed at the stop point. Limiters placed at the stop point
17	El Centro	Horizontal	0.33	Intensive vibration; stop point in motion
18	Petrovac	Horizontal	0.4	
19	Mexico	Horizontal	0.21	Intensive vibrations, stable stop point
20	Bregin	Horizontal	1.0	Intensive but short vibrations without any special effects
21	Petrovac	Simultaneous	0.43H 0.26V	Strong vibrations

In the course of test 11 (Mexico earthquake), the motion was so intensive that the steel balls were displaced from their beds at the stop point, whereas the fixed leading support was strongly banging into the structure. These intensive motions were evident on the entire model, the springs and the structure. The steel balls were also displaced under the Petrovac earthquake (simultaneous), test 16. The El Centro earthquake caused intensive motion, with strong but stable vibration, while the Bregin earthquake caused strong motion without visible effects.

Maximal displacement values for the model without limiters were measured at the spring hangers with measuring channels CH5 and CH6 under Petrovac earthquake (horizontal direction) amounting to 41.7mm and 21.4mm on the spring hanger CH7 and fixed leading support CH8 under Petrovac earthquake, simultaneous direction. At the stop point, channels 46, 47, 48, the greatest displacements ranging from 19.1 to 112.6 mm were obtained under the Mexico earthquake.

While measuring the absolute displacements in respect to the referent column, maximal values were recorded at the stop point in all the three directions as well as on spring hangers CH44 and CH45 under the Mexico earthquake. The displacement of the steel frame was the largest under the Mexico and Petrovac earthquakes (simultaneous direction).

Maximum values of acceleration were recorded under the Petrovac earthquake, at the second spring hanger, from the stop point upwards, in longitudinal direction CH29 and CH30 transverse direction. The Petrovac earthquake (simultaneous) caused maximal acceleration values at measuring channels CH23, CH24, CH25, CH26, CH28, CH31, CH32, CH36, CH37, CH38, CH40 accompanied by strong blows at the measuring points at the stop point and at the fixed leading support in horizontal direction, while at the spring hangers, in vertical direction CH31 and CH37. At the measuring channels recording in vertical direction, there occurred strong blows under excitation due to all the earthquakes, except for the El Centro earthquake.

At points of measuring stress, maximum values were recorded under excitation due to Petrovac earthquake (horizontal) and Petrovac Earthquake (simultaneous) direction. The Mexico, Bregin and El Centro earthquakes yielded lower values.

From the experiments done under earthquakes of higher intensities, it was concluded that deformations of certain segments of the structures take place and may lead to catastrophic consequences for the structure. Such deformations occurred under the Mexico earthquake with acceleration of 0.21 g and the simultaneous Petrovac earthquake, with horizontal acceleration of 0.41 g and vertical acceleration of 0.26 g, when at the stop point, the steel balls that supported the pipeline came out of their beds. This proves that this bearing is instable under long periodic far field earthquakes as are the Mexico and Petrovac earthquakes in combination with a vertical component.

Taking into account the observed dynamic effects and the behaviour of the supporting points – the fixed leading support and the stop point, after test 16 some interventions were carried out to improve the stability of the system under intensive earthquakes. The interventions on the fixed leading support consisted of placement of a thin rubber around the tube and the place where it passes through the floor slab. The intervention at the stop point was aimed at preventing the motion of both steel balls outside the stop point in case of large displacements of the pipe at the base. For this purpose, horizontal and vertical limiters were placed to control the displacement to an acceptable level, Fig. 14. These limiters enabled motion of 30mm in y-y direction, 35mm in x-x direction and –10mm in +z direction.

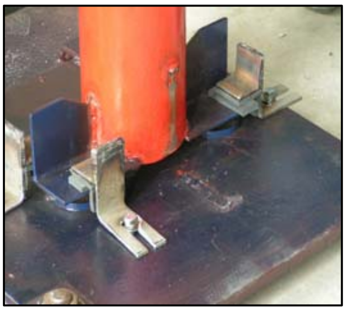


Fig. 14. The limiters at the stop point

After these interventions, the model was subjected to the same intensive tests under the stated earthquakes. With the placement of the limiters at the stop point, the motion was without larger inclinations and was controlled within the field of the limiters.

At the model with limiters, maximum values of quantities, mainly at all the measuring points, were recorded under Petrovac (horizontal) and Petrovac (simultaneous) earthquake. Blows were recorded at measuring channels that measure in vertical direction and measuring channel CH38 of the fixed leading support. Graphical presentation of max. accelerations recorded during the most intensive seismic tests under different earthquakes are shown on Fig. 15, for model without and for model with limiters, respectively. As shown in Table 4, the input acceleration of different earthquakes was in range of 0.15-1.0g., which was higher than the expected ones (0.15-0.25 g) on the site. This is because in the first stage the realistic excitation has been used and no damage occured. Then, the next tests have been performed with higher intensity in order to provoke damage. Fig. 12 shows the maximum response acceleration at different points of the model under above mentioned input intensity. As can be noticed the response is several times amplified comparing to the input (from 1.0-7.5g) which indicates that system responds at the resonance with very small damping.

With the placement of the limiters at the stop point, under Mexico earthquake excitation (at which the four steel balls were displaced), the maximum values were reduced as follows: the displacement at the fixed leading support was reduced for 50%, while that at the stop point was reduced for 30%. Under the El Centro earthquake, the motion of the fixed leading support was reduced for more than 50%, while that at the stop point was reduced for 20%. Under the Petrovac earthquake (horizontal direction), the displacement at the fixed leading support was reduced for 45%, while that at the stop point, was reduced for 25%. Under the Petrovac (simultaneous) earthquake, the displacement of the fixed leading support was reduced for 45%, while that of the stop point was reduced for 50%. Only in the case of the Bregin earthquake, the displacement at the stop point was increased by placement of the limiters for more than 50%, while that of the fixed leading support was decreased for 50%.

The placement of the limiters had positive effects upon the motion of the fixed leading support which was within the limits of the design displacement, not striking the structure.

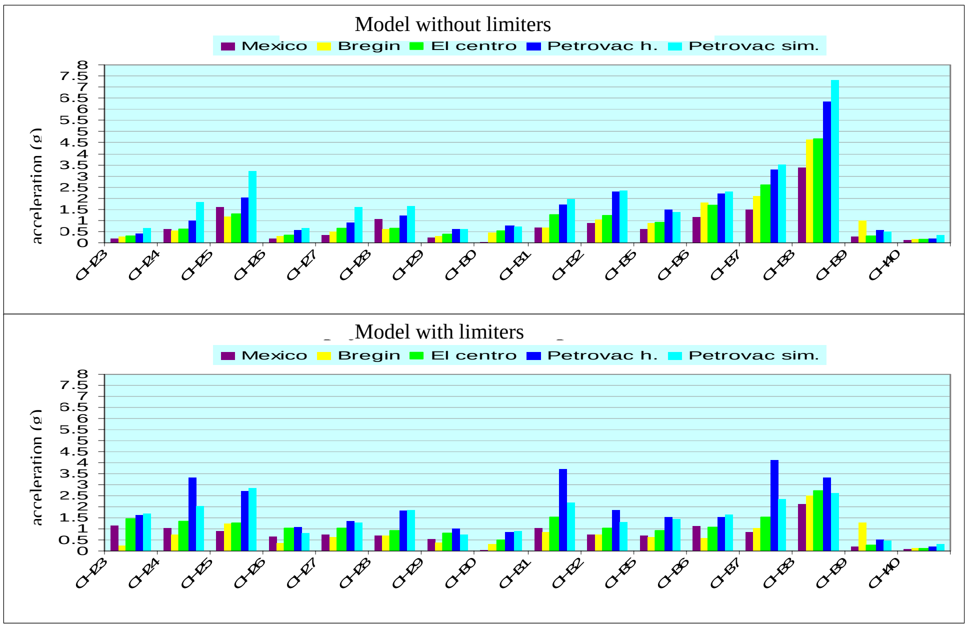


Fig. 15. Max. accelerations recorded during most intensive seismic tests

Comparative presentation of the response of the model without and with limiters is given in Figs. 16 and 17. Fig. 16 presents the response of the spring supports with and without limiters, while Fig. 17 shows the response of the stop point with and without limiters.

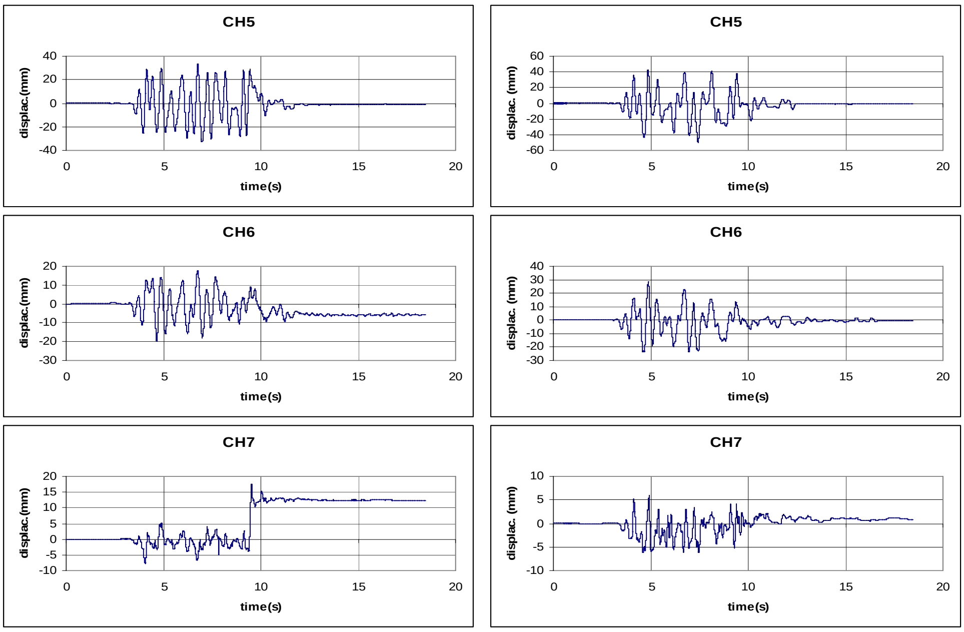


Fig.16. Time history response of spring supports without (left) and with limiters (right)

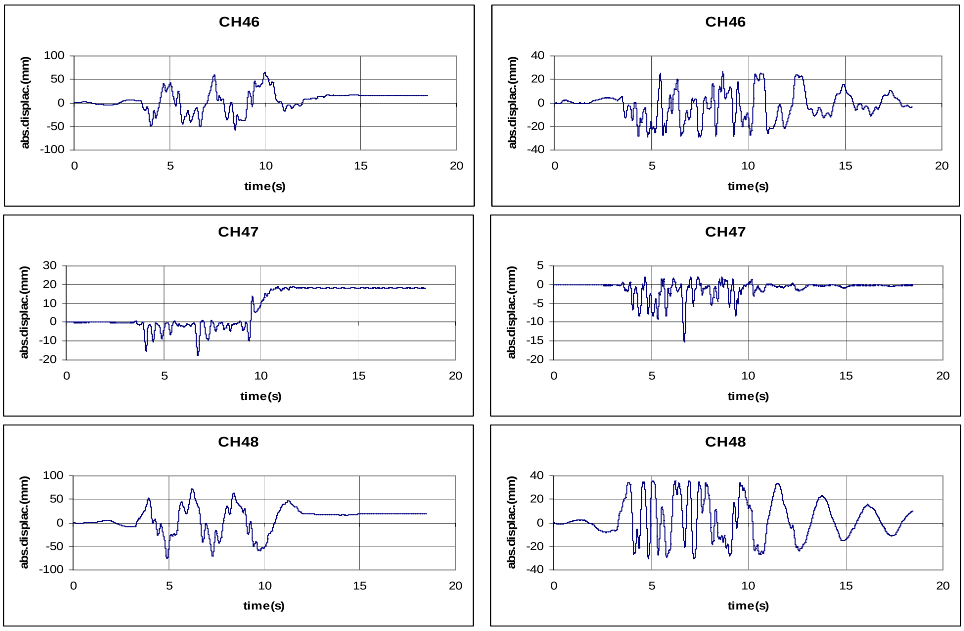


Fig.17. Time history response of the stop point without (left) and with limiters (right)

4. Conclusions

Based on analysis of the model test results as well as visual effects during the seismic tests, it can be concluded that:

- The behaviour of the model is complex , with significant spatial vibration;
- The spring supports control the behaviour of the model efficiently;
- The dynamic action of the pipeline model on the frame structure is significant even under excitation of lower intensity;
- The stop point controls the pipeline behaviour successfully until a limited level of excitation. However, under more intensive far distance earthquakes, the spherical steel balls go out of the bearing producing impact effects and creating possibilities for displacement of the entire system.
- With the placement of limiters at the stop point, the displacement of the steel balls under more intensive earthquakes is limited enabling complete control of the entire pipeline.
- By placement of a rubber ring on the pipeline, at the place of the fixed leading support, the effects from striking against the structure were reduced resulting in soft contact with the steel structure.
- With the introducing of limiters, the displacement at the stop point and at the fixed leading support was reduced to 50%.
- For the spring hangers, the placement of limiters does not have any significant effect.
- With the placement of the limiters, the acceleration values were reduced.

Based on the model testing results, related to the prototype pipe-line system it can be concluded that:

- For the design earthquake intensity of 0.13g significant damage of the pipe-line system is not expected.
- For intensities higher than 0.2g serious damage of some parts of the system could be expected, particularly at the stop point and at the fixed leading support, which may require re-designing or some modifications of these parts.
- When designing structures of this type, the seismic safety criterion should be made more stringent.
- For existing structures of such type, re-evaluation of the seismic safety of the pipe-line systems is recommended.

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