Seismodynamics of Segmented Underground Pipeline Systems Based on Real Earthquake Records

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**Abstract.** The article studies longitudinal and bending forces in the joint, as well as joint deformations of a complex underground segmented pipeline under the influence of seismic waves (I- and III-component). To solve the problem we used the finite element method and the implicit Newmark method in time. The results of joint deformations are obtained from I- and III-component records of real earthquakes in different regions (El Centro, Gazli, Buxarest, Tabas).

**Keywords:** Soil, Interaction, Segmented pipeline systems, Real earthquake records, Finite element metod

# INTRODUCTION

It is important that the underground pipeline system that provides life support isn't damaged during earthquakes. Damage to underground pipeline systems during an earthquake can lead to serious disasters and large-scale epidemics.

The theory of seismodynamics of underground structures has seen significant progress in recent years. Foundational concepts regarding the interaction between underground structures and the surrounding soil have become well-established and serve as a basis for modern theoretical and practical developments. These concepts have catalyzed experimental research and facilitated the integration of findings into engineering applications. While the core principles of seismodynamics remain relevant, the field continues to evolve with new insights and methodologies. Recent advancements include experimental investigations into the rheological behavior of the soil-structure system, which accounts for how structures interact with soils under varying stress and strain. Since seismic waves affect underground structures with time-dependent and spatially varying intensity, analyzing the stress-strain state of pipelines under dynamic loading is a key area of study. Although the seismic resistance of ductile cast iron pipeline systems is a well-developed topic, selecting appropriate computational models tailored to specific engineering conditions remains an area that requires continued innovation [1, 2, 3, 4, 5, 10, 11, 12].

Underground pipelines typically span extensive areas and are exposed to various geotectonic hazards. Numerous approximate analytical and numerical methods exist to evaluate the seismodynamic response and stress conditions of such systems. Reviews of theoretical and experimental studies on mathematical modeling of dynamic processes in underground pipelines under the impact of seismic waves are given in [5, 6, 7].

The seismic response of underground segmented pipelines is evaluated using the identical deformation method, first introduced by Newmark et al. [8, 9]. In this method, the pipeline is assumed to deform identically to the surrounding soil, while its inertia forces are disregarded.

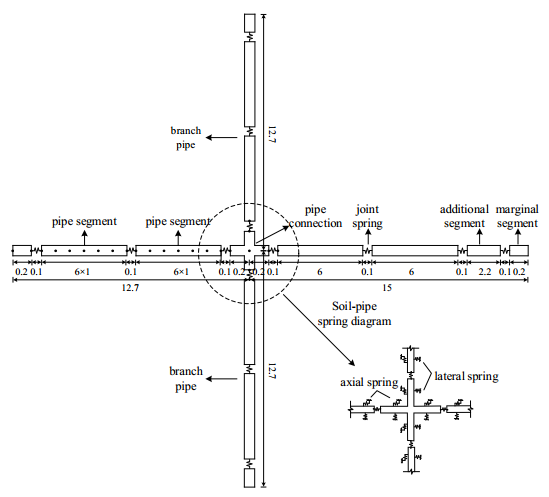
Anаlysis of thе еffеcts of strong еаrthquakes hаvе shown that the seismic resistаnce of underground pipelines is significantly influenced by the direction of seismic wave propаgаtion. Sincе sеismic wаves can act in any direction, underground pipеlines are subjected to complex deformаtions, including bеnding аnd torsion. As a result, it is essential to ensure the strength and stability of these structures under multi-directional seismic loading conditions [3, 5, 6].

# METHODOLOGY

In the mаthemаticаl formulаtion of the problem, it is assumed that a propagating near-surface seismic wave is given. Due to the reason that the length of the seismic wave is significantly larger than the diameter of the pipeline, the pipeline is modeled as a rod operating in tension or compression, torsion and bending taking into account a shear deformation, and the interaction “soil-pipeline” system is carried out using spring stiffness coefficients. The seismic impact propagating in the soil is transmitted to the underground segmented pipeline through I-component or III-component accelerogram of the earthquake. The spatial underground segmented mutually perpendicular pipeline system can be divided into linear pipes, massive nodes and rigid or flexible joints.

To solve the dynamic issue of such structures under seismic impact, we use a finite element method and the implicit Newmark method in time [15].

For the numerical solution of a class of issue of seismodynamics of spatial underground segmented pipeline system, a convenient method for their discretization is a FEM. We divide the underground segmented mutually perpendicular pipeline system into finite elements, then construct matrices of mass, rigidity and interaction for a linear and nodal element after, and then assemble matrices for an entire segmented pipeline system. Moreover, each pipeline element has its own mass and rigidity parameters. A software package for seismodynamics of underground segmented pipeline system is developed. Figure 1 shows the modеl of spatial underground segmented mutually perpendicular ductile cast iron pipeline system [14].



**FIGURE 1.** Modеl of underground segmented ductile cast iron pipeline with cruciform connection [14]

Seismic impacts can significantly change the behavior of segmented mutually perpendicular pipeline system and the distribution of longitudinal forces in joints. This depends on the intensity of earthquakes, the direction of the seismic wave, wave’s components, the physical and mechanical parameters of the pipe and joint material.

# RESULTS AND DISCUSSIONS

In [14], Wei Liu et al. was studied the deformation of a segmented mutually perpendicular pipeline system using a one-component accelerogram of the 1940 El-Centro earthquake. In this article, calculations were performed for a similar pipeline system under the influence of a three-component accelerogram (Figure 1). The calculations obtained results were compared with the results presented in the article [14].

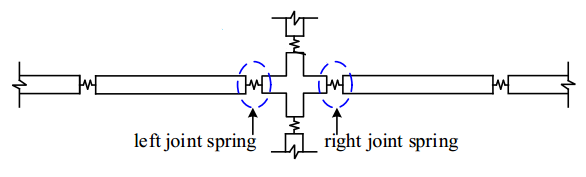
Table 1, presents the spring stiffness coefficients of the “soil-pipeline” system ( is “soil-pipeline” interaction coefficient) [14].

**TABLE 1.** Аxial and lаteral “pipeline-soil” spring stiffness in soil conditions

|  |  |  |
| --- | --- | --- |
| **Site №** | **kx (N/m2)** | **ky (N/m2)** |
| **I** | 3.4748×108 | 1.8596×109 |
| **II** | 1.3048×108 | 6.6940×108 |

Thе mechаnical and geоmetrical parameters of the ductile cast iron piping system are as follows: *DN*= 0.3 m, *E*=1.5×1011 N/m2. Axial and lateral “soil-pipeline” spring stiffness in soil conditions are taken from [14].

To study the effect of the connection, two joints, left and right, are selected (Figure 2).



**FIGURE 2.** Model of underground left and right joint spring segmented pipeline [14]

The calculations used real three-component records of the 9\*-point (MSK-64) earthquake that occurred in Gazli (Uzbekistan) 1976 [13], 9-point real records of the 1940 El Centro earthquake, 9-point (MSK-64) earthquake that occurred in Buxarest (Ruminia) 1977 [13] and 9-point real records of the 1978 Tabas (Iran) earthquake [13].

The results presented in [14] used real one-component record of El Centro earthquake. Table 2 compares the results on the real one-component earthquake records obtained by the authors of the article with the results in [14].

**TABLE 2.** Results of comparison of joints deformation

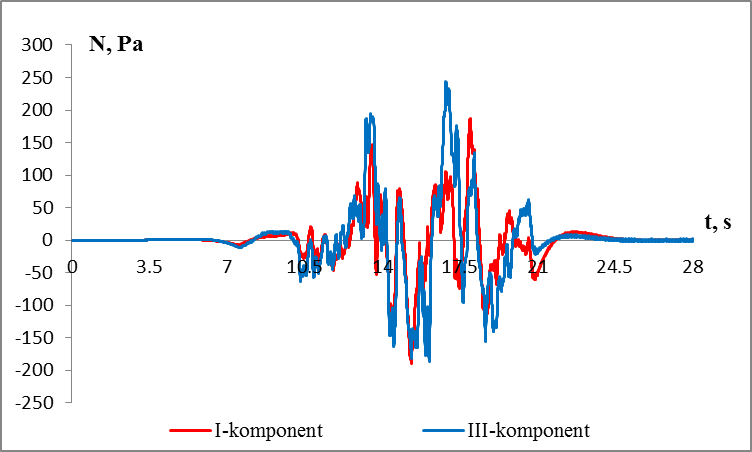
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Site №** | **Real earthquake recordings** | **Results in [15]** | | **Calculation results** | | **Difference (%)** |
| ***JD*left** | ***JD*right** | ***JD*left** | ***JD*right** |
| **I** | El Centro (1-komp) | 0.221 | 0.221 | 0.229 | 0.229 | 3.5% |
| **II** | El Centro (1-komp) | 0.291 | 0.291 | 0.301 | 0.301 | 3.3% |

The results of the calculations show that our obtained results are almost consistent with the results [14]. The following calculations in Table 3 were performed on real three components records of earthquakes occurring in different regions.

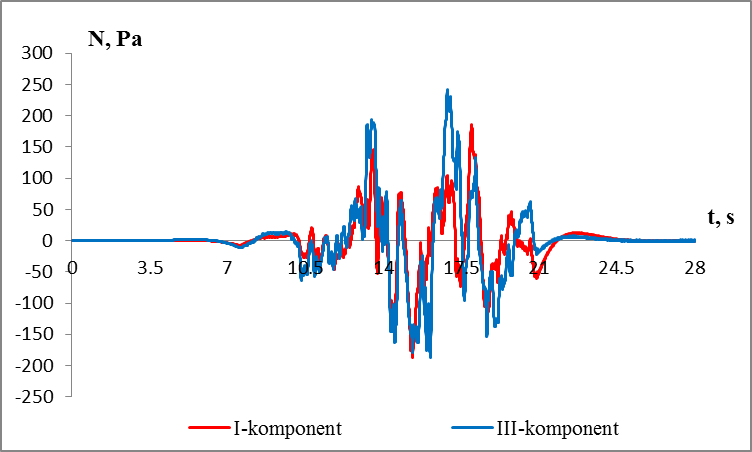
**TABLE 3.** Results of comparison of joints deformation on three-component real earthquake records in different regions

|  |  |  |  |
| --- | --- | --- | --- |
| **Site №** | **Real earthquake recordings** | **Calculation results** | |
| ***JD*left** | ***JD*right** |
| **I** | El Centro (I-component) | 0.229 | 0.229 |
| El Centro (III-component) | 0.289 | 0.289 |
| **II** | El Centro (I-component) | 0.301 | 0.301 |
| El Centro (III -component) | 0.421 | 0.421 |
| **I** | Gazli (I-component) | 0.250 | 0.250 |
| Gazli (III -component) | 0.324 | 0.324 |
| **II** | Gazli (I-component) | 0.326 | 0.326 |
| Gazli (III -component) | 0.430 | 0.430 |
| **I** | Buxarest (I -component) | 0.327 | 0.327 |
| Buxarest (III -component) | 0.330 | 0.330 |
| **II** | Buxarest (I -component) | 0.431 | 0.431 |
| Buxarest (III -component) | 0.433 | 0.433 |
| **I** | Tabas (I-component) | 0.412 | 0.412 |
| Tabas (III -component) | 0.558 | 0.558 |
| **II** | Tabas (I-component) | 0.544 | 0.544 |
| Tabas (III -component) | 0.736 | 0.736 |

Figures 3-4 show a comparative graphs of the change in time of the longitudinal forces generated in the joints of the complex underground pipeline located to the left and right sides of the center of the OX axis when the underground pipeline is exposed to a seismic wave (I- and III- component) in the form of real earthquake recordings of the 1976 Gazli earthquake at the angle α=0º to the OX axis.

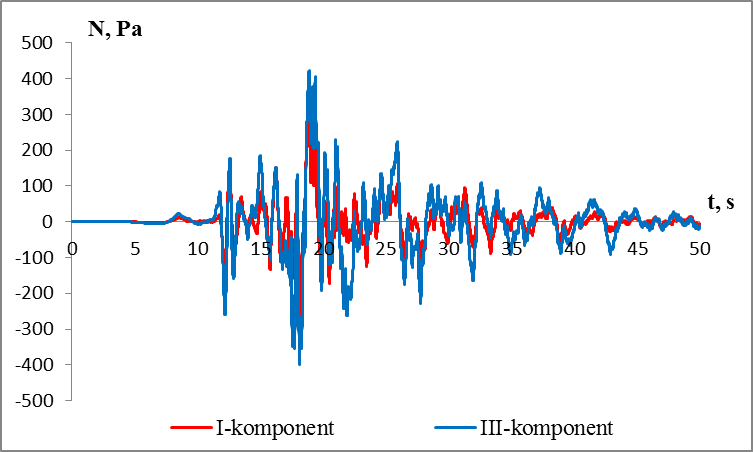


**FIGURE 3.** Graphs of the change in time of the longitudinal forces in the joint of a complex underground pipeline located to the left of the center of the OX axis

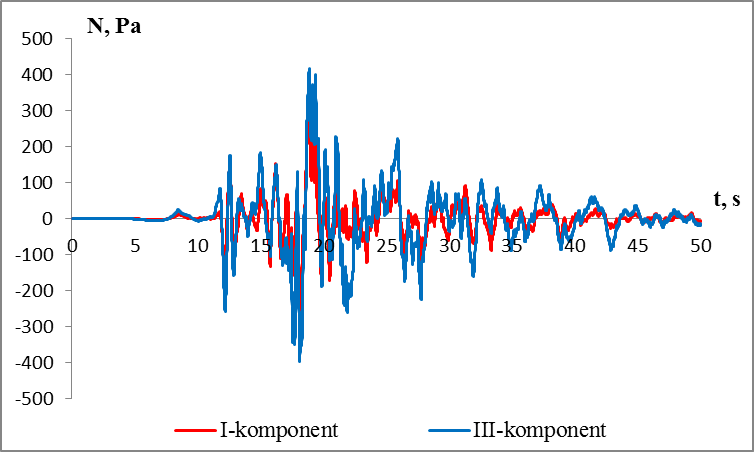


**FIGURE 4.** Graphs of the change in time of the bending forces in the joint of a complex underground pipeline located to the right of the center of the OX axis

Figures 5-6 show the graphs of the change in time of the longitudinal forces generated in the joints of the complex underground pipeline located to the left and right sides of the center of the OX axis when the underground pipeline is exposed to a seismic wave (I- and III- component) in the form of real earthquake recordings of the 1978 Tabas earthquake at the angle α=0º to the OX axis.

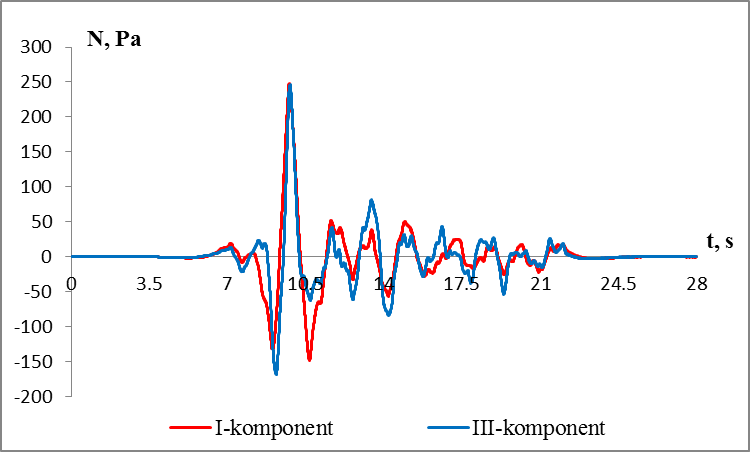


**FIGURE 5.** Graphs of the change in time of the bending forces in the joint of a complex underground pipeline located to the left of the center of the OX axis

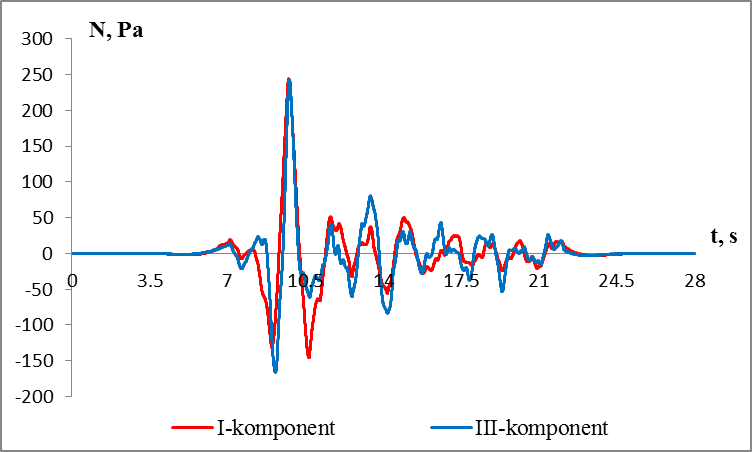


**FIGURE 6.** Graphs of the change in time of the bending forces in the joint of a complex underground pipeline located to the right of the center of the OX axis

Figures 7-8 show of the change in time of the bending forces generated in the joints of the complex underground pipeline located to the left of the center of the OX axis when the underground pipeline is exposed to a seismic wave  
(I- and III-component) in the form of real earthquake recordings of the 1977 Bucharest earthquake at the angle α=0º to the OX axis.

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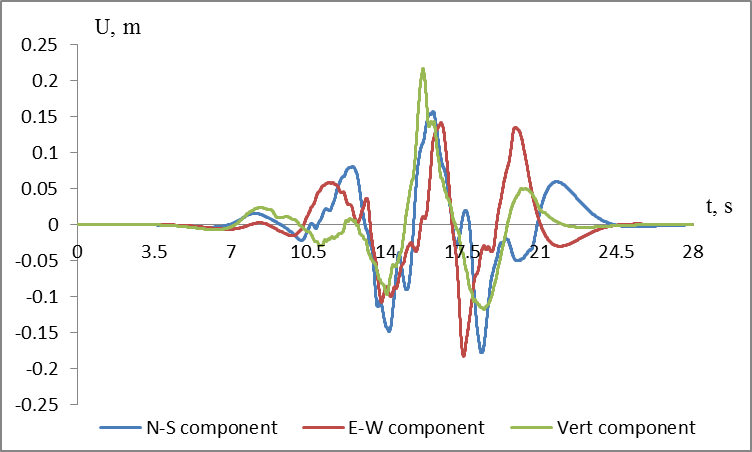
**FIGURE 7.** The graph of the change in time of the bending forces in the joint of a complex underground pipeline located to the left of the center of the OX axis

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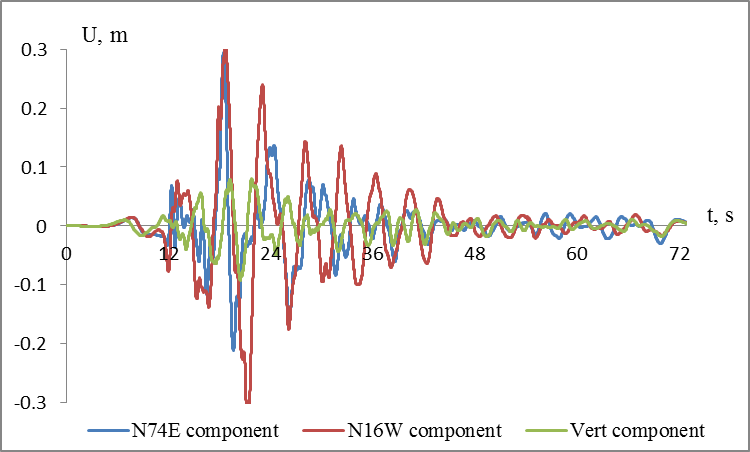
**FIGURE 8.** Graphs of the change in time of the bending forces in the joint of a complex underground pipeline located to the right of the center of the OX axis

Figures 9-11 shown the graphs of the change in time of the displacements of the joint of the complex underground pipeline located to the left of the center of the OX axis when the underground pipeline is exposed to a seismic wave   
(III-component) in the form of real earthquake recordings of the 1976 Gazli earthquake, the 1977 Bucharest earthquake and the 1978 Tabas earthquake at the angle α=0º to the OX axis.

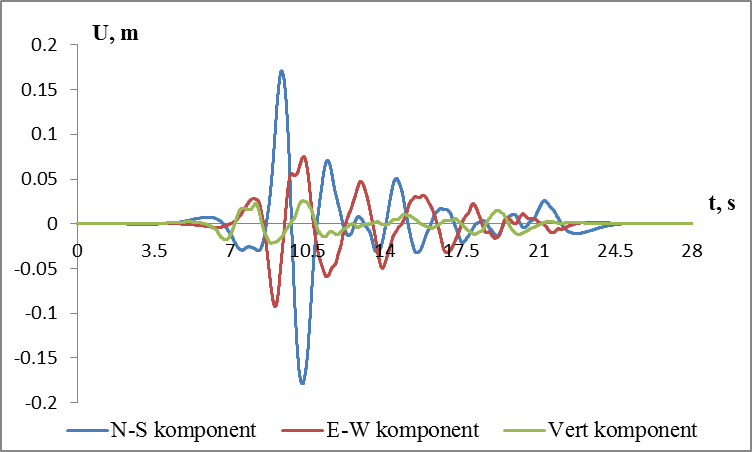
The graph shows that the maximum values of each component of III-component seismic waves are different. The above tables show that the results obtained under the influence of I and III-component seismic waves differ from each other. Therefore, it is advisable to carry out calculations under the influence of III-component seismic waves.



**FIGURE 9.** Graphs of the change in time of the displacements in the joint of a complex underground pipeline located to the left of the center of the OX axis



**FIGURE 10.** Graphs of the change in time of the displacements in the joint of a complex underground pipeline located to the left of the center of the OX axis



**FIGURE 11.** Graphs of the change in time of the displacements in the joint of a complex underground pipeline located to the left of the center of the OX axis

# CONCLUSION

The paper analyzed the seismodynamic behavior of segmented pipeline systems installed in the ground due to exposure to real three-component earthquakes. The obtained results clearly show that increase in intensity of earthquakes makes the internal forces of pipeline structure manifest more to the deformation of the joints. Such a correlation can be used to evaluate and forecast the possible joint failures when subjected to certain seismic scenario. It has been noted that there are a number of factors that contribute to the aspect of joint deformation and which are dominant on the orientation of the seismic wave propagation, orientations of the respective constituents and the physical mechanical attributes of the pipeline and joint materials. It was remarkable that the answers to I-component and III-component seismic actions were different with measurable values and thus we shall consider all the three components in engineering calculations. To add, the differences between maximums of each seismic wave component remind of the importance of using three-component earthquake recordings in pipelining design and investigation. The results emphasise that the orientation of seismic waves can be changed by the angle of incidence, hence causing differences in stress strain responses, which influences safety reserves of structures. In general, the study supports the relevance of the shift of realistic, multi-directional seismic input data in order to ensure proper performance analysis within underground pipelines with segmentation. This would increase the soundness of your seismic design measures and it can help in developing more resilient lifeline infrastructure networks.

**FUTURE IMPLICATIONS**

The conclusions of this research open the path to future developments in seismic resistance and seismic safety of the segmented pipeline system underground. Considering the high sensitivity of the direction of seismic waves, component elements, and material properties on the behavior of the joints in terms of deformation, further studies must focus on forming better multidirectional Earthquake models that incorporate the total 3D characteristics of wave propagation and its angles of incidence. Research into high-performance ductile materials, optimum joint geometries, and energy dissipating connections may also advance performance of structures with complex seismic loading. Moreover, combination of predictive structural models with real time surveilling and early warning of seismic events may offer the power to conduct active precautionary measures within operations e.g. local shutdowns within an area to mitigate the damages and loss of services. Adequate field and laboratory testing will permit refinement of soil pipeline interaction parameters which will increase the accuracy of the numerical modelling in a wide range of geologic settings. In addition, translating these insights into performance-based seismic design codes and integrating multi-hazard risk analyses, including the joint impacts of earthquakes, flooding or soil liquefaction will be essential to developing more reliable, flexible and durable lifeline infrastructure in seismically active areas.

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