Stress concentration in parallel fluid-filled underground cylindrical pipes under harmonic and recorded seismic excitation

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Received 12 April 2026; accepted 4 June 2026; published online 16 July 2026
DOI https://doi.org/10.21595/vp.2026.26537

77th International Conference on Vibroengineering in Almaty, Kazakhstan, June 11-12, 2026

Abstract. This paper investigates the dynamic stress concentration in two parallel underground cylindrical pipes filled with a compressible fluid and subjected to seismic excitation. The pipe-soil–fluid system is described as a coupled boundary-value problem within the plane dynamic theory of elasticity, in which each pipe is modelled as a thick-walled, homogeneous, isotropic, linearly elastic cylinder embedded in an infinite elastic medium and filled with an inviscid compressible fluid. The wave field around the two parallel cylinders is represented in bipolar cylindrical coordinates, and the displacement potentials are expanded in cylindrical wave functions of Bessel and Hankel type. Continuity of displacements and tractions at the outer pipe-soil interface, matching of normal velocity and pressure at the inner pipe–fluid interface, regularity at the pipe axis, and the Sommerfeld radiation condition in the surrounding medium are imposed simultaneously, leading to an infinite system of linear algebraic equations whose unknowns are obtained numerically. The model is first verified under harmonic P-, SV-, and SH-wave excitation; it is then extended to realistic seismic loading through an FFT-based transfer-function procedure, in which the harmonic solution serves as the frequency-domain Green operator. Numerical results show that the maximum dynamic stress concentration coefficient under the incident P-wave reaches 1.76 at d/D = 1.0; the limiting non-resonant distance between pipe centres increases from 5.0 m to 10.0 m as the incidence angle changes from 0° to 90°; and the presence of the internal fluid increases the seismic response by 10-20 %. Time-history analysis with the 1940 El Centro NS and 1966 Tashkent records confirms that these trends persist under realistic broadband ground motion. The novelty of the study lies in the simultaneous treatment of pipe–pipe interaction, internal fluid coupling, multiple incident wave types, and recorded seismic input within a single bipolar-coordinate analytical framework. The results are useful for the seismic design and resilience assessment of multi-line buried pipeline systems.

Keywords: underground pipeline, seismic excitation, fluid-filled cylindrical pipe, stress concentration, bipolar coordinates, dynamic analysis, recorded accelerogram, resilience.

1. Introduction

Seismic assessment of engineering structures remains an important task in earthquake-prone regions, since dynamic loading may significantly affect structural safety and serviceability [1]. Underground pipeline systems are critical elements of urban and transport infrastructure and must maintain their serviceability under seismic loading. In earthquake-prone regions, buried pipes are subjected to dynamic soil pressure, wave diffraction, and interaction effects that may significantly increase local stresses and reduce structural reliability [2-5]. These effects become even more pronounced in multi-line pipeline systems, where adjacent pipes may influence each other through the surrounding deformable medium.

The dynamic response of buried pipelines has been investigated in the context of elastic wave propagation, soil–structure interaction, and seismic design of underground lifelines [2-4, 6, 7]. Recent theoretical and numerical studies have advanced the understanding of stress fields and dynamic response of buried cylindrical structures under seismic wave action, including non-uniform multi-point excitation and broadband ground motion [5, 8, 9]. More recent studies have considered vibrations of buried pipes and cylindrical shell-type systems under dynamic loading, including cases with soft surrounding soil and viscoelastic filler [10, 11].

Despite this body of work, the stress concentration in parallel fluid-filled underground cylindrical pipes under seismic excitation is still insufficiently studied. In particular, the case in which pipe-pipe interaction, the type of incident wave, the angle of incidence, the spacing between the pipes, and the presence of an internal compressible fluid are all considered simultaneously, within a single analytical framework, has not been reported in the literature available to the authors. From a practical point of view, this question is important because an unfavourable spacing may lead to resonance-like amplification of stresses and to an increase of the dynamic soil pressure transmitted to the pipeline system.

Therefore, the aim of this study is to investigate the stress–strain state of two parallel underground cylindrical pipes filled with a compressible fluid under seismic loading. The problem is formulated within the plane dynamic theory of elasticity using bipolar cylindrical coordinates and is solved analytically in terms of Bessel and Hankel functions. Special attention is paid to the influence of pipe spacing, seismic-wave type and incidence angle, and fluid presence on the dynamic stress concentration. The harmonic solution is then used as a frequency-domain transfer operator, and an FFT-based superposition is applied to evaluate the response of the system under realistic recorded earthquake accelerograms.

The novelty of the present study, with respect to the literature cited above, lies in the simultaneous combination of four features within a single analytical framework: (i) two parallel buried pipes are treated together by means of bipolar cylindrical coordinates, so that the pipe-pipe interaction is captured exactly rather than approximated by far-field expansions; (ii) each pipe is filled with a compressible fluid, so that the fluid-shell-soil coupling is enforced at all interfaces; (iii) three types of incident wave (P, SV, SH) and an arbitrary angle of incidence are considered, so that the dependence of the response on the wave type is quantified; (iv) the harmonic solution is used as a frequency-domain transfer operator to extend the analysis to realistic recorded accelerograms, so that the resilience of the pipe system to non-stationary seismic input can also be assessed.

To the best of the authors' knowledge, no previous study has reported all four features together for parallel fluid-filled buried pipes. The present work therefore complements the existing literature on single-pipe and shell-only formulations and provides design-oriented results for multi-line buried pipeline systems in seismic regions.

2. Problem formulation and analytical model

Two parallel underground cylindrical pipes filled with a compressible fluid and embedded in an elastic surrounding medium are considered. The analysis is performed within the framework of the plane dynamic theory of elasticity. The problem is focused on the interaction between adjacent pipes and on the corresponding modification of the dynamic stress concentration under seismic-wave action [2, 4, 8-11].

2.1. Geometry and material model of the pipe

Each of the two pipes is geometrically defined by its inner radius R_1, outer radius R_2, and wall thickness $h = R_2 - R_1$. The two pipes are identical, and their axes are parallel and located at the same depth. The distance between the centres of the pipes is denoted by d, and the normalised spacing ratio d/D, with $D = 2R_2$, is used as the main geometric parameter. Both pipes are assumed to be much longer than their diameters, so the problem is reduced to plane strain in the cross-sectional plane (x, y).

The pipe wall is treated as a homogeneous, isotropic, linearly elastic continuum characterised by Young's modulus E_p, Poisson's ratio ν_p, and mass density ρ_p, so that the corresponding Lamé constants are $\lambda_p = \frac{E_p \nu_p}{[(1+\nu_p)(1-2\nu_p)]}$ and $\mu_p = \frac{E_p}{[2(1+\nu_p)]}$. Although the wall thickness is small compared with the radius, the pipe is here modelled as a two-dimensional elastic continuum rather than as a thin shell, in order to retain a uniform elastodynamic formulation across the soil-pipe-fluid system and to allow direct evaluation of the radial and circumferential stress components in the wall, which control the dynamic stress concentration.

The internal fluid is assumed inviscid and barotropic, with bulk modulus K_f, density ρ_f, and acoustic sound speed $c_f = \left(K_f/\rho_f\right)^{1/2}$. Its motion is described by an acoustic potential φ_f satisfying the Helmholtz equation $\nabla^2 \varphi_f + k_f^2 \varphi_f = 0$, with $k_f = \omega/c_f$.

2.2. Surrounding soil and embedment conditions

The surrounding soil is treated as an unbounded, homogeneous, isotropic, linearly elastic medium of mass density ρ_s, Lamé constants λ_s and μ_s, P-wave velocity $c_p = \left[\frac{\lambda_s + 2\mu_s}{\rho_s}\right]^{1/2}$, and S-wave velocity $c_s = (\mu_s/\rho_s)^{1/2}$. The corresponding wave numbers are $k_p = \omega/c_p$ and $k_s = \omega/c_s$. Material damping is neglected in the frequency band of engineering interest; however, it can be reintroduced through complex Lamé constants without modifying the structure of the solution.

The pipes are buried at a depth H sufficient for the incident seismic wave field to be considered approximately planar in the vicinity of the structures and for reflections from the free surface to be neglected over the time window of interest. This assumption is standard in the analytical study of stress concentration around buried inclusions [2, 4, 8, 9] and is consistent with pipes laid below the seismic active layer; if necessary, free-surface effects can be incorporated by image-source superposition without altering the analytical structure of the present solution.

The outer surface of each pipe is assumed to be in perfect bond with the surrounding soil, so that no slip or separation occurs along the pipe-soil interface. This represents a conservative upper bound on the dynamic load transmitted to the pipe wall and is consistent with field observations for steel pipelines installed in well-compacted backfill [2-4].

2.3. Wave-potential representation in bipolar coordinates

To describe the wave field around two parallel cylinders, bipolar cylindrical coordinates (ξ, η, z) are introduced. Their relation to the Cartesian coordinates is:

$$x = \frac{a \sin\xi}{(\cosh\eta - \cos\xi)}, \quad y = \frac{a \sinh\eta}{\cosh\eta - \cos\xi}, \quad z = z, \tag{1}$$

where a is the geometric parameter that defines the distance between the coordinate poles. The two pipe surfaces correspond to the bipolar coordinate lines $\eta = \pm\eta_0$, with η_0 chosen so that $R_2 = a/\sinh\eta_0$.

For harmonic motion with time factor $e^{-i\omega t}$, the displacement field in each elastic medium (soil or pipe wall) is decomposed by the Helmholtz decomposition into a scalar potential φ and a vector potential ψ; under plane-strain conditions the latter reduces to a single scalar component. The potentials satisfy:

$$\nabla 2\varphi + kp2\varphi = 0, \quad \nabla 2\psi + ks2\psi = 0, \tag{2}$$

where k_p and k_s are the wave numbers of the compressional and shear waves in the relevant medium. The general solution in bipolar coordinates is sought in series form:

$$\begin{aligned} \varphi &= \Sigma n\, A_n Z_n(2akp\; e - \eta)\cos(n\xi)\; e - i\omega t, \\ \psi &= \Sigma n\, B_n\, Z_n(2aks\; e - \eta)\sin(n\xi) e - i\omega t, \end{aligned} \tag{3}$$

where $Z_n(\cdot)$ denotes a cylindrical wave function: Bessel J_n in the pipe annular region (regularity inside the wall), Hankel $H_n^{(1)}$ in the unbounded soil (radiation condition at infinity), and a linear combination of J_n and Y_n across the annular pipe wall. The constants A_n and B_n are unknown complex coefficients to be determined from the boundary conditions. A similar expansion is used for the acoustic potential φ_f of the internal fluid, with $Z_n = J_n$ to ensure regularity at the pipe axis.

2.4. Boundary conditions

Six sets of conditions are imposed simultaneously on the coupled problem:

(a) At each outer pipe-soil interface ($r = R_2$) – continuity of radial and tangential displacements and tractions:

$$ur(1) = ur(2),\; u\theta(1) = u\theta(2),\; \sigma rr(1) = \sigma rr(2),\; \sigma r\theta(1) = \sigma r\theta(2). \tag{4}$$

(b) At each inner pipe–fluid interface ($r = R_1$) – continuity of normal velocity, equality of fluid pressure with the normal traction, and vanishing tangential traction in contact with the inviscid fluid:

$$vn = \frac{\partial ur}{\partial t}, \quad \sigma rr = -pf, \quad \sigma r\theta = 0. \tag{5}$$

(c) Regularity of the fluid acoustic potential at each pipe axis ($r \to 0$).

(d) Sommerfeld radiation condition at infinity in the soil for the scattered wave field, which guarantees that no energy is reflected back from infinity.

(e) The incident seismic action is prescribed as a plane harmonic P-, SV-, or SH-wave of unit amplitude propagating at angle γ with respect to the line connecting the pipe centres.

(f) Absence of body forces in the soil, in the pipe walls, and in the fluid.

2.5. Solution procedure

By substituting the wave-potential expansions Eq. (3) into the boundary conditions Eqs. (4-5) and projecting onto the bipolar harmonics $\cos(n\xi)$ and $\sin(n\xi)$, the problem is reduced to a complex linear algebraic system for the unknown coefficients A_n, B_n, and the corresponding fluid coefficients. The infinite system is truncated at a sufficiently large order N and solved by Gaussian elimination with partial pivoting. Series convergence is verified by progressively increasing N until the maximum dynamic stress concentration coefficient changes by less than 0.5 %; in the parameter range of practical interest ($k_pR_2 \le 3$, $d/D \in [0.5, 4]$) this is achieved with $N = 12$-18.

The obtained solution makes it possible to evaluate the dynamic stress concentration in the pipe system as a function of pipe spacing d/D, the type and incidence angle of the seismic wave, and the properties of the internal fluid. These parameters are used in the next sections to analyse the maximum dynamic concentration coefficient and the limiting non-resonant distance between the pipes.

3. Extension to recorded seismic excitation

Harmonic analysis is the natural setting for the analytical formulation of Section 2 and is essential for the initial verification and parametric study of the model. Real earthquakes, however, are non-stationary and broadband. To assess the resilience of the pipeline system under realistic ground motion, the harmonic solution is therefore used here as a frequency-domain Green operator within an FFT-based superposition scheme.

Let $a_g(t)$ denote the recorded ground acceleration along the direction of the incident wave, sampled with time step Δt over the duration T_g, and let $A_g(\omega) = FFT\{a_g(t)\}$ be its discrete Fourier transform. For each circular frequency ω_k of the discrete spectrum, the harmonic solution of Section 2 yields a complex stress concentration coefficient $\eta(\omega_k; \gamma, d/D$, fluid properties), evaluated at the most stressed point of the pipe wall. The time history of the stress concentration coefficient is then reconstructed as:

$$\eta(t) = \text{IFFT}\left\{\eta(\omega_k) \cdot \frac{Ag(\omega_k)}{-\omega k_2}\right\}, \tag{6}$$

and the peak dynamic stress concentration coefficient under the recorded record is:

$$\eta_{peak} = \text{max}t\, |\eta(t)|. \tag{7}$$

Within the assumptions of linearity and time-invariance, this procedure is exact and does not require any additional approximation beyond the harmonic solution itself.

Two recorded accelerograms are used in the present study. The first is the well-known 1940 El Centro NS record (PGA = 0.319 g, total duration 31.18 s), which is a widely accepted benchmark in earthquake engineering and contains significant energy in the band 0.5-10 Hz – the band of interest for medium-diameter buried pipes. The second is the 1966 Tashkent earthquake record (Markaz station, EW component, PGA ≈ 0.16 g), which corresponds to a near-source moderate event in the seismic environment of the case-study region. The use of two records of different intensity and frequency content allows the trends predicted by the harmonic analysis to be confirmed under different broadband inputs.

4. Results and discussion

4.1. Verification and computational parameters

The numerical results presented below were obtained for representative parameters of a buried steel pipeline embedded in stiff soil: pipe outer diameter $D = 1.0$ m, wall thickness $h = 0.012$ m, $E_p = 210$ GPa, $\nu_p = 0.30$, $\rho_p = 7850$ kg/m^3; soil $c_p = 600$ m/s, $c_s = 300$ m/s, $\rho_s = 1900$ kg/m^3; internal fluid (water) $c_f = 1480$ m/s, $\rho_f = 1000$ kg/m^3. The truncation order $N = 16$ was verified to provide three-digit convergence of η_{max} for all spacings considered. In the limit $d/D \to \infty$ and in the absence of fluid, the obtained value of η_{max} recovers the well-known single-pipe result reported in [2], which validates the numerical implementation.

4.2. Results under harmonic excitation

The analytical solution of Section 2 was first used to evaluate the dynamic stress concentration in the parallel underground fluid-filled pipes under harmonic seismic excitation. Special attention was paid to the influence of the normalised spacing ratio, the angle of wave incidence, and the presence of fluid inside the pipes. The results show that the interaction between adjacent pipes significantly modifies the stress state of the system in comparison with a single buried pipe.

Table 1 presents the variation of the maximum dynamic concentration coefficient $\eta_{\max}$ for different spacing ratios in the case of an incident P-wave. The results show that η_{max} increases from 1.68 at $d/D = 0.5$ to 1.76 at $d/D = 1.0$, and then decreases to 1.61 and 1.60 at $d/D = 2.0$ and $d/D = 4.0$, respectively. Thus, the strongest interaction is observed at relatively small spacing, while at larger distances the effect gradually stabilises and approaches the response of a single pipe. This behaviour indicates that the mutual influence of parallel pipes is significant mainly when $d/D \leq 4.0$.

Table 1. The value of the dynamic concentration coefficient for different distances between the pipes in the case of an incident P-wave

d/D	0.5	1.0	2.0	4.0
η_{max}	1.68	1.76	1.61	1.60

The increase in η_{max} at small spacing is associated with superposition and interference of waves reflected between the surfaces of adjacent pipes. From an engineering point of view, this effect is important because it may lead to local amplification of the dynamic soil pressure transmitted to the buried pipeline system. According to Table 1, in the considered range the most favourable spacing is $d/D = 0.5$, where the dynamic concentration coefficient is lower than at $d/D = 1.0$.

An additional design aspect concerns resonance-like effects in multi-line pipelines. As shown in Table 2, the limiting non-resonant distance between the pipe centres increases with the angle of wave incidence γ: from 5.0 m at 0° to 10.0 m at 90°. Therefore, when the seismic wave approaches the pipeline at smaller angles, the pipes should be placed closer to each other in order to avoid resonance and to ensure seismic safety.

Table 2. Dependence of the limiting non-resonant distance d_{max} on the angle of wave incidence γ

γ, deg	0	30	45	60	70	80	90
d_{max}, m	5.0	5.36	5.86	6.66	7.45	8.52	10.0

The numerical analysis also shows that the wave type affects the stress concentration level. The local resonance effect is more pronounced for SV-wave excitation than for P-wave excitation. The presence of fluid inside the pipes increases the seismic effect by approximately 10-20 %, while for two-line pipe systems the increase in the maximum dynamic pressure is generally about 5-10 %. For pipes arranged in two lines at $d < 3.0D$, the maximum dynamic soil pressure may exceed that of a single pipe by up to 15 %.

4.3. Results under recorded earthquake excitation

The FFT-based procedure described in Section 3 was applied to the worst harmonic case under P-wave excitation, namely $d/D = 1.0$. With the El Centro NS record as input, the peak stress concentration coefficient is $\eta_{peak} \approx 1.71$. This value is approximately 3 % below the harmonic peak $\eta_{max} = 1.76$ reported in Table 1, because the recorded record does not concentrate all of its energy at the resonance frequency of the two-pipe system. Conversely, η_{peak} is approximately 8 % higher than the value that would be obtained from a single-pipe analysis under the same record, which confirms that the pipe-pipe interaction effect identified in the harmonic case persists under realistic broadband loading.

The 1966 Tashkent record produces $\eta_{peak} \approx 1.66$ at the same spacing, with a similar relative increase over the corresponding single-pipe value. This confirms the practical relevance of the harmonic-domain results in the seismic context of the region considered. From a resilience point of view, the small reduction of η_{peak} with respect to η_{max} indicates that the harmonic analysis used in design provides a slightly conservative – but physically consistent – estimate of the dynamic stress concentration; the safety margin is, however, narrow at the resonance spacing $d/D \approx 1.0$, which reinforces the importance of avoiding this spacing in multi-line layouts.

4.4. Engineering implications

The obtained tendencies are of practical interest for the seismic design of underground multi-line pipeline systems. They show that an unfavourable spacing between adjacent pipes may intensify dynamic stresses, whereas a rational choice of spacing can reduce the stress concentration and prevent resonance-like amplification. The results also confirm that denser embankment soil reduces the seismic effect on underground pipes, and that at sufficiently large distances the dynamic problem tends towards a quasi-static response. The 10-20 % increase produced by the internal fluid implies that water-filled fire-protection lines and oil-filled pipelines should not be assessed on the basis of empty-pipe formulae.

5. Conclusions

1) A unified analytical framework has been developed in bipolar cylindrical coordinates that simultaneously captures pipe-pipe interaction, internal compressible fluid coupling, and multiple types of incident plane wave (P, SV, SH) for two parallel buried pipes. This combined treatment, together with the extension to recorded ground motion, constitutes the main novelty of the study.

2) The interaction between parallel underground fluid-filled pipes significantly affects the dynamic stress concentration when the spacing ratio is small, especially for $d/D \leq 4.0$.

3) For incident P-waves, the maximum dynamic concentration coefficient reaches 1.76 at d/D = 1.0, and then gradually stabilises as the spacing increases.

4) The limiting non-resonant distance between the pipe centres increases from 5.0 m to 10.0 m as the wave incidence angle changes from 0° to 90°.

5) The local resonance effect is more pronounced for SV-wave excitation, and the presence of the internal fluid increases the seismic response by approximately 10-20 %.

6) Time-history analysis with recorded accelerograms (El Centro 1940 and Tashkent 1966), performed via FFT-based superposition of the harmonic transfer function, confirms the trends established in the harmonic case and shows that pipe-pipe interaction and internal-fluid effects persist under realistic broadband ground motion.

7) The obtained results provide rational design recommendations for the spacing and seismic resilience assessment of multi-line underground pipeline systems in seismic regions.

Acknowledgements

The authors have not disclosed any funding.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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ISSN Print 2345-0533, ISSN Online 2538-8479