# Winkler Springs for Embedded Beams Subjected to S-Waves

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**Abstract :** Shear waves that propagate through the ground impose deformations that must be taken into account in the design and assessment of buried longitudinal structures such as tunnels, pipelines, and piles. Conventional engineering approaches for seismic evaluation often rely on a Euler-Bernoulli beam models supported by a Winkler foundation. This approach, however, falls short in capturing the distortions induced when the structure is subjected to shear waves. To overcome these limitations, in the present work an analytical solution is proposed considering a Timoshenko beam and including transverse and rotational springs. The present research proposes ground springs derived as closed-form analytical solutions of the equations of elasticity including the seismic wavelength. These proposed springs extend the applicability of previous plane-strain models. By considering variations in displacements along the longitudinal direction, the presented approach ensures the springs do not approach zero at low frequencies. This characteristic makes them suitable for assessing pseudo-static cases, which typically govern structural forces in kinematic interaction analyses. The results obtained, validated against existing literature and a 3D Finite Element model, reveal several key insights: i) the cutoff frequency significantly influences transverse and rotational springs; ii) neglecting displacement variations along the structure axis (i.e., assuming plane-strain deformation) results in unrealistically low transverse springs, particularly for wavelengths shorter than the structure length; iii) disregarding lateral displacement components in rotational springs and neglecting variations along the structure axis leads to inaccurately low spring values, misrepresenting interaction phenomena; iv) transverse springs exhibit a notable drop in resonance frequency, followed by increasing damping as frequency rises; v) rotational springs show minor frequency-dependent variations, with radiation damping occurring beyond resonance frequencies, starting from negative values. This comprehensive analysis sheds light on the complex behavior of embedded longitudinal structures when subjected to shear waves and provides valuable insights for the seismic assessment.

**Keywords :** shear waves, Timoshenko beams, Winkler springs, sol-structure interaction
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