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ANALIZA DINAMIČKE INTERAKCIJA TLA I RAMOVSKIH KONSTRUKCIJA PRIMENOM SPEKTRALNIH ELEMENATA DEO II

Rezime
U radu je prikazani rezultati dinamičke analize jedne konzolne grede i dimnjaka modeliranih spektralnim elementima. Greda je izložena dejstvu harmonijske sile na vrhu, dok je dinamička analiza dimnjaka sprovedena za slučaj pomeranja osnove usled Razleigh-evilih talasa. Analiziran je uticaj deformacije smicanja, interakcije tla i objekta i mase fundamenta na deformaciju, kao i na prigušenje sistema.

Ključne riječi
Interakcija tla i objekta, spektralni elementi, Timošenko greda, dinamička krutost.

DYNAMIC SOIL-STRUCTURE INTERACTION OF FRAME STRUCTURES WITH SPECTRAL ELEMENTS – PART II

Summary
The dynamic response of a single cantilever beam and a tower-like structure modeled with spectral elements is investigated. A beam is subjected to a harmonic point load at the top of the structure while a harmonic free field Rayleigh wave is selected as excitation of the tower-like structure. The influence of shear deformation, soil-structure interaction and foundation mass as a function of the excitation frequency on deformation and damping are shown.

Key words
Soil-structure interaction, spectral element, Timoshenko beam, dynamic stiffness

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1. INTRODUCTION

With simple models insight can be gained about the factors influencing the response of soil-
structure systems. Our structural model is one spectral beam element founded on half-space.
Firstly, a harmonic point load at the top of the beam, secondly a harmonic Rayleigh wave is selected as
excitation. Theory, basic equations and definitions related to the applications are presented in the first
part of this paper 0, also presented at this conference.

1.1. CANTILEVER-BEAM SUBJECTED TO HARMONIC FORCE

A computer program in MatLab for dynamic analysis of the frame structures using
spectral elements was made. The investigations of the dynamic response of the cantilever-
beam subjected to a harmonic force at the top of the beam were performed for a beam
including shear deformation (Timoshenko beam) and for a beam neglecting shear
deformation (Bernouli beam); without soil-structure interaction (SSI), i.e. fix base, and
with SSI included; with foundation mass and without foundation mass. All material
damping was neglected in order to show the effects of radiation damping.

The beam has the length of 3.5 m and a Young’s modulus of \(E=2 \times 10^7\) kN/m\(^2\). In
order to show the effects of shear deformation beams with different cross sections were
investigated using Euler-Bernouli and Timoshenko beam spectral elements 0. The results
for the beam with cross section \(A=30/100\) cm\(^2\) are presented.

### Table 1. Eigen frequencies for the fixed beam

<table>
<thead>
<tr>
<th>(n)</th>
<th>(\omega) [rad]</th>
<th>(f) [Hz]</th>
<th>(\omega) [rad]</th>
<th>(f) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>259.04</td>
<td>38.04</td>
<td>219.84</td>
<td>34.99</td>
</tr>
<tr>
<td>2</td>
<td>1498.01</td>
<td>238.42</td>
<td>1091.00</td>
<td>173.64</td>
</tr>
<tr>
<td>3</td>
<td>4194.47</td>
<td>667.57</td>
<td>2401.00</td>
<td>382.13</td>
</tr>
</tbody>
</table>

In SSI analysis the dynamic stiffness of the rectangular footing (\(B \times L \times D=0.5 \times 1.0 \times 0.8\)
\(m, \gamma=2,403\) t/m\(^3\)) is represented by an equivalent circular footing on the surface of the soil
(embedment neglected). The characteristics of the soil are \(v=0.25, G=24138\) kN/m\(^2\), \(\rho=1.90\)
t/m\(^3\). The impedance functions of a circular foundation are obtained from \([5]\), in the form
\[
K_j = K_{s,j} \left( K_{p,j}(a_o) + ia_o C_{p,j}(a_o) \right), \quad a_o = \omega r/v_s, \quad j = v, h, r, hr
\]
where \(K_{s,j}\) is the static stiffness, \(K_{p,j}(a_o)\) and \(C_{p,j}(a_o)\) are the dimensionless functions of stiffness
and damping in \(j\)-direction, respectively, \(a_o\) is the dimensionless frequency, \(r\) is the
radius of equivalent footing, \(v_s\) is the velocity of the shear wave in the soil.

The horizontal displacements at the top for Euler-Bernouli and Timoshenko beam
are calculated for three cases: fixed beam, beam with SSI, beam with SSI and mass of the
footing as a function of the excitation frequencies, and presented in Fig. 2, 3, 4.
The eigen frequency obtained for Bernoulli and Timoshenko beam using spectral elements Figure 2, are equal to the eigen frequencies given in Table 1 which are obtained analytically.

The amplitudes at higher frequencies are damped if SSI is included, but less damped if the foundation mass is taken into account, see Figure 3, 4.

Snapshots of the displacements along the Timoshenko beam for selected frequencies are presented in Figures 5, 6 and 7. For the beam without SSI the beam deformations show fixed vibration nodes in time. For the beam with SSI the beam deformations the vibration nodes disappear due to radiation damping, see Figures 5, 6.

Figure 2. Fixed beam

Figure 3. Beam with SSI

Figure 4. Beam with SSI and foundation mass

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Figure 6. Timoshenko fixed beam: frequencies 20 and 259 Hz

Figure 7. Timoshenko beam with SSI; frequencies 8 and 298 Hz
1.2. STRUCTURE EXCITED WITH HARMONIC RAYLEIGH WAVE

A tower-like structure is represented as Bernoulli beam with a rigid circular foundation block resting on a homogeneous half-space. The properties of the beam and of the soil are given in Figure 9. The structure is excited through a harmonic Rayleigh wave. Material damping is neglected in the beam and in the soil.

Material damping is neglected in the beam and in the soil.

The retrograde motion of the Rayleigh wave traveling in the positive x-direction at the surface of a half-space with Poisson’s number equal $\nu = 0.45$ is expressed with horizontal and vertical components

$$v_x(t) = \tilde{v}_x \cos \omega t; \quad v_y(t) = 2.5 \tilde{v}_y \sin \omega t; \quad \omega = \frac{2\pi}{T}.$$

For a very stiff sub-grade the motion of the structure due to the elliptical free field motion of the base is calculated. The frequency response of the amplitudes in horizontal and vertical motion on top of the structure is shown in Figure 10. Since damping is neglected the resonances show singularities at the eigenfrequencies. In the chosen example the third resonance in bending (represented by $\tilde{v}_x$), is very close with the first resonance in elongation (represented by $\tilde{v}_y$).

Figure 11 shows maximal bending displacements along the beam at times $t = (n-1)T$, $n = 1,2,3, \ldots$ for those 5 frequencies which are marked in Figure 10. The deformations change the shape when the frequency of excitation crosses the resonance frequencies. Ten
snapshots taken in the first half period show in Figure 12 the motion of the beam for an excitation frequency of $\omega=8 \text{ rad/s}$.

![Figure 10: Frequency response of horizontal, $v_{h}$, and vertical displacement, $v_{v}$, at the top of the structure, at selected frequencies: $\omega = 1, 2, 8, 11, 30 \text{ rad/s}$.

In Figure 13 effects of SSI is shown. Due to radiation damping the singularities for the situation in Figure 10 disappear. Due to the 2 additional DOFs at the base new resonances occur in swaying and rocking motion. These motions are influenced by the foundation mass, as can be seen in Figure 13. Also of interest is, that only the first resonance frequency in bending is considerably damped while the 2nd and 3rd show still high amplification. This shows that the different foundation motions radiate different energy away from the foundation.

Unfortunately the effect of vertical excitation with SSI could not be included in the written version of our contribution.
2. CONCLUSION

The results show that it is of advantage to use spectral elements together with dynamic stiffnesses of the soil in soil-structure analysis. This methods enable the engineers to understand better the phenomena of soil structure interaction. More research and teaching is needed to make this method powerful for practical applications. If such an impuls is given the paper fulfilled its purpose.

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LITERATURE