Assessment of the Soil-Structure-Interaction based on Dynamic Measurements

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Motivation

Many monitoring campaigns show large differences between the theoretical model and the practical measurements. A major part of it can be attributed to soil-structure-interaction. It is therefore desirable to have methodologies available that enable quantifying these effects through monitoring campaigns.

Main Results

In an outstanding monitoring campaign a reliable approach has been demonstrated to quantify soil-structure-interaction effects. The power of ambient vibration monitoring on soil has been demonstrated.
19-1 Introduction

The Leitturm in Augarten (Vienna) was built from 1943 till 1944 under the responsibility of Prof. Dr. h.c. Dipl.-Ing. Friedrich Wilhelm August Tamms. It was created as one of three flak-positions, which were designed as a triangle around the centre of the city. At each position there are two towers, one for the radar (Leitturm) and one for the battle (Gefechtsturm). The platforms of the towers were constructed on the same height, so that collimation calculations could be handled more easily. The real purpose of the towers during World War II was as bunkers for the civil population.

The towers are now under monument protection. The Leitturm in the Augarten has been closed since the end of the war and was only inhabited by countless pigeons, which created a huge amount of waste. Nevertheless, historic documents, letters etc. can be still found there. The measurements were also a chance for historians to gain access to the structure, and they found some very interesting documents.

The rigidity of the structure and its tall shape make it the ideal test object. Apart from the special geometry and constitutive features, the location also plays an important part. Since the bunker is located in a quiet park, the data acquisitions were affected by very limited noise.

From the dynamic point of view, the main advantage of this structure is the possibility to distinguish between the vibration of the soil occurring at lower frequencies, and the vibration of the building and its members, which occurs at higher frequencies. Due to the high mass of the structure, the building behaves like a rigid body in the low frequency band, whereas the vibrations of the walls are in a much higher frequency band. Between
high frequencies and low frequencies there is a significant gap. Most of the "normal" buildings do not have such a gap. In that case the frequency bands are mixed and it is very difficult to distinguish between them. In this case, the SSI phenomenon can be determined very conveniently, which is the reason why the Leitturm was instrumented.

The dynamic properties of the soil can be determined in two different ways. The first one is the common way, using the Rayleigh Waves dispersion on the soil surface, and the back calculation to shear wave profiles. The second approach is the back calculation of the soil stiffness, based on the soil-structure-interaction.

The simultaneous measurement of the dynamic movements of the building allows the determination of the kinematic behaviour of the SSI. The tilting oscillations of the tower occur in both directions with different frequencies. They are transmitted to the soil and they can be measured in the surroundings.

The measurements were carried out separately on the soil surface for the assessment of the soil parameters, and on the tower structure to record the building movements. The next steps were: the measurement of the influence of the tower oscillation on the soil; the determination of the decay of the influence with the distance, and the qualitative estimation of the influence on the H/V-method results.

The results of the dynamic measurements were compared to different numerical simulations. Numerical models present the benefit to be tuned with the real dynamic properties of the measured SSI-system. The methods were compared, highlighting benefits and disadvantages of each one. The calibration of these methods with the measured conditions led to scientific findings and the opportunity to evaluate the different methods.
19-2 Measurements on the Soil Surface

The vibrations of the soil surface were measured for the documentation of the surface wave propagation. The phase velocity of Rayleigh waves on the surface is not constant but it depends on the frequency of the wave. Usually the Rayleigh waves with low frequencies are faster than those with higher frequencies. This results in the fact that a vibration signal containing a wide frequency spectrum changes shape with the propagation. This phenomenon is called “dispersion of the waves”. Low frequency waves, characterized by longer wave length, reach the measurement point distanced from the impact first. Contrarily, the high frequencies follow later.

To measure this effect, two artificial excitation types were applied: an impulse (for the high frequencies) and a harmonic excitation of the soil (for the low frequencies). The ambient vibrations were recorded in several triangular setups with different dimensions. By analysing the measured vibrations the dispersion curve could be evaluated.

The interpretation of the dispersion curve of the surface waves by means of analytic models was affected by imperfections, arising from working outside of the method assumptions. The natural soil is indeed not a homogeneous infinite half-space but consists of different layers of soil types with diverse soil properties.

The evaluation of the dispersion curve was possible through the numerical simulation of differently layered soil profiles. By modelling each different soil profile it was possible to get an artificial dispersion curve as outcome. A special optimization algorithm was then useful to do the best fitting with the measured one. Even if this inverse analysis method does not yield a unique result, a most likely soil profile can be identified.

The results of these tests are the shear wave velocity profiles of the soil, the leading parameter for the assessment of the dynamic soil properties. It is a real material parameter because it is constant for all frequencies (shear waves do not disperse).
Dispersion curve with misfit-values and corresponding shear wave velocity profile (Geopsy software)

Triangle setup: dispersion of best fitting profiles (left) and shear wave velocities of best fitting profiles (right)
19-3 Measurements on the Tower

The ambient vibrations of the Leitturm-structure were measured with three very sensitive geophones (Lennartz LE-3D-5s) on different levels. The Fast Fourier Transformation (FFT) analysis of the measured data of vibrations on the 11th floor shows the eigenfrequency of 1.6 Hz for the tilting motion in the “weak”, y-direction and 2.0 Hz in the “stiffer”, x-direction. The peak of the vertical oscillation is not as significant but can be found at 3.9 Hz. Because of the tower’s rigid structure, the soil-structure interaction behaviour is governed by the mass of the tower and the stiffness of the soil. By use of the Random Decrement Technique (RDT), the damping ratio of the vibrations can be separately evaluated for each frequency. The algorithm analyses ambient vibrations and looks for “events”
in the signal. All the detected events can be averaged to an artificial event which contains information about the vibrations' decay. The damping ratio of the relating vibration mode can be then determined.

The artificial excitation with impulses of a medicine ball (5 kg) on the gallery of the Leitturm (mass about 40000000 kg) could be detected inside the tower with its 2.5 m thick walls and a ceiling with more than 3.5 m concrete slab. Each individual impact could be clearly detected. From the analysis it was possible to get the natural frequencies caused by the SSI in the low frequency domain, and after a gap without any significant peaks, the internal vibrations of the building in the high frequency domain. In this special case of the Leitturm the metrological evidence of separation between internal vibrations of the building and global movements caused by the soil-structure interaction (F.19-10) subsists. In usual buildings the effects are overlapping and it leads to mixed effects in the measurement signals and difficulties in the interpretation.

### RDT-analysis of signals in z-direction, corner points in gallery level

<table>
<thead>
<tr>
<th>Eigenfreq. [Hz]</th>
<th>Intensity [μm]</th>
<th>Zone</th>
<th>RDT [%]</th>
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<tbody>
<tr>
<td>0.257</td>
<td>1</td>
<td>I</td>
<td>1033.772</td>
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<tr>
<td>1.627</td>
<td>2</td>
<td>1</td>
<td>104.011</td>
</tr>
<tr>
<td>2.000</td>
<td>3</td>
<td>1</td>
<td>133.753</td>
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<tr>
<td>1.621</td>
<td>4</td>
<td>0</td>
<td>0.000</td>
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<tr>
<td>1.984</td>
<td>5</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>2.000</td>
<td>6</td>
<td>I</td>
<td>133.753</td>
</tr>
<tr>
<td>3.937</td>
<td>7</td>
<td>I</td>
<td>7.643</td>
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</table>

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Epi x [m/s²]</th>
<th>Epi y [m/s²]</th>
<th>Epi z [m/s²]</th>
<th>Walesch x [m/s]</th>
<th>Walesch y [m/s]</th>
<th>Walesch z [m/s]</th>
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<tr>
<td>0</td>
<td>45·10⁻⁹</td>
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<tr>
<td>20</td>
<td>40·10⁻⁹</td>
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<td></td>
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<td>35</td>
<td>35·10⁻⁹</td>
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<tr>
<td>60</td>
<td>25·10⁻⁹</td>
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<td></td>
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<tr>
<td>80</td>
<td>20·10⁻⁹</td>
<td></td>
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</tr>
<tr>
<td>100</td>
<td>15·10⁻⁹</td>
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<tr>
<td>120</td>
<td>10·10⁻⁹</td>
<td></td>
<td></td>
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<tr>
<td>140</td>
<td>5·10⁻⁹</td>
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<tr>
<td>160</td>
<td>2·10⁻⁹</td>
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<tr>
<td>180</td>
<td>1·10⁻⁹</td>
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<tr>
<td>200</td>
<td>5·10⁻¹⁰</td>
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</tbody>
</table>
In a first approximation the soil structure interaction of the Leitturm can be understood as a rigid body motion of a concrete block socketing in an elastic half space of soil.

To prove the existence of a centre of rotation for both tilting modes and to find its position, vibration measurements were performed in the cellar of the tower and the signals were processed with the following procedure. In a first approximation, the tilting of the tower can be divided into a rigid translational component and into an independent rigid rotatory one. Combining the signals of two sensors is possible to identify the position of the centre of rotation, in relation to the measurement level. A fixed rotation centre exists only if both the translational and the rotatory oscillation components are oscillating either exactly in phase or exactly out of phase. The outcomes of the evaluation of the level of
the centre of rotation are represented in F.19-12 as a cloud of blue dots. Every dot corresponds to the centre of rotation for the tilting movement in x-direction for each sample of the FFT analysis in correct phasing. The position of the rotation centre at the eigenfrequency of the tower (2.0 Hz) is well identified. It is the highest density within the red dotted cloud in this domain. It can be seen that a fixed centre of rotation does exist but the position depends on the frequency. This fact that the centre of rotation depends on the frequency is the reason why the frequency at the maximum of the translational component (turquoise, blue) is lower than the related rotatory components (green) in F.19-13. It is not trivial because both of the peaks indicate the frequency of the same oscillation mode and should be exactly the same. But since there are also frequencies besides the eigenfrequency and the translational component is also influenced by the distance to the rotation centre, the peak of this component is shifted according to the sketch in F.19-14.

Translational and rotatory oscillation components of tilting oscillation whose maxima have different positions

Sketch of coherence between rotatory oscillation component (green), translational component (turquoise) and distance to rotation centre (blue)
19-4 Measurements of Soil-Structure Interaction

According to the soil-structure interaction mechanism the soil stiffness influences the movements of the building just as the building affects the soil. To measure the effect of the movement in the interaction, the tower oscillation and the vibration on the soil surface were measured simultaneously. One sensor was fixed on the tower and the others were placed in a line on the soil in both axis directions.

The FFT-analysis shows how the tower with its significant eigenfrequencies of 1.6 Hz and 2.0 Hz affects the soil. The movement of the building produces a vibration in the soil, detected with the geophones. This influence (velocity $V$) decreases with the distance $r$ to the tower (F.19-17). According to the influence depth of the different modes (see F.19-19)
there is more damping in the propagation function in y-direction. The deeper the influence, the less is the decay. This effect can be seen in the value of the damping exponent in this function. Due to the eccentricity of the sensor setup in y-direction, the peak of the x-direction movement (2.0 Hz) can be also detected in F.19-16 (right). Due to the different damping exponents in the formula of propagation, the effect of y-movement becomes dominant with increasing distance from the tower.

The H/V-method evaluates the relationship between the horizontal and the vertical vibrations. This "ellipticity" of the ambient vibrations is an indicator for site effects in case

H/V – evaluation of measurements in x-direction, distances 5, 10, 15, 20, 30 and 40 m (evaluation with Geopsy)
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of earthquakes and the eigenfrequency of the soil (peak at 0.9 Hz, 40 m-line) can be evaluated in case of special soil conditions. The soil structure interaction causes a magnification of the vertical vibration component at the eigenfrequency of the tower (2.0 Hz in x-direction) causing a depression of the curves of F.19-18 in the near-field of the tower. Within the first 30 m the vibrations of the tower influence the H/V values.

19-5 Numerical Simulation

To show the potential achievement of the different dynamic calculation methods, several numerical analyses have been carried out as shown in F.19-19.

Different methods of numerical modelling

<table>
<thead>
<tr>
<th>Analytical with FEM</th>
<th>Stiffness method</th>
<th>Analytical for rigid circular foundation on half space</th>
<th>Finite element method (FEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of subgrade reaction</td>
<td>Dynamic soil parameter? E_s, G, ν</td>
<td>Dynamic soil parameter: ν_s, G, ρ, ν, E</td>
<td></td>
</tr>
</tbody>
</table>

Eigenfrequencies with dynamical modulus of subgrade reaction method: F.19-20

tilting motion and vertical motion

\[
\begin{align*}
\sigma &= \frac{b \cdot \psi}{2} k_s \\
F &= \sigma \cdot \frac{b}{4} \\
M &= \frac{2}{3} b \cdot F = \psi \cdot \frac{b^3}{12} k_s \\
k_s &= \frac{M}{\psi} \\
\omega_s &= \sqrt{\frac{k_s}{m}} \\
\end{align*}
\]

Modulus of subgrade reaction

Moment of inertia

Mass moment of inertia
19-5-1 Method of Modulus of Subgrade Reaction

The method of “modulus of subgrade reaction” is the most common method. The effect of the soil is simulated by linear elastic springs distributed on the horizontal projection. The modulus of subgrade reaction $k_s$ is meant as a spring stiffness per square metre. It is not a real soil parameter because it may depend on the geometry, shape, and scale of the building as well as on the influence depth for layered soil profiles.

In F.19-21 the results of the calculation with the modulus of subgrade reaction method are reported beside the “reality” case. The results of the measurements are represented with dotted lines. The modulus of subgrade reaction is plotted versus the eigenfrequency of the interaction system.

The problem of the method of modulus of subgrade reaction is evident in F.19-21. There is no value for the modulus of subgrade reaction to fulfil all the oscillation mode frequencies measured in the field on the same soil conditions. This effect can be explained by F.19-22 where the different soil loading and the influence depth of the modes are shown.

Coherence between modulus of subgrade reaction and eigenfrequency for different oscillation modes, comparison with measured values

Effect of missing scale effect on the results of the dynamic modulus of subgrade reaction method

Vertical  
Tilting longitudinal  
Tilting lateral

38 MN/m$^3$  
145 MN/m$^3$  
180 MN/m$^3$
The method is theoretically and practically not able to describe the real physical situation. It can only be used for simple estimations within the frame of existing experiences.

19-5-2 Stiffness Method

While the method of modulus of subgrade reaction is limited to normal stresses in the subgrade, the stiffness method allows to take shear stresses into account as well. Therefore the deformation of a single point in the area of contact between soil and tower depends on the loading of the point itself as well as the loading of the surrounding area. Moreover it is possible to take the flexibility of the tower structure into consideration. The method is based on the oedometric modulus, a real physical soil parameter. The oedometric modulus is assumed to be constant for the whole soil domain influenced by the foundation. A stress-dependency of the oedometric modulus and a layered soil structure were not taken into account. For the stiffness method the geometry of the tower is segmented into \( n \) single, finite elements. To determine the deformation characteristics of the interacting soil – tower system, a single element \( i \) is loaded with the single load \( p = 1 \), which causes a settlement trough with its maximum \( c_0 \) under the loaded element \( i \). The settlement under the adjacent elements \((i−1)\) and \((i+1)\) is \( c_1 \) et cetera.

The settlement \( c_0 \) is evaluated for the characteristic point. The actual settlements can be calculated with these lines of influence and the real loads for each element.

For the natural frequency of the vertical motion the settlements under the dead load of the tower are calculated. An equivalent stiffness per square metre \( k_s \) can be derived from the mean settlement \( w_m \). The total equivalent stiffness can be written as
where $A$ is the ground area of the building. With the buildings mass $m$, the natural frequency of the vertical motion is defined as

$$\omega_v = \frac{k_v}{\sqrt{m}}.$$

The angle $\psi$ of rotation is calculated for a tilting moment of $M=1$ to evaluate the natural frequency for the tilting motions, which can be written as

$$\omega_{r} = \frac{k_{r}}{I},$$

with $k_r = m / \psi$ and the mass moment of inertia $I$ of the building.

### 19-5-3 Analytic Formulas for Circular Rigid Body on Linear Elastic Half-Space

It is possible to use the analytic formulas for circular rigid bodies on linear elastic half-space to get reliable results if the foundation of the building is rigid and can be described by a circular shape. The method is based on real physical soil parameters (shear modulus) [Flesch, 1993; Wolf, 1985]. F.19-24 shows that the results are very well corresponding to the measured tilting modes from the field test. The relationship between the damping ratios fits with the test results, but not in absolute values, because of the small amplitudes.

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**Results of numerical estimation of eigenfrequencies with dynamic parameters**

F.19-24 for a rigid circular foundation on elastic isotropic half-space

![Graph showing the relationship between dynamic shear module and shear wave velocity with measured and calculated frequencies for vertical, x-direction, and y-direction motions.](image-url)
19-5-4 Finite Element Method (FEM)

The Finite Element Method (FEM) was used for two separate analyses. First, the method of the modulus of subgrade reaction was applied to investigate the flexibility of the tower structure. The resulting consideration was that as shown in F.19-26, a modulus fulfilling the real dynamic soil conditions for all modes at the same time cannot be found. The reason is described in 19-5-1 and pictured in F.19-22.

In the second analysis with FEM, the soil was modelled with linear elastic elements. This is acceptable because the ambient measurements focus on waves with limited amplitude. By updating the model according to the measured dynamic soil profile and by

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**Results with dynamic substitute parameters for a rigid circular foundation on elastic isotropic half-space [Studer, 2007]**

<table>
<thead>
<tr>
<th>Circular foundation</th>
<th>Stiffness $\overline{B}$</th>
<th>Mass ratio $m \cdot \left(1 - \nu\right)$</th>
<th>Damping ratio $D$</th>
<th>Additional mass $\overline{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical</strong></td>
<td>$k_v = \frac{4 \cdot G \cdot r}{1 - \nu}$</td>
<td>$\frac{4 \cdot \rho \cdot r^3}{\sqrt{B}}$</td>
<td>0.425</td>
<td>0.27 $\cdot \overline{B}$</td>
</tr>
<tr>
<td><strong>Tilting</strong></td>
<td>$k_t = \frac{8 \cdot G \cdot r^3}{3(1 - \nu)}$</td>
<td>$\frac{8 \cdot \rho \cdot r^3}{(1 + B) \sqrt{B}}$</td>
<td>0.15</td>
<td>0.24 $\cdot \overline{B}$</td>
</tr>
</tbody>
</table>

Damping measured RDT | Analytical circular foundation | Relationship RDT/analyt.

- **x-direction: longitudinal** 1.915 % 7.686 % 0.25
- **y-direction: lateral** 0.959 % 4.186 % 0.23
- **z-direction: vertical** 7.643 % 36.859 % 0.21

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Coherency between modulus of subgrade reaction and eigenfrequency for different modes of vibration in case of rigid body movement and elastic building characteristic; comparison of FE computations with measured results
adjusting the soil stiffness, the determination of a solution fulfilling the tilting mode frequencies, the position of the rotation centre and the damping exponent for vibration decay with distance was possible. The fact that the soil of the updated model is stiffer, leads to get higher shear wave velocities than measured, but in this case the fitting relationship between the layers is known.

19-6 Conclusions

The target of the research work was to find a method to determine dynamic soil parameters using dynamic surface measurements, to find calculation parameters for different numeric simulations and to compare the results with the dynamic measurements of the soil-structure interaction, performed on a simple test object.

It is possible to formulate two main reasons to explain the demonstrated differences between the measured soil properties in the adjacent domain and the stiffer soil behaviour from the back calculation: The water content of the soil has no relevant effect on the shear wave velocity (just the mass difference) but it is important for the dynamic compression stiffness of the soil because of the pore water pressure. The considered modes are dominated by the compression stiffness of the soil.

The second reason for the stiffer soil properties beneath the Leitturn building is the soil consolidation. The average soil pressure of 610 kN/m² of the foundation slab of 31 m × 21 m has been loading the soil for the last 66 years. The measurements of the shear wave profiles were carried out on unaffected soil conditions in the adjacent park.

Summarizing the experiments in and around the Leitturn in Augarten in Vienna led to two different metrological approaches for determination of the dynamic soil properties connected with numerical inverse analysis. The benefits and the disadvantages of several
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Comparison of the obtained soil-parameters: results from measuring the Rayleigh-waves and from inverse analysis of the soil-structure interaction

Modulus of subgrade-reaction method:

\[ k_x = 145 - 175 \text{ MN/m}^2 \]
\[ k_y = 180 - 255 \text{ MN/m}^2 \]
\[ k_z = 30 - 38 \text{ MN/m}^2 \]

Analytical formulas for rigid circular foundation on elastic isotropic half-space:

\[ G_{x_1} = 580 \text{ MN/m}^2 \]
\[ G_{y_1} = 580 \text{ MN/m}^2 \]
\[ G_{z_1} = 410 \text{ MN/m}^2 \]

Assumption: \( \rho = 1800 \text{ kg/m}^3 \), \( \nu = 0.3 \)

Finite element method (linear elastic):

Quaternary gravels

\[ G = 317 \text{ MN/m}^2 \]
\[ v = 420 \text{ m/s} \]
\[ \nu = 0.3 \]

Neogene clays

\[ G = 908 \text{ MN/m}^2 \]
\[ v = 710 \text{ m/s} \]
\[ \nu = 0.35 \]

Numerical methods which are used in engineering practice could be pointed out. There is a difference between the dynamic soil structure interaction for the usual load cases (live loads, ambient excitation) and for the extraordinary conditions of earthquakes; the shear wave velocity profile and the H/V-method are developed for these conditions.

References

Seismid. Boden-Gebäude Interaktion. Internal report in the project SEISMID.

www.seismid.com


