

Assessment of Soil-Structure-Interaction by measurement

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Abstract. In common buildings the soil-structure-interaction (SSI) is governed by the elastic behaviour of the building. The best conditions to see the soil effect predominate would be a dynamic rigid body movement of a massive building. For this reason measurements were carried out on an old anti-aircraft tower from World War II on typical Viennese soil conditions. The dynamic properties of the soil could be determined in two different ways. The first one is the common way using the dispersion of the Rayleigh waves 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. With the simultaneous measurement of the dynamic movement of the building the kinematic behaviour of the SSI could be determined. The tilting oscillations of the tower in both directions with different frequencies transmitted to the soil could be measured in the surroundings. The decay of these vibrations and their influence on the H/V-method results was studied. The results of the dynamic measurements were compared with different methods of numerical simulation. The benefits and the disadvantages of the methods can be compared. The calculation values of the numerical models could be calibrated with the real dynamic properties of the measured SSI-system.

Keywords: Soil-Structure-Interaction SSI; Dynamic Measurements; Rayleigh Waves; H/V-method; Back Calculation; Modulus of Subgrade Reaction

1 INTRODUCTION

The Leitturm in Augarten (Vienna) was part of an anti-aircraft defence system in World War II. It has not been used since those times. For the rigidity of the structure and its tall shape it is considered to be an ideal test object. Since there is a quiet park surrounding this building it was the ideal test field to carry out the measurements. Measurements for the soil structure interaction were carried out separately on the soil surface for assessment of soil parameters and on the tower structure to record the building movements. The next step was to measure the influence of the tower oscillation on the soil and the decay of this influence with distance. Numerical simulations were carried out based on different methods. The calibration of these methods with the measured conditions led to scientific findings and the opportunity to evaluate the different methods.



Figure 1. The Leitturm in Augarten, Vienna, built during World War II (left) and aperture in the 2.5 m concrete wall of the tower seen from inside (right).

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 the dispersion of the wave because low frequency waves will reach a measurement point distanced from the impact first and the high frequencies will follow later. To measure this effect, two artificial excitation types: an impulse (for the high frequencies) and a harmonic excitation of the soil (for the low frequencies) were applied. The ambient vibrations were recorded in several triangular setups with different dimensions. By analysing the measured vibrations the dispersion curve could be evaluated.

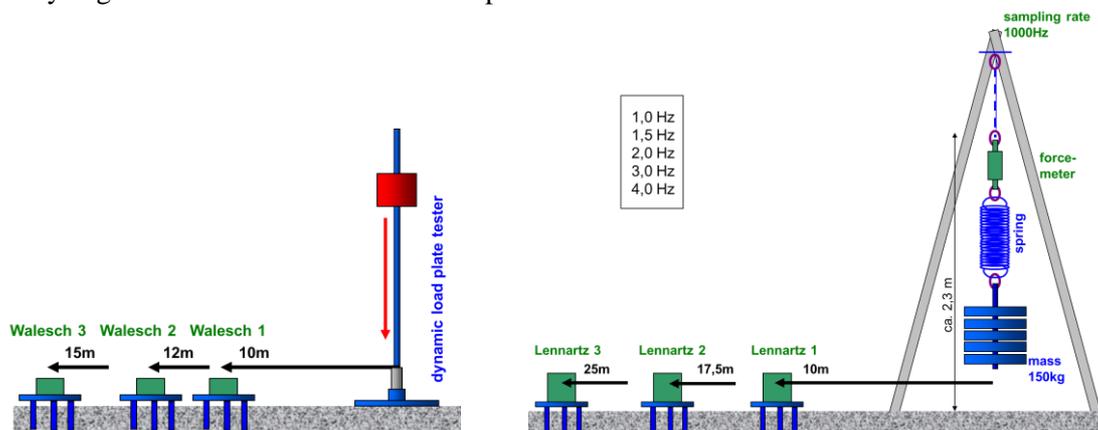


Figure 2. Surface-wave dispersion test setup with artificial impulse excitation using a light falling weight device (left), and harmonic excitation using a “shaker” as a mass-spring-system (right).

Since the natural soil is no homogeneous infinite half-space but consists of different layers of soil types with diverse soil properties, the dispersion curve of the surface waves is influenced by this. By means of numerical simulations of different layered soil profiles the corresponding dispersion curves can be evaluated. The artificial dispersion curve best fitting to the measured one can be found by a special optimization algorithm. This inverse analysis method does not give a unique result but a most likely soil profile can be found. The results of these tests are the shear wave velocity profiles of the soil. The shear wave velocity is the leading parameter for assessment of the dynamic soil properties. The shear wave velocity is a real material parameter and it is constant for all frequencies (shear waves do not disperse).

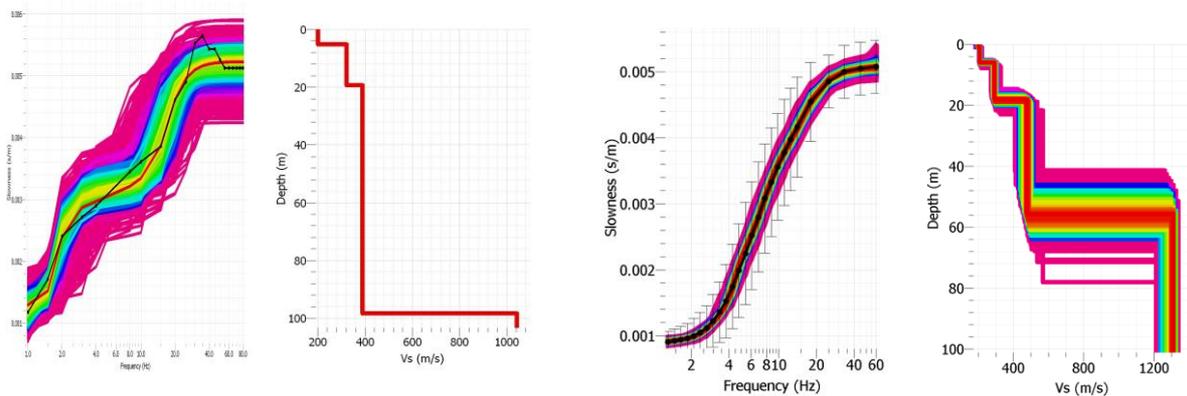


Figure 3. Dispersion curve with misfit-values and corresponding shear wave velocity profile (left), Triangle setup: dispersion of best fitting profiles (left) and shear wave velocities of best fitting profiles (right).

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 (blue) and 2.0 Hz in the “stiffer”, x-direction (red). 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.

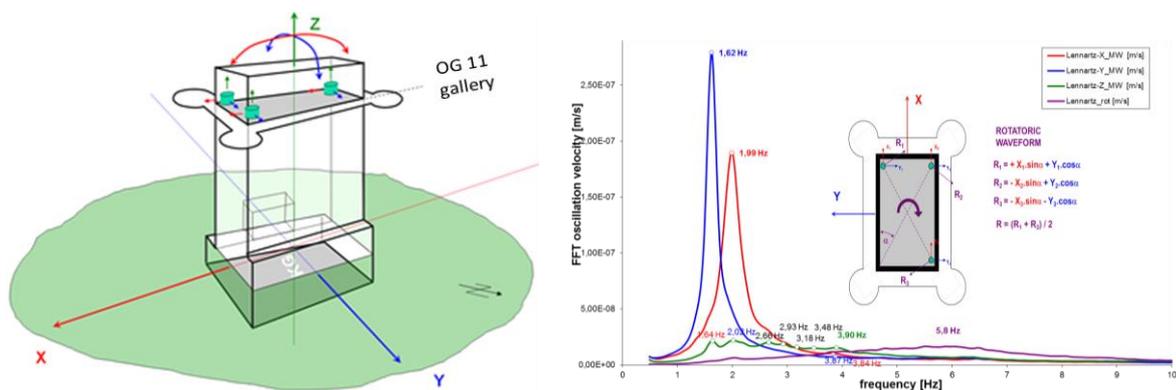


Figure 4. Sensor setup for the measurement on the gallery level inside the tower (left), FFT-analysis of combined values from measurements in the corner of the gallery (right).

By use of the Random Decrement Technique (RDT), the damping ratio of the vibrations can be detected for each frequency separately. The algorithm analyses ambient vibrations and looks for “events” in the signal. Averaging all detected events lead to an artificial event, where the decay of vibration can be evaluated and the damping ratio of the relating vibration mode can be determined. The artificial excitation with impulses of a medicine ball (5 kg) on the gallery of the Leitturm (mass about 40.000.000 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. The analysis gives the natural frequencies caused by the soil-structure interaction in the low frequency domain, and after a gap without any significant peaks, the internal vibrations of the building in the high frequency domain. It is the metrological evidence for the separation of internal vibration of the building from the global movements caused by the soil-structure interaction in this special Leitturm case. At usual buildings both effects are overlapping which leads to mixed effects in the measurement signals and difficulties for the interpretation.

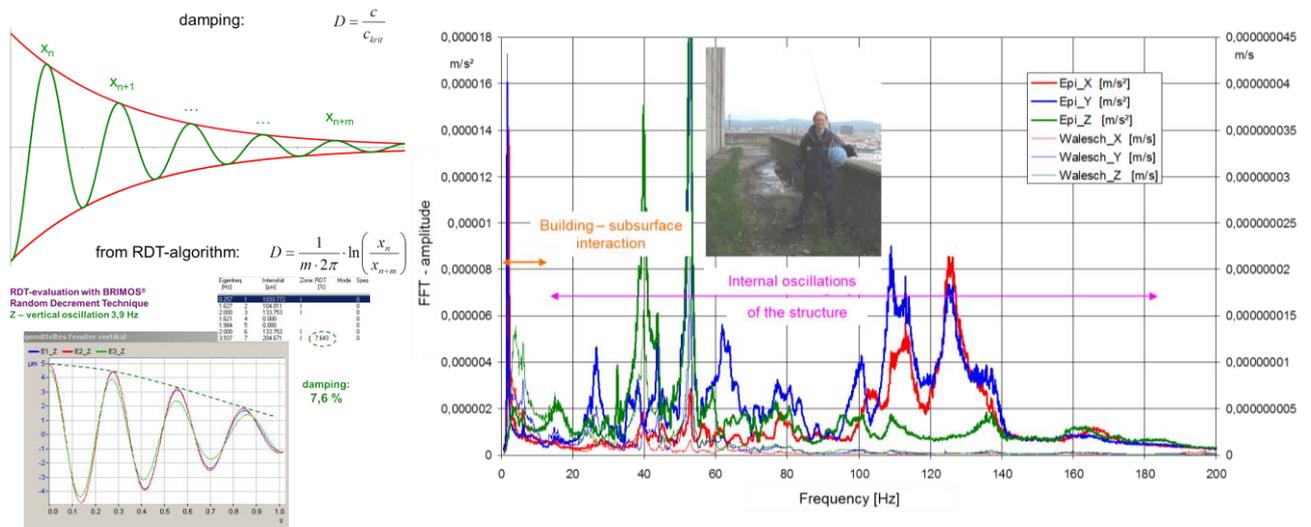


Figure 5. RDT-analysis of signals in z-direction, corner points in gallery level (left). FFT- analysis of signals (acceleration, oscillation velocity) for impulse-excitation of the Leitturm at gallery level (right).

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 answer the question if a centre of rotation exists for both tilting modes and to find its position, vibration measurements in the cellar of the Leitturm were analysed by the following procedure. Combining the signals of two sensors the tower movement can be divided in a translational and a rotatory component. The relationship of these components will lead to 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.

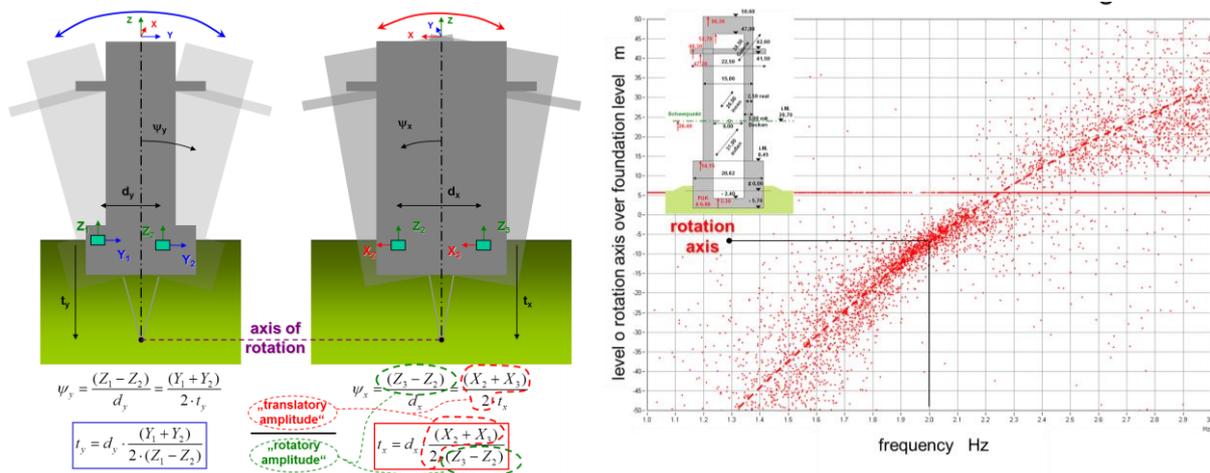


Figure 6. Determining the rotatory centre of the rigid body by analysing signals from two sensors on one level (left), Level of the rotatory centre for tilting oscillations in x-direction depending on the frequency. Only the oscillations in phase or out of phase are considered (right).

The evaluation of the level of the centre of rotation for the tilting movement of the Leitturm for each sample or the FFT analysis with correct phasing is shown in the Figure 6 as a cloud of red dots. The position of the rotation centre at the eigenfrequency of the tower (2.0 Hz) is found. 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 moving centre is the reason, why the frequency at the maximum of the translational component (red, blue) is lower than the related rotatory

components (green) in Figure 6. That 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 Figure 7.

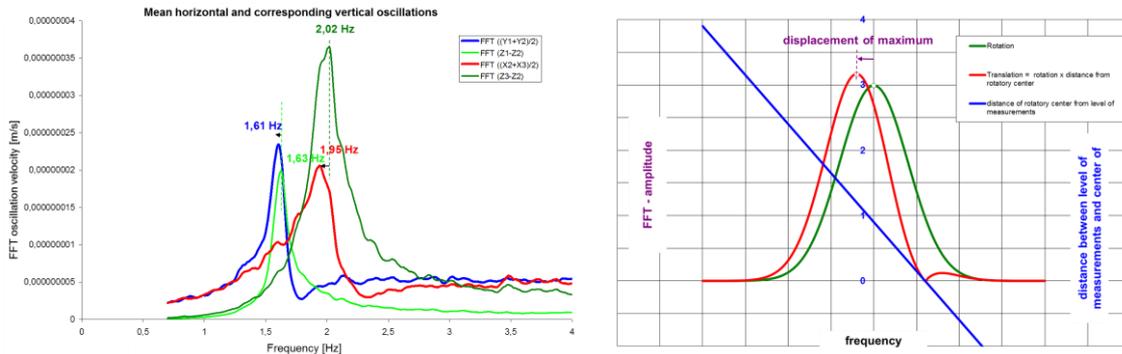


Figure 7. Translational and rotatory oscillation components of tilting oscillation whose maxima have different positions (left), right: Sketch of coherence between rotatory oscillation component (green), translational component (red) and distance to rotation center (blue); (red line) = (green line) x (blue line).

4 MEASUREMENTS OF SOIL STRUCTURE INTERACTION

According to the soil-structure interaction mechanism the soil stiffness influences the movements of the building just as well the building affects the soil. To measure the effect of movement in the interaction, the tower oscillation and the vibration on the soil surface was measured simultaneously. One sensor was fixed on the tower and the others placed in a line on the soil in both axis direction. In the FFT-analysis of these measurements the influence of the tower with its significant eigenfrequencies of 1.6 Hz and 2.0 Hz can be detected. This influence (velocity V) decreases with the distance r to the tower (Figure 8). According to the influence depth of the different modes (see Figure 13) there is more damping in the propagation function in the y-direction. The deeper the influence, the less is the decay, which can be seen in the value of the damping exponent in this function.

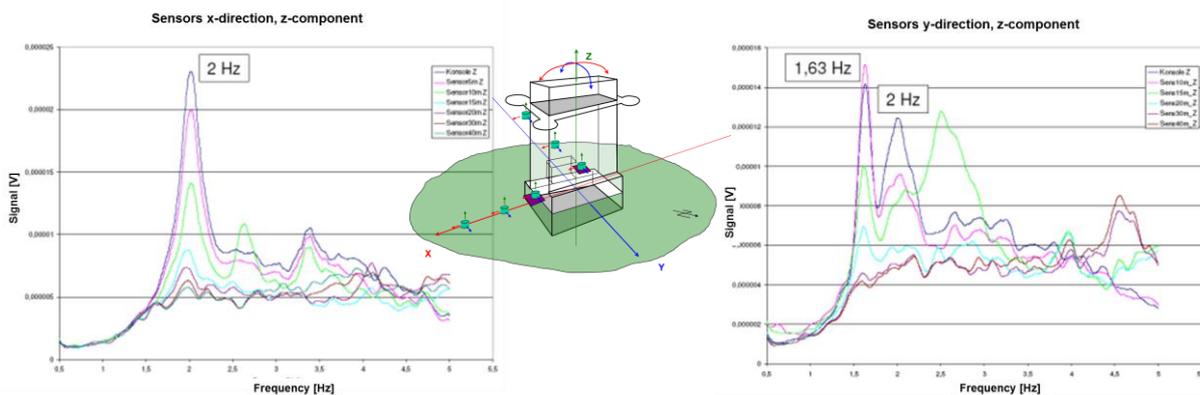


Figure 8. Acceleration measurements for the x-direction array: z-component of the sensors (left), and for the x-direction array: z-component of the sensors (right).

Due to the eccentricity of the sensor setup in y-direction the peak of the x-direction (2.0 Hz) movement can be also detected in Figure 8. Due to the different damping exponents in the formula of propagation the effect of y-movement becomes dominant with increasing distance to the tower.

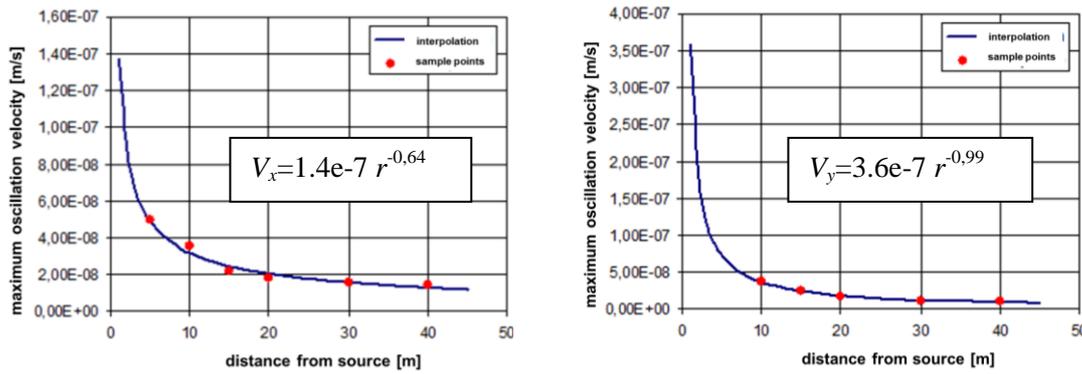
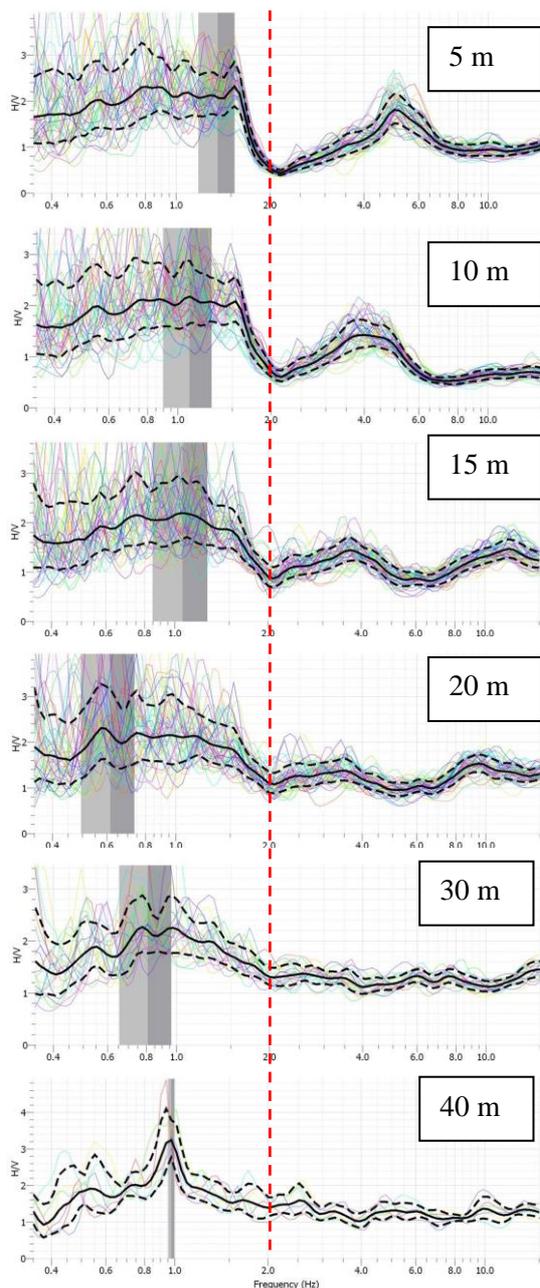


Figure 9. Damping function in x-direction of the tower (left), and y-direction (right).



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 of earthquakes and the eigenfrequency of the soil (peak at 0.9 Hz, 40m-line) can be evaluated in case of special soil conditions. The soil structure interaction effects more magnification of the vertical vibration component at the eigenfrequency of the tower (2.0 Hz in x-direction) causing a depression in the curves of Figure 11 in the near-field of the tower. Within the first 30m the vibrations of the tower influences the H/V values.

5 NUMERICAL SIMULATION

To show the achievement potential of the different dynamic calculations methods several numerical analyses had been carried out as shown in Figure 10.

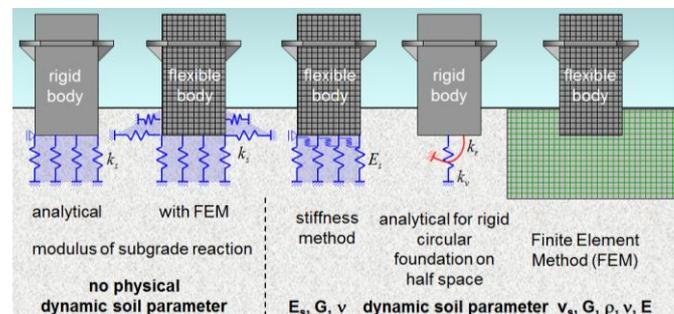


Figure 10. Different methods of numerical modeling.

Figure 11. H/V – evaluation of measurements in x-direction, distances 5, 10, 15, 20, 30 and 40 m (left).

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 this spring stiffness per square meter and it is not a real soil parameter because the geometry, shape, scale of the building and influence depth for layered soil profiles has to be taken into account.

In Figure 12 the results of the calculation with the method of modulus of subgrade reaction are compared with “reality” – the results of the measurements (dotted lines). The modulus of subgrade reaction is plotted versus the eigenfrequency of the interaction system.

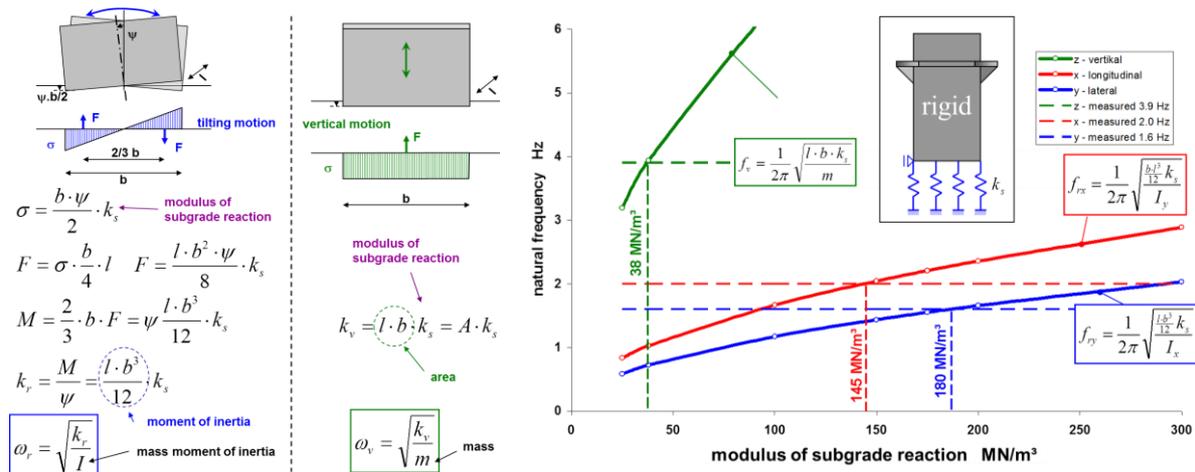


Figure 12. Eigenfrequencies with dynamical modulus of subgrade reaction method: tilting motion and vertical motion (left). Coherence between modulus of subgrade reaction and eigenfrequency for different oscillation modes, comparison with measured values (right).

The problem of the method of modulus of sub-grade reaction is evident in Figure 12 (right). 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 Figure 13 showing the different soil loading and influence depth of the modes. 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.

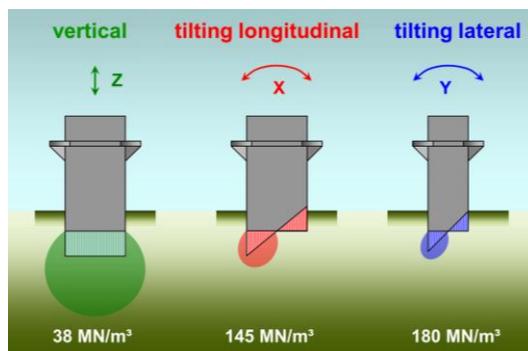


Figure 13. Effect of missing scale effect on the results of the dynamic modulus of subgrade reaction method.

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 $p = I$, 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 meter k_s can be derived from the mean settlement w_m . The total equivalent stiffness can be written as

$$k_v = k_s \cdot A \tag{1}$$

where A is the ground area of the building. With the buildings mass m , the natural frequency of the vertical motion is defined as

$$\omega_v = \sqrt{\frac{k_v}{m}} \tag{2}$$

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

$$\omega_r = \sqrt{\frac{k_r}{I}} \tag{3}$$

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

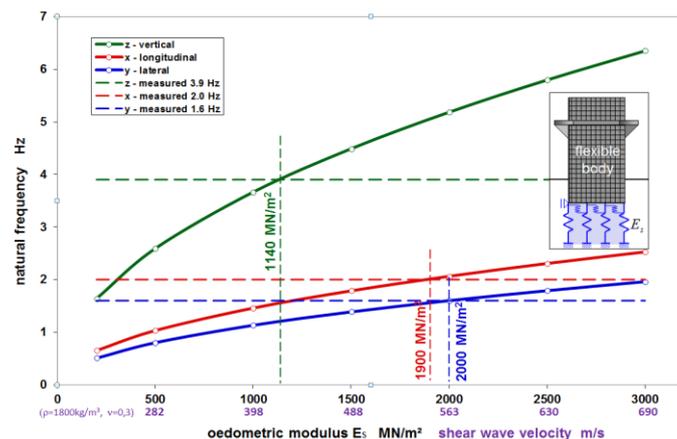


Figure 14. . Results of back-calculation of eigenfrequencies with the stiffness method.

5.3 Analytic formulas for circular rigid foundation on linear elastic half-space

Using analytic formulas for circular rigid bodies on linear elastic half-space provides reliable results if the foundation of the building is rigid and can be described with a corresponding circular shape. The method is based on real physical soil parameters (shear modulus). Figure 15 shows that the results are

corresponding very well with the measured tilting modes from the field test. The relationship between the damping ratios fits with the test results, but not the absolute values, because of the small amplitudes.

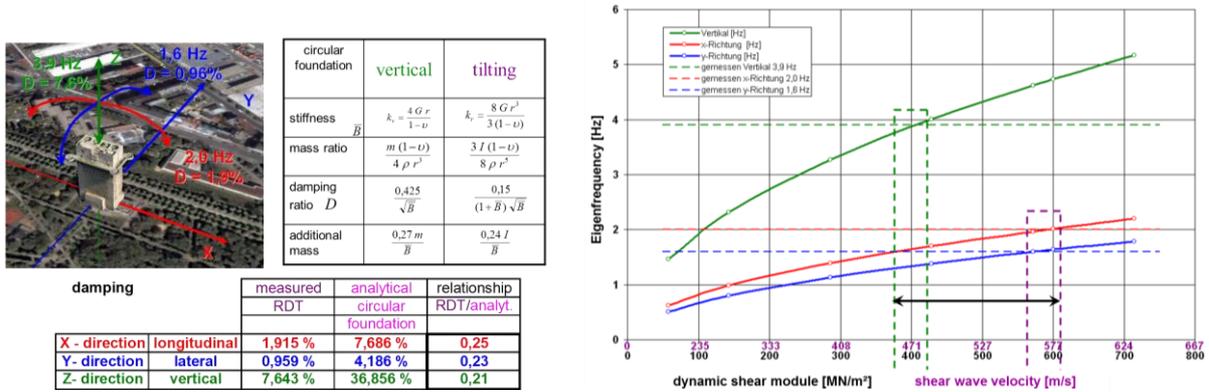


Figure 15. Results with dynamic substitute parameters for a rigid circular foundation on elastic isotropic half-space (left), Results of numerical estimation of eigenfrequencies with dynamic parameters for a rigid circular foundation on elastic isotropic half-space (right).

5.4 Finite Element Method (FEM)

The Finite Element Method (FEM) was used for two separate analyses. First, the method of modulus of subgrade reaction was carried out with FEM to take into consideration the flexibility of the tower structure. The problem of this method still exists as shown in Figure 16. A modulus which could fulfil the real dynamic soil conditions for all modes at the same time cannot be found.

In the second analysis with FEM the soil was modelled by linear elastic elements. Especially for the small amplitudes of the ambient measurements this is feasible. With updating the model according to the measured dynamic soil profile and by changing soil stiffness, it was possible to find a solution fulfilling the tilting mode frequencies, the position of the rotation centre and the damping exponent for vibration decay with distance. The soil properties of the updated model are stiffer leading to higher shear wave velocities than the measurements in the field but with a fitting relationship between the layers.

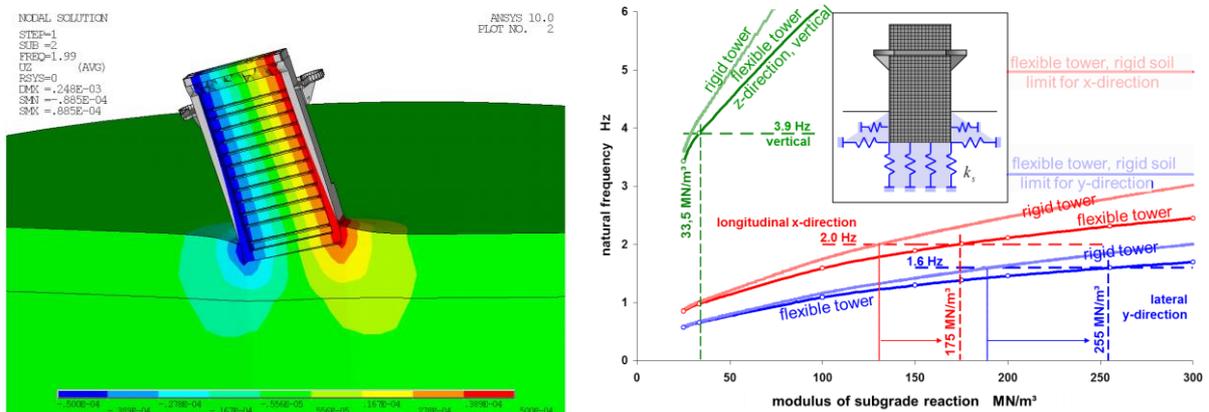


Figure 16. FE calculation result: deformation in z-direction, 1st harmonic mode (left), Coherency between modulus of subgrade reaction and eigenfrequency for different modes of vibration for rigid body movement and elastic building characteristic; comparison of FE-computations with measured results.

6 CONCLUSION

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 check the results with dynamic measurements of soil-structure interaction on a simple test object.

There are two main reasons for 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 to 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 Leitturm building is the soil consolidation. The average soil pressure of 610 kN/m² of the foundation slab of 31 m times 21 m has been loading the soil for the last 66 years. The measurements for the shear wave profiles were carried out on unaffected soil conditions in the adjacent park.

Summarizing the experiments in and around the Leitturm in Augarten in Vienna led to two different metrological approaches for determination of the dynamic soil properties connected with numerical inverse analysis.

The power and the disadvantages of several 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 earthquake; the shear wave velocity profile and the H/V-method are developed for these conditions.

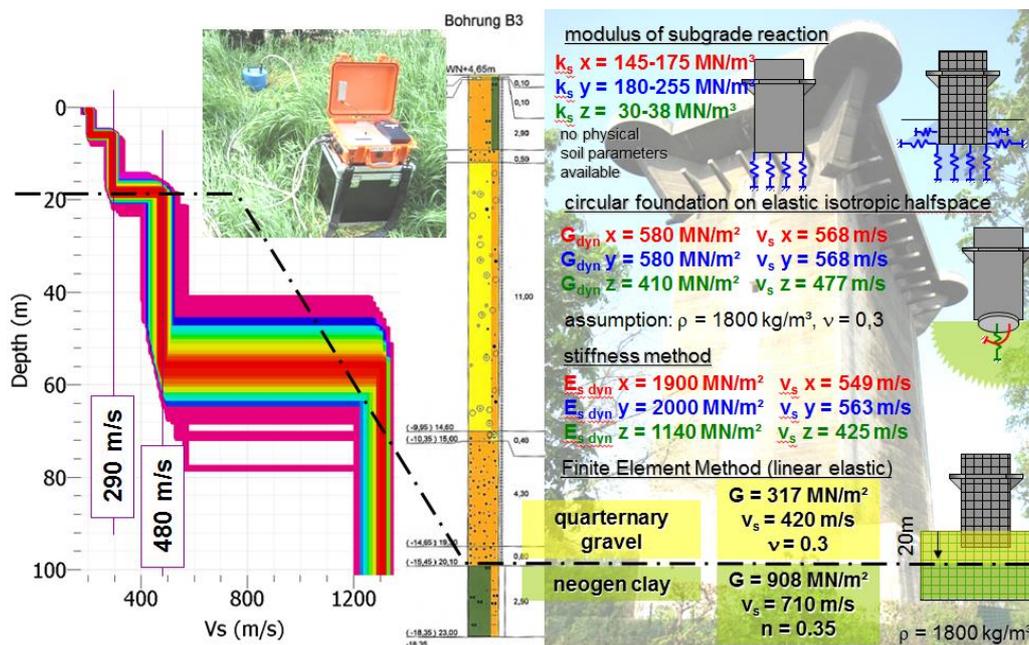


Figure 17. Comparison of the obtained soil-parameters: results from measuring the Rayleigh-waves and from inverse analysis of the soil-structure interaction with different methods.

REFERENCES

- Seismid Bericht, „Boden-Gebäude Interaktion“, *interner Bericht im Projekt SEISMID*, www.seismid.com
 J. Studer, J. Laue, M. Koller (2007) „Bodendynamik“, 3. Auflage, Springer Verlag
 R. Flesch (1993) „Baudynamik“, Band 1, Bauverlag
 G. Achs et al (2011) „Erdbeben im Wiener Becken“ VCE Eigenverlag