Soil-Structure-Interaction: Analysis through measurements

F. Kopf,
FCP– Fritsch, Chiari & Partner, Vienna, Austria
D. Schäfer
VCE – Vienna Consulting Engineers ZT GmbH, Vienna, Austria
J. Pistrol
TU – University of Technology, Vienna, Austria

ABSTRACT: In common buildings the soil-structure-interaction (SSI) is governed by the elastic behavior 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 behavior 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.

1 INTRODUCTION

The Leitturm in Augarten (Vienna) was part of an anti-aircraft defense 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.

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).

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.

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 analyzing the measured vibrations the dispersion curve could be evaluated.

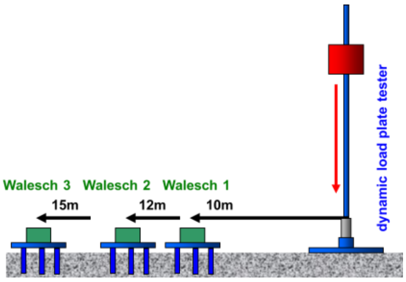

Figure 2. Surface-wave dispersion test setup with artificial impulse excitation using a light falling weight device.

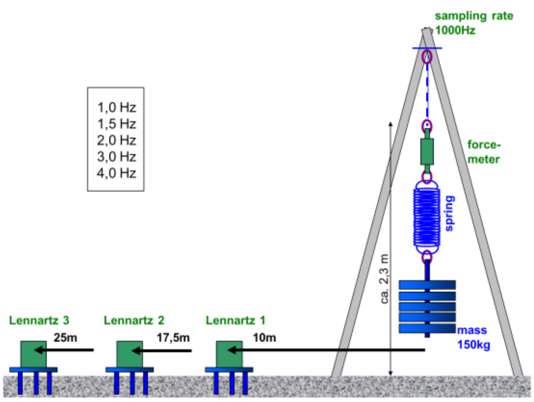

Figure 3. Surface-wave dispersion test setup with artificial harmonic excitation using a "shaker" as a mass-spring-system.

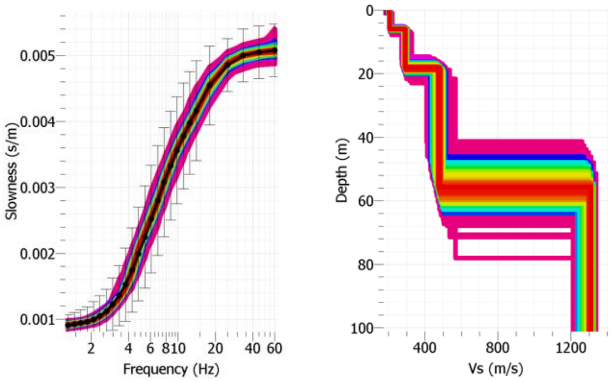

Figure 4. Triangle setup: dispersion of best fitting profiles (left) and shear wave velocities of best fitting profiles (right).

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).

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 11^{th} 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 behavior is governed by the mass of the tower and the stiffness of the soil.

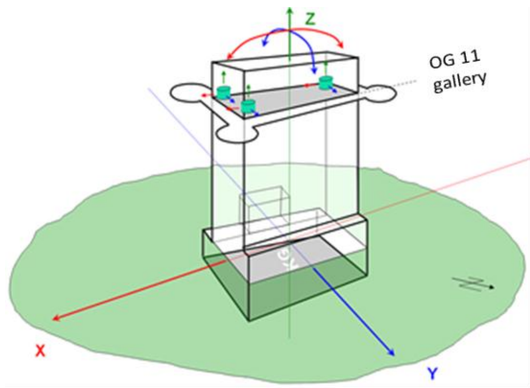

Figure 5. Sensor setup for the measurement on the gallery level inside the tower.

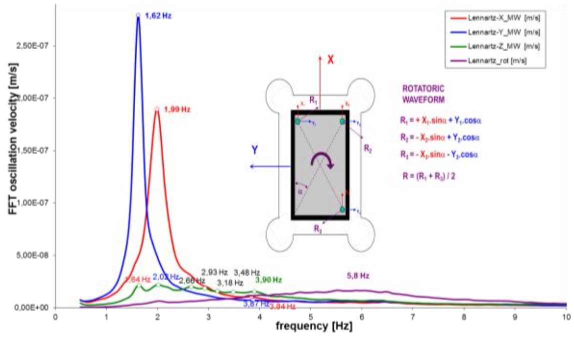

Figure 6. FFT-analysis of combined values from measurements in the corner of the gallery.

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.
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 center of rotation exists for both tilting modes and to find its position, vibration measurements in the cellar of the Leitturm were analyzed 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 center of rotation in relation to the measurement level. A fixed rotation center exists only if both, the translational and the rotatory oscillation components are oscillating either exactly in phase or exactly out of phase.

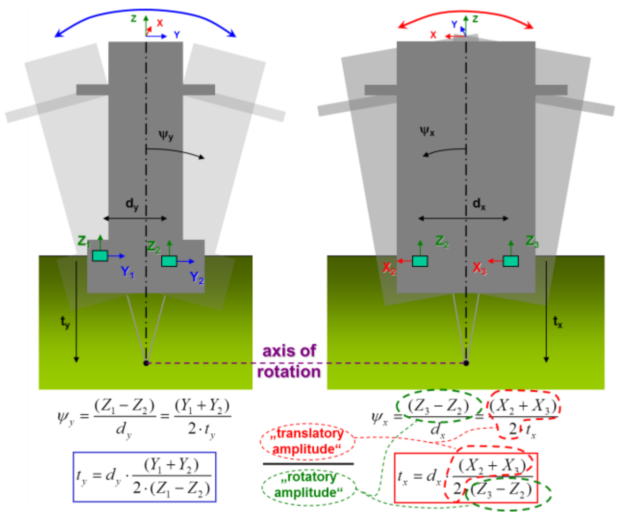

Figure 7. Determining the rotatory center of the rigid body by analyzing signals from two sensors on one level.

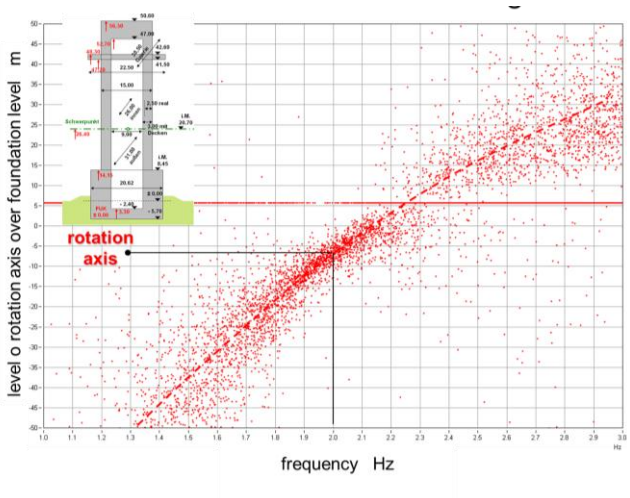

Figure 84. Level of the rotatory center for tilting oscillations in x-direction depending on the frequency. Only the oscillations in phase or out of phase are considered.

The evaluation of the level of the center of rotation for the tilting movement of the Leitturm for each sample or the FFT analysis with correct phasing is shown in the Figure 8 as a cloud of red dots. The position of the rotation center 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 center of rotation does exist but the position depends on the frequency. This moving center 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 9. 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 center, the peak of this component is shifted according to the sketch.

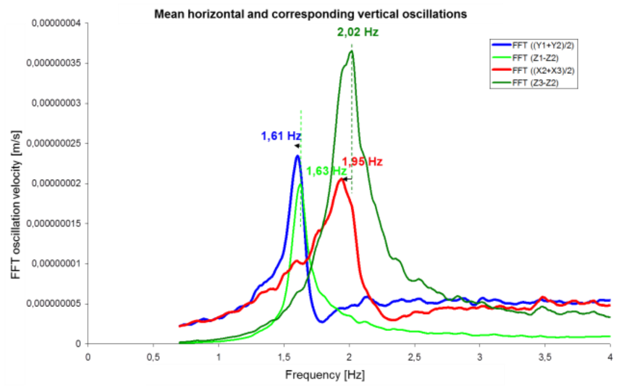

Figure 9. Translational and rotatory oscillation components of tilting oscillation whose maxima have different positions.

3.1 *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. According to the influence depth of the different modes 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.

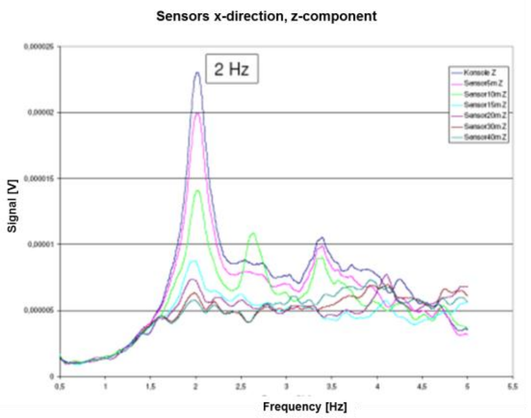

Figure 10. Acceleration measurements for the x-direction array: z-component of the sensors.

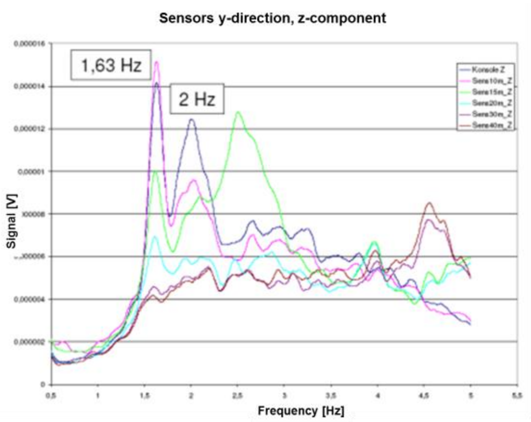

Figure 11. Acceleration measurements for the y-direction array: z-component of the sensors.

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 11. Due to the different damping exponents in the formula of propagation the effect of y-movement becomes dominant with increasing distance to the tower.

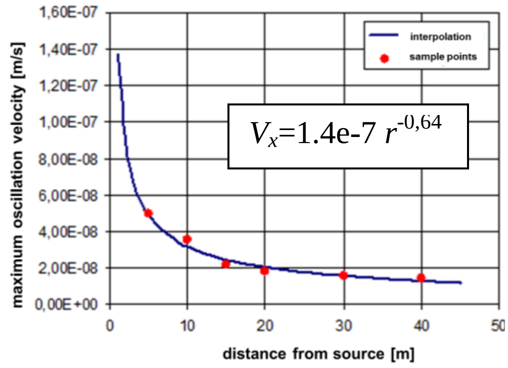

Figure 52. Damping function in x-direction of the tower.

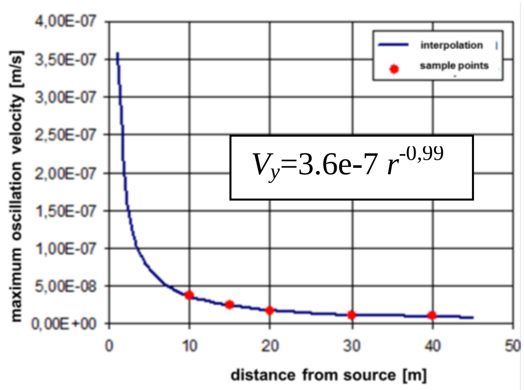

Figure 13. Damping function in y-direction of the tower.

4 NUMERICAL SIMULATION

4.1 *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.

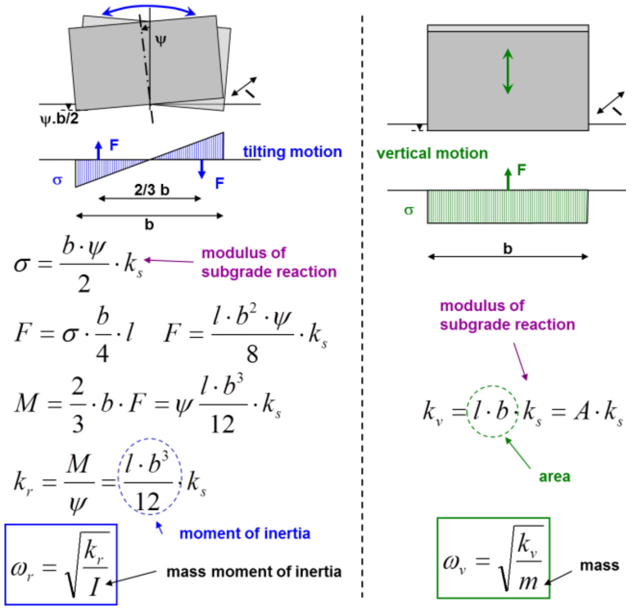

Figure 14. Eigenfrequencies with dynamical modulus of subgrade reaction method: tilting motion and vertical motion.

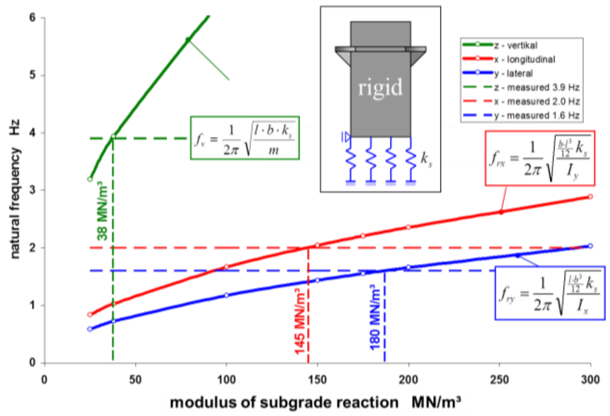

Figure 15. Coherence between modulus of subgrade reaction and eigenfrequency for different oscillation modes, comparison with measured values.

The problem of the method of modulus of subgrade reaction is evident in Figure 15. There is no value for the modulus of subgrade reaction to fulfill all the oscillation mode frequencies measured in the field on the same soil conditions. This effect can be explained by 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.

4.1 *Stiffness method*

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 meter k_s can be derived from the mean settlement w_m. The total equivalent stiffness can be written as

$$k_v = k_s \cdot A$$

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

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

The angle ψ 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

$$\omega_r = \sqrt{\frac{k_r}{I}} \quad .$$

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

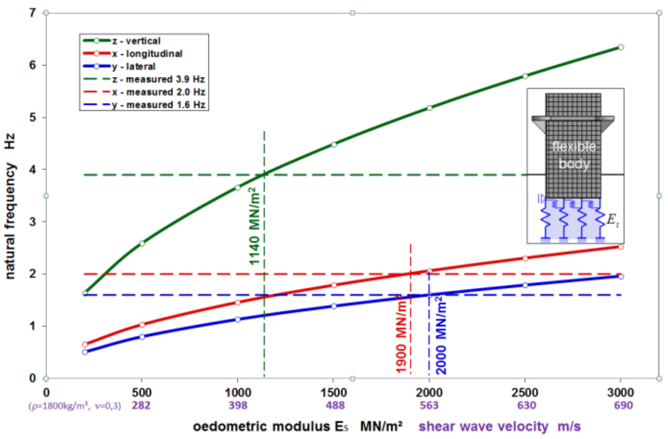

Figure 16. Results of back-calculation of eigenfrequencies with the stiffness method.

4.2 *Analytic formulas for circular rigid body 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). 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.

4.3 *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. A modulus which could fulfill the real dynamic soil conditions for all modes at the same time cannot be found. In the second analysis with FEM the soil was modeled 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 center 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.

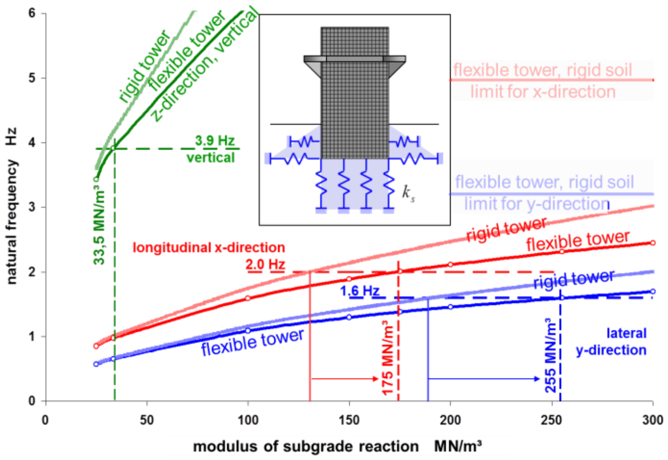

Figure 17. Coherency between modulus of subgrade reaction and eigenfrequency for different modes of vibration for rigid body movement and elastic building characteristic; comparison of FE-computations with measured results.

5 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 behavior 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.

6 REFERENCES

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