Vienna Congress on Recent Advances in
Earthquake Engineering and Structural Dynamics 2013 (VEESD 2013)
C. Adam, R. Heuer, W. Lenhardt & C. Schranz (eds)
28-30 August 2013, Vienna, Austria
Paper No. 167

Ambient vibration of oscillating and vibrating rollers

J. Pistrol[1], F. Kopf[2], D. Adam[1], S. Villwock[3], W. Völkel[3]

[1] Institute of Geotechnics, Vienna University of Technology, Vienna, Austria
[2] FCP - Fritsch, Chiari & Partner ZT GmbH, Vienna, Austria
[3] HAMM AG, Tirschenreuth, Germany

Abstract. Ambient vibrations of dynamic rollers may limit their applicability in sensitive areas. In the presented study two different types of excitation for the dynamic roller drum are tested on their influence on ambient vibration, the oscillating and the vibrating drum. Two approaches for the assessment of the damage potential of dynamic roller compaction are discussed. The results of large-scale in situ tests are provided to outline the influence of the type of excitation and the right parameter setting for excitation frequency, amplitude of the drum, or roller speed on the magnitude and propagation of ambient vibrations.

Keywords: Soil dynamics; Compaction; Rollers; Vibration; Oscillation; Ambient vibration

1 INTRODUCTION

1.1 Motivation

Near-surface compaction plays an important role for the construction of various civil engineering structures such as dams and embankments for roads and railways. Dynamic roller compaction has become the common method of near-surface compaction since dynamic rollers are much more efficient than common static rollers. However, dynamic methods cause ambient vibration that may affect adjacent buildings, buried pipes, etc. or limit the applicability of dynamic methods in sensitive areas like inner city construction sites or on and near bridges.
To minimize the damage potential of dynamic roller compaction the right parameter-setting for excitation frequency, amplitude of the drum, or speed of compaction has to be done as well as the choice of the suitable type of excitation for the dynamic roller drum.
Large-scale in situ tests were performed with a tandem roller equipped with an oscillating and a vibrating drum. Ground accelerations in three orthogonal directions were measured on selected spots perpendicular to the direction of compaction. The way of vibration propagation as well as the magnitude of ambient vibration were investigated for both excitation methods as well as their frequency dependence.

1.2 Oscillation vs. Vibration

The torsional motion of an oscillatory drum is caused by two opposed, rotating eccentric masses, which shafts are mounted eccentrically to the drum axis. Soil is dynamically loaded horizontally by the drum motion (blue in Fig. 1) and statically loaded by the dead weight of the drum and roller in vertical direction (green in Fig. 1). Mainly tangential forces are transmitted in the soil by shear waves. The amplitude of the torsional motion is constant. However, the frequency may vary from 20 to 70 Hz with 39 Hz as the commonly used frequency.

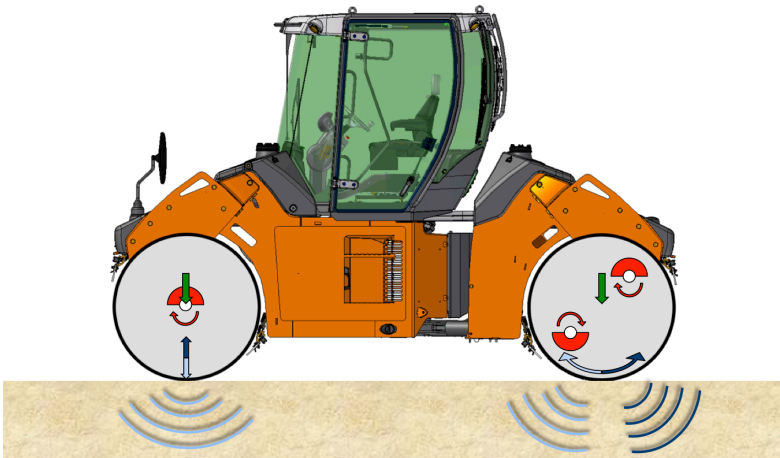

Figure 1. Forces and moments of dynamic drums: vibrating drum (left), oscillating drum (right).

The eccentric masses of a vibrating drum are shafted concentrically to the drum axis resulting in a significantly higher vertical loading but also increased ambient vibration. Usually vibrating rollers use a larger amplitude with a lower frequency (40 Hz) for deeper compaction and a smaller amplitude with a higher frequency (50 Hz) for near-surface compaction.

2 ASSESSMENT OF THE DAMAGE POTENTIAL OF DYNAMIC ROLLER COMPACTION

2.1 Fundamentals

An evaluation of ambient vibrations caused by dynamic roller compaction may not only put buildings and structures at risk, but also affect persons in buildings (e.g. DIN 4150-2 1999). It is noted that this study only addresses the damage potential of dynamic roller compaction on buildings and structures.
Vibrations propagate through waves in the ground. Dynamic roller compaction is based on a near-surface dynamical excitation of the ground. Hence, the wave propagation is dominated by energy-rich surface waves, known as Rayleigh waves (Verruijt 2010). Their behaviour is similar to water waves.
Two other commonly known seismic wave types are compression waves (Primary waves or P-waves) and shear waves (Secondary waves or S-waves). Both types are body waves and of less importance for near-surface wave propagation.
The amplitude of the Rayleigh waves induced by dynamic roller compaction decreases with increasing distance from the vibration source (the roller) due to damping. The damping comprises the emission of energy through waves referred to as geometrically damping and material damping. The material damping is an energy loss due to hysteresis and inner rearrangement of soil particles. The inner rearrangement is dominant in the near-field where vibrations change the soil packing from loose to dense (basic principle of dynamic compaction). Material damping depends on many parameters such as soil density, moisture content, etc. While the material damping is almost independent of usual compaction frequencies, it is a function of the vibration amplitude (Studer et al. 2007).
Dynamic roller compaction is a periodic loading of soil causing plastic soil deformations in the near-field (compaction) and elastic wave propagation in the far-field (wave propagation in the ground).

2.2 Vibration immission on buildings and structures

Apart from the characteristics of the excitation (duration, frequency, magnitude, etc.) the immission on buildings highly depends on the type of structure, material properties, stiffening elements, inherent damping, natural frequencies and other building parameters.

According to Austrian Standard ÖNORM S 9020 and many other international standards vibration measurements have to be carried out where vibrations hit the structure, i.e. the foundations.
The representative parameter for the assessment of the damage potential of roller induced vibrations on buildings and structures is the peak velocity magnitude (ÖNORM S 9020 1986). The velocity, or acceleration respectively, is measured in three orthogonal directions denoted by x, y and z. The maximum of the peak velocity magnitude for a single event $v_{R,\max}$ is the square root of the sum of squares of the velocity components in x, y and z in millimetres per second [mm/s]:

$$v_{R,\max} = \left| \sqrt{v_x^2(t) + v_y^2(t) + v_z^2(t)} \right|_{\max} \tag{1}$$

In this definition t denotes the instant of time where the peak velocity magnitude $v_{R,\max}$ is at its maximum.
For an upfront estimation of the dynamic behaviour of a building the evaluation of the parameters in Tab. 1 is indispensable (Adam et al. 2011).

Table 1. Building parameters and their impact on the dynamic structural parameters (Adam et al. 2011).

Building parameter		Impact on dynamic structural parameter
Dimension:	Building dimension and number of floors	Natural frequencies of the structure
Foundation:	Strip foundation, foundation slab, deep foundation	Damping
Structural system:	Brick/concrete structure, structure of pre-fabricated segments, steel frame supporting structure, timber structure	Vibration behaviour
Slab structure:	Timber/lightweight structure of pre-fabricated segments or concrete structure, and span width	Natural frequencies of the slab, vibration behaviour
Construction history:	Construction year, rebuilding, damages due to war, etc.	Stability

Table 2. Building classes according to Austrian Standard ÖNORM S 9020.

Building class	Structure
I	Industrial structures • Frame structures (with or without core) of steel and/or reinforced concrete • Wall structures (concrete, pre-fabricated segments) • Engineering timber structures (e.g. halls)
II	Residential buildings • Frame structures (like I) • Wall structures (like I) • Structures with concrete slabs, walls made of concrete, brick, masonry with cement or lime mortar • Timber structures, except half-timbered buildings
III	Frame structures with less strength than structures of class I and II: Structures with basement slabs of concrete or brick arches and pre-fabricated parts, timber beam or pre-fabricated brick slabs in the upper floors Brick lined half-timbered buildings
IV	Listed buildings particularly sensitive to vibrations

In Tab. 1 the structural system is the most significant parameter. Thus the Austrian Standard ÖNORM S 9020 requires a classification of the monitored buildings according to Tab. 2. An individual classification for every single building is necessary, where the state of construction, the foundation, the age of the building and in particular existing structural damages that may affect the stability of the building have to be evaluated.
The Austrian Standard ÖNORM S 9020 specifies allowable peak velocity magnitudes $v_{R,\max}$ for each building class depending on the vibration source. Dynamic roller compaction work causes long-lasting temporary vibrations. Thus the values in the last column of Tab. 3 are allowable at the building foundation.

Table 3. Reference values for the allowable peak velocity magnitude $v_{R,\max}$ [mm/s] (measured at the foundation) according to Austrian Standard ÖNORM S 9020.

Building class	Allowable peak velocity magnitude max $v_{R,\max}$ [mm/s]		
	Infrequent blasting (weekly)[1]	Frequent blasting (daily)[2]	Long-lasting temporary vibrations[3]
I	30	24	12
II	20	16	8
III	10	8	4
IV	5	4	2

[1] according to ÖNORM S 9020, Table 3
[2] values according to ÖNORM S 9020, Table 3, reduced by 20% according to ÖNORM S 9020
[3] values according to ÖNORM S 9020, Table 3, reduced by 60% according to experience

Table 4. Reference values for the peak velocity v_i [mm/s] for the evaluation of the damage potential of temporary vibrations on buildings according to German Standard DIN 4150-3.

Line	Type of building	Reference values for the peak velocity v_i [mm/s]			
		Foundation Frequencies			Top level slab horizontal
		1 Hz to 10 Hz	10 Hz to 50 Hz	50 Hz to 100 Hz*)	all frequencies
1	Industrial buildings and buildings of similar structure	20	20 to 40	40 to 50	40
2	Residential buildings and buildings of similar structure or use	5	5 to 15	15 to 20	15
3	Buildings that are not according to Line 1 and Line 2, due to their vibration sensitivity or buildings of special interest (e.g. listed buildings)	3	3 to 8	8 to 10	8

*) For frequencies of more than 100 Hz the minimum reference values for 100 Hz have to be used

Contrary to the Austrian Standard the German Standard DIN 4150-3 defines the allowable velocities dependent on the excitations frequencies (see Tab. 4). Moreover, DIN 4150-3 refers to the maximum peak velocity v_i in one of the three orthogonal directions $i = x, y, z$ as the characteristic parameter for the evaluation and not the peak velocity magnitude as defined in the Austrian Standard ÖNORM S 9020. The relevant frequency range for dynamic roller compaction is 10 Hz to 50 Hz in the fourth column of Tab. 4 where the allowable velocity v_i ranges from 3 to 40 mm/s depending on

the building type. The German standard also provides allowable values for the peak velocities at the top level ceiling. Usually the frequencies of dynamic compaction are much higher than the natural frequencies of slabs and ceilings. Consequently, these values are of lower importance. It is noted that dynamic rollers still may affect adjacent building slabs and ceilings by exciting them with their natural frequency when powering up or shutting down the dynamic drum.

3 IN SITU TESTS WITH OSCILLATING AND VIBRATING DRUMS

In the following, results of large-scale in situ tests are presented. The tests were performed with a tandem roller equipped with an oscillating and a vibrating drum to evaluate the differences in the magnitude of ambient vibration, vibration propagation and damage potential of oscillating and vibrating drums.
Moreover, the influence of different excitation amplitudes, excitation frequencies and roller speeds during compaction passes were investigated.

3.1 Test-layout

The test area comprised four parallel test lanes of loose sandy gravel (to be compacted) with a length of 20 m and a thickness of 0.5 m (named Spur 1 to Spur 4 in Fig. 2). Two ramps served for the roller handling, acceleration and deceleration of the roller and lane changes. The subgrade consisted of a dense and highly compacted mix of sandy gravels.
A container was installed to coordinate the test runs, the variation of compaction parameters and the measurements.
Nine tri-axial accelerometers were positioned perpendicular to the direction of compaction in the centre axis of the test field on the subgrade (blue points in Fig. 2).
Three chronological synchronised "Brimos Wireless" units recorded three tri-axial accelerometer measurements each.

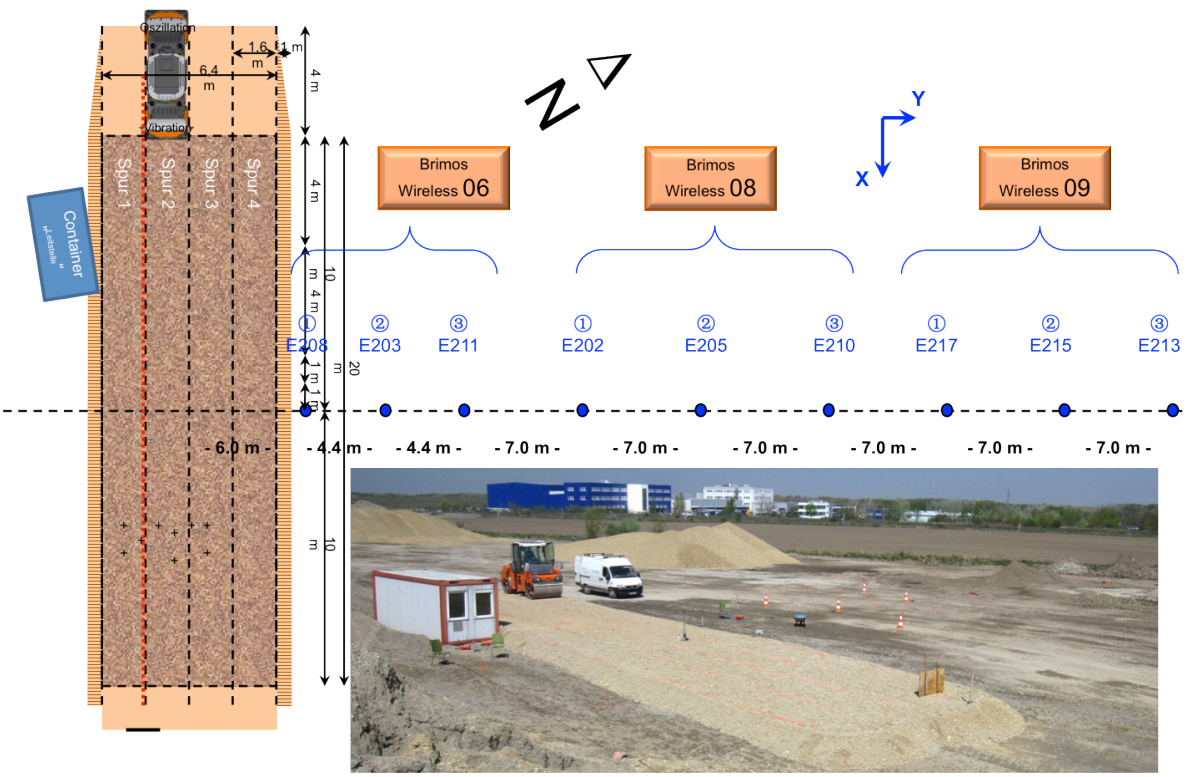

Figure 2. Layout for the experimental field tests.

3.2 Vibration source

A HAMM HD+90 VO tandem roller was used as vibration source. The roller comprises a total mass of 9380 kg and two drums of about 1900 kg each.
The typical speed of the roller during compaction is 4 km/h. Unless otherwise noted, all tests were performed with 4 km/h.
The drum on the rear of the roller is an oscillating drum that uses a fixed tangential amplitude of 1.44 mm. The standard frequency of oscillation is 39 Hz. Moreover, tests were also performed with 20 Hz, 50 Hz and 70 Hz respectively.
Depending on the rotational direction of the eccentric masses the vibratory drum on the front operates with a vertical amplitude of 0.34 mm or 0.62 mm respectively. For the smaller amplitude of 0.34 mm a frequency of 50 Hz was used, while 40 Hz is the standard frequency for compaction with the large amplitude.

3.3 Vibration emission

The ground surface accelerations were measured with 9 accelerometers in three orthogonal directions according to Fig. 2. The x-axis of the accelerometers was defined parallel to the direction of compaction, while the y-axis was defined perpendicular to the direction of compaction to measure the horizontal accelerations. The vertical accelerations were determined by the accelerometers in the z-axis.
The data of all accelerometers was recorded by 3 "Brimos Wireless" units and chronologically synchronised by GPS-timesync. The data processing was performed using MATLAB 2012a. The time-velocity signals were determined through integration of the acceleration signals and the peak velocity magnitudes $v_{R,\max}$ were calculated according to ÖNORM S 9020.

3.4 Selected results: magnitude of ambient vibration and vibration propagation

Subsequently, a double logarithmic scaling is used for depicting the propagation of vibrations for various compaction tests.

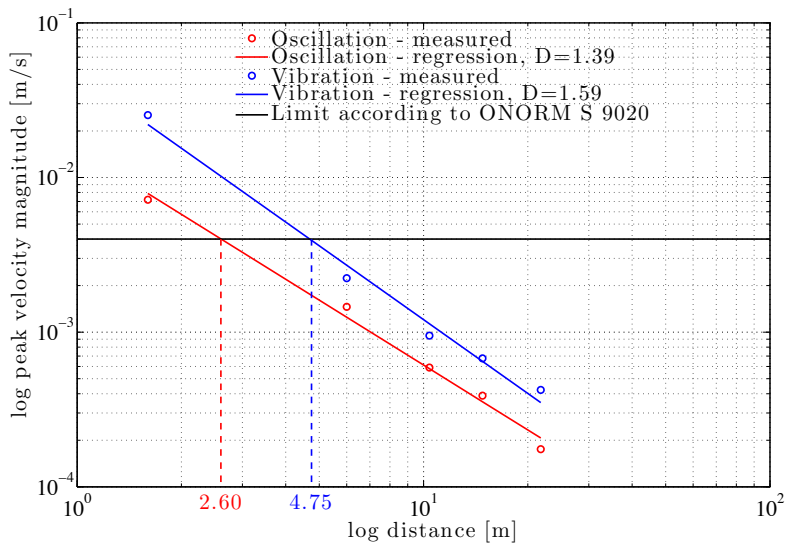

Figure 3. Peak velocity magnitudes $v_{R,\max}$ [m/s]: Comparison of an oscillation and a vibration test according ÖNORM S 9020.

In Fig. 3 peak velocity magnitudes $v_{R,\max}$ of an oscillation test (red) and a vibration test (blue) are compared. The peak velocity magnitude decreases almost linearly in a double logarithmic scale for both excitation methods. Therefore, the peak velocity magnitude in a distance r from the vibration source can be calculated regarding Eq. 2.

$$v_{(r)} = v_{(1)} \cdot r^{-D} \tag{2}$$

$v_{(1)}$ is the peak velocity magnitude in a distance of $r = 1\text{m}$ from the vibration source and D denotes the coefficient of decay. Peak velocity magnitudes are larger for vibratory compaction at all measured positions. However, the coefficient of decay is larger too ($D = 1.59$ vs. $D = 1.39$), resulting in a higher damping of wave propagation for vibratory drums. A reason for the higher damping of the vibrations caused by the vibrating drum might be the higher damping of vertical velocities which have a significantly larger share of the vectorial velocity in case of the vibrating drum.
The difference in absolute values does not seem to be too big in the double logarithmic scaled image. However, the difference becomes clearer when the measured velocities and distances are compared for an allowable peak velocity magnitude. Therefore, Fig. 3 shows the allowable peak velocity magnitude for building class III according to Austrian Standard ÖNORM S 9020 ($v_{R,\max} = 4\text{mm/s}$). To avoid structural damage, dynamic compaction work should not be carried out closer than 4.75 m to a sensitive building when a vibrating roller is used. The closest allowable distance of the roller to adjacent buildings is significantly smaller for oscillating rollers. The allowable distance decreases to 2.60 m in this case. Note, that this might be an important factor especially in sensitive areas like inner city construction sites.
In Fig. 4 the same oscillation and vibration tests are evaluated according to DIN 4150-3. Only the maximum peak velocity amplitude v_i of the three orthogonal axes x, y, z is used to assess the damage potential of dynamic excitation. Therefore, absolute values are smaller in Fig. 4 than in the corresponding evaluation according to ÖNORM S 9020. The vertical component of velocity dominates in the near-field of the vibration source while one of the horizontal velocity components becomes authoritative in the far-field. Thus, the decay is larger for both kinds of excitation in Fig. 4. Tolerable minimum distances are evaluated for an allowable peak velocity range of $v_i = 3 \div 8\text{mm/s}$ (according to Line 3 in Tab. 4 for excitations of 10 to 50 Hz). Hence, only one velocity component of each accelerometer is taken into account, minimum distances are smaller according to the DIN 4150-3 than the distances derived from the Austrian standard.

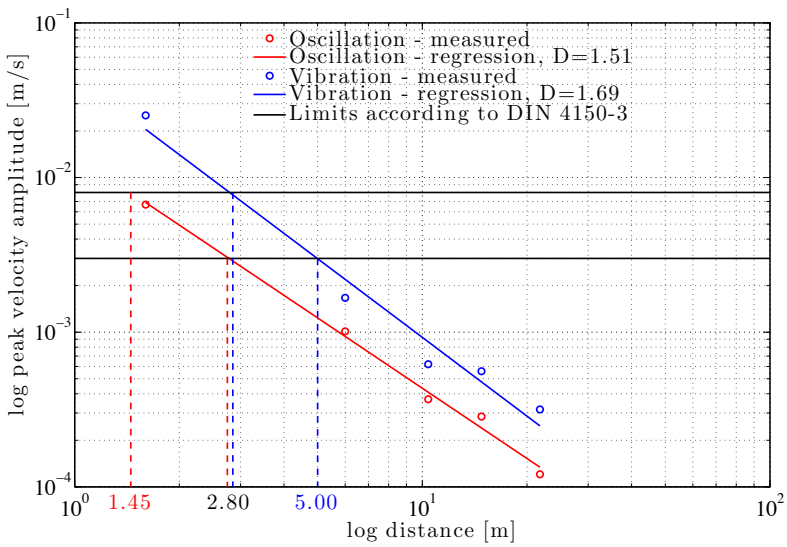

Figure 4. Peak velocities v_i [m/s]: Comparison of an oscillation and a vibration test according DIN 4150-3.

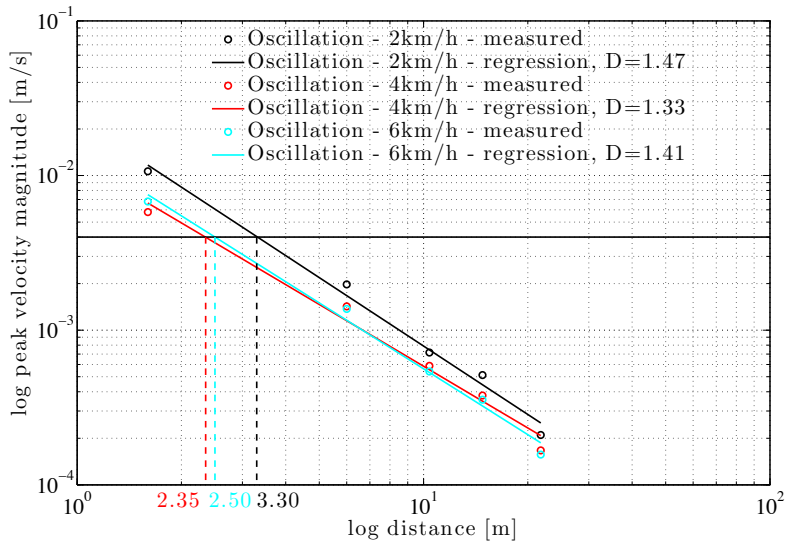

Figure 5. Peak velocity magnitudes $v_{R,\max}$ [m/s] of oscillation tests: Influence of compaction speed.

For the oscillating excitation the minimum distance between roller and foundation of the sensitive structure is 1.45 to 2.80 m, while the minimum distance increases for vibratory drums to a range from 2.80 to 5.00 m.

The influence of roller speed for oscillation tests is depicted in Fig 5. Aside from the standard compaction speed of 4 km/h tests were also performed with speeds of 2 km/h and 6 km/h, respectively. While velocities and vibration propagation are almost equal for the 4 km/h and 6 km/h tests, the decrease of roller speed to 2 km/h results in slightly higher velocities in the near-field and in the far-field of the compacted track. For an allowable peak velocity magnitude of $v_{R,\max} = 4\text{mm/s}$ the minimum allowable distance increases from about 2.4 m to 3.3 m.

A comparison of various frequencies of oscillation excitation is given in Fig. 6. An oscillation frequency of 20 Hz causes least ambient vibrations.

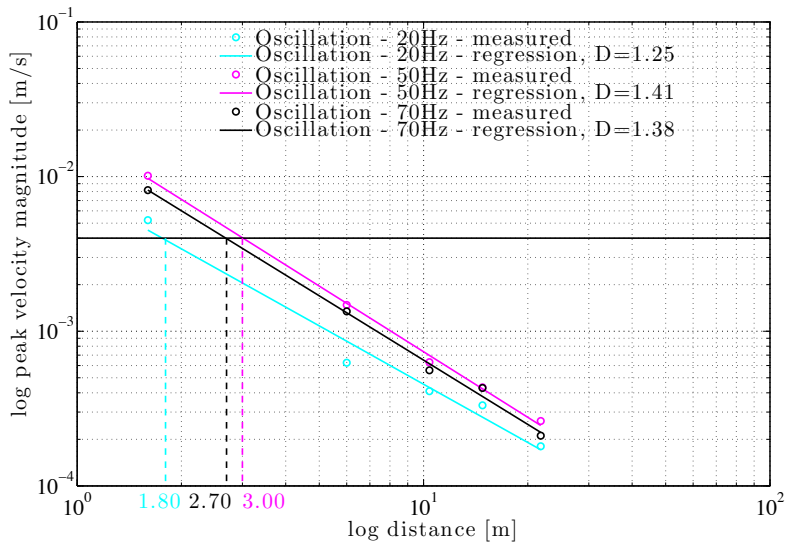

Figure 6. Peak velocity magnitudes $v_{R,\max}$ [m/s] of oscillation tests: Influence of excitation frequency.

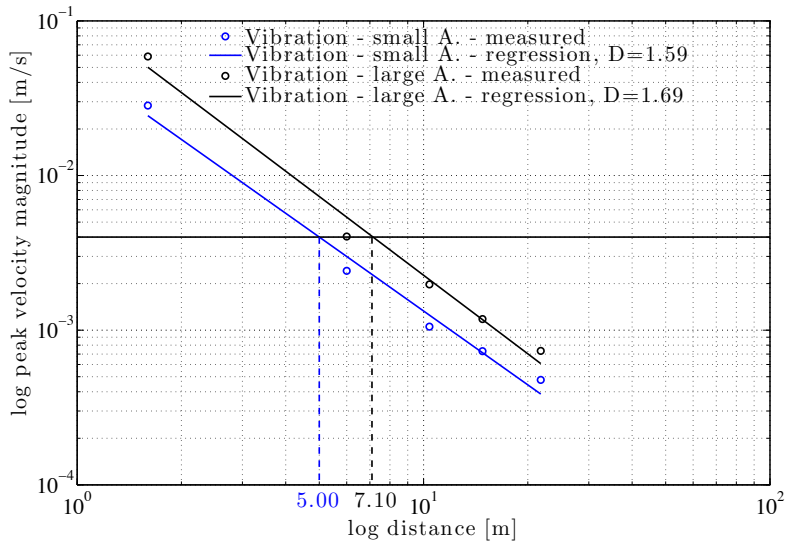

Figure 7. Peak velocity magnitudes $v_{R,\max}$ [m/s] of vibration tests: Influence of excitation amplitude.

In comparison with an excitation of 20 Hz the minimum distance between roller and adjacent buildings yields to 0.9 m and 1.2 m for 70 Hz and 50 Hz, respectively. Note, that the measured velocities are larger for 50 Hz. Obviously, one of the natural frequencies seems to be close to 50 Hz resulting in such high values. However, dynamic compaction work is highly efficient when the excitation frequency is close to the natural frequency of the soil to be compacted.
In Fig. 7 a second parameter set for compaction with the vibrating drum (large amplitude and 40 Hz) is compared to the standard parameters of vibratory compaction (small amplitude and 50 Hz). The larger amplitude causes significantly higher ambient vibrations. The minimum distance between vibration source and sensitive structure increases by 2.1 m for the given example for building class III of the Austrian Standard ÖNORM S 9020.

4 CONCLUSIONS

In this paper the magnitude of ambient vibrations and the vibration propagation were evaluated for dynamic roller compaction. The approaches of the German Standard DIN 4150-3 and the Austrian Standard ÖNORM S 9020 for the assessment of the damage potential of dynamic roller compaction were compared and discussed.
Large in situ tests with a tandem roller consisting of an oscillating and a vibrating drum were performed to evaluate the influence of different excitation types and machine parameters on the ambient vibrations and the damage potential.
The vibration propagation is very similar for all tested configurations with a linear decrease of the peak velocity magnitude (as in Eq. 2) in a double logarithmic scale. The coefficient of decay varies between 1.25 and 1.69.
The type of excitation has the biggest influence on the magnitude of ambient vibrations. The minimum distance between roller and sensitive structure for a vibratory drum is almost the double compared to the distance for an oscillating drum of same size and weight. Note that the compaction depth of vibratory drums is larger as well.
Velocities of the same order were measured for roller speeds of 4 km/h and 6 km/h. Tests with 2 km/h resulted in slightly larger vibrations.
For the oscillating drum largest velocities were measured for an excitation frequency of 50 Hz obviously close to the natural frequency of the soil, while ambient vibrations are smaller for 20 Hz and

70 Hz. However, dynamic compaction is highly efficient with excitation frequencies close to the natural frequency of the soil to be compacted.
The vibratory drum offers a large amplitude for compaction in larger depths. Tests with the larger amplitude showed significantly higher velocities at all measured positions.
According to the results of this study oscillating drums reduce ambient vibrations significantly and are recommended for compaction in sensitive areas like inner city construction sites or on and near bridges.

REFERENCES

Adam, D., Adam, C., Falkner, F.-J. and Paulmichl, I. (2011). Vibration emission induced by Rapid Impact Compaction. In: De Roeck, G., Degrande, G., Lombaert, G. and Müller, G. (eds), *Proceedings of the 8th International Conference on Structural Dynamics (EURODYN 2011);* July 4-6, 2011, Leuven, Belgium. 914-921.

DIN 4150-1. (2001). *Vibrations in buildings - Part 1: Prediction of vibration parameters* (in German).

DIN 4150-2. (1999). *Vibrations in buildings - Part 2: Effects on persons in buildings* (in German).

DIN 4150-3. (1999). *Vibrations in buildings - Part 3: Effects on structures* (in German).

ÖNORM S 9020. (1986). *Building vibrations; blasting vibrations and comparable immissions of impulse shape* (in German).

SN 640 312 a. (1992). *Vibration-effects on buildings* (in German and French).

Studer, J., Laue, J. and Koller, M.G. (2007). *Bodendynamik. Grundlagen, Kennziffern, Probleme und Lösungsansätze.* Springer Berlin Heidelberg New York.

Verruijt, A. (2010). *An introduction to soil dynamics*. Springer, Dordrecht.