

# Movement of vibrating and oscillating drums and its influence on soil compaction

## Mouvements vibratoires et oscillatoires d'un rouleau et son influence sur le compactage du sol

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**ABSTRACT** Dynamic roller compaction has become the common method for near-surface compaction, because dynamic rollers are much more efficient compared to static rollers. Two types of excitation are mainly used for dynamic roller compaction, the vibratory and the oscillatory roller. In the presented study the differences in functioning, mode of operation and loading the soil are outlined for the two types of excitation. First results of large-scale in-situ tests are presented in which the vertical earth pressure and tri-axial accelerations have been measured. Moreover a new indicator for the evaluation of the slip between the surface of an oscillatory drum and soil is presented.

**RÉSUMÉ** La méthode du rouleau compacteur dynamique est devenue une des méthodes communes du compactage à proximité de la surface, parce que le rouleau compacteur dynamique est plus efficace que le rouleau compacteur statique. Il existe deux types d'excitations pour le rouleau compacteur dynamique principalement utilisés, le rouleau vibratoire et le rouleau oscillatoire. L'étude, qui est présentée décrit les différences de fonctionnements, d'opérations et de chargements du sol pour les deux types d'excitations. Les premiers résultats des tests in situ à grande échelle sont présentés, dans lesquels la pression verticale du sol et l'accélération triaxiale ont été mesurées. En outre un nouvel indicateur d'évaluation du glissement de la surface d'un rouleau oscillatoire et du sol est présenté.

## 1 INTRODUCTION

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 for near-surface compaction, since they are much more efficient compared to static rollers.

There are various types for the excitation of a dynamic drum, which not only differ in their structure but also in their mode of operation. The most popular dynamically excited drum is the vibratory drum followed by the oscillatory drum. While the vibratory drum is capable of compacting in larger depths, the oscillatory drum reduces ambient vibrations significantly and is therefore used in sensitive areas like inner city construction sites.

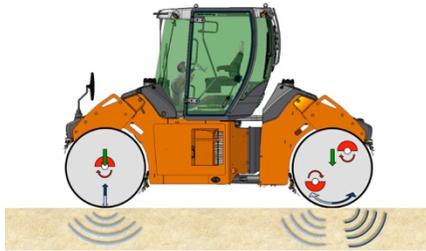
In the presented study the characteristics of the drum movement and their effects on the roller-soil interaction and compaction of an oscillatory drum are investigated and compared to those of a vibratory drum.

### 1.1 *Vibration vs. Oscillation*

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.

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 and statically loaded by the dead weight of the drum and roller in vertical direction (see Figure 1). Mainly tangential forces are transmitted in the

soil by shear waves, the volume decreases while the stiffness increases.



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

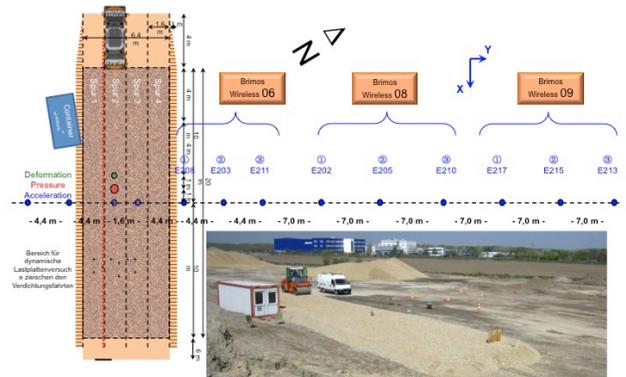
## 2 IN-SITU TESTS WITH A TANDEM ROLLER

### 2.1 Test area, test layout and measuring technique

A test area was prepared and equipped in a gravel pit near Vienna for the large-scale in-situ tests. 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 Figure 2). The lanes of the test area were filled on the plane of the gravel pit, which was already highly compacted by the site traffic. Usually the thickness of the compacted layer would range from 15 to 20 cm but was chosen larger to be able to run more tests without over-compacting the layer. The four lanes were intended for static, vibratory, oscillatory and combined vibratory and oscillatory compaction. Two ramps at the beginning and at the end of the test lanes served for roller handling, speeding up and down the roller as well as for lane changes.

Two tri-axial accelerometers were buried in the test field by installing them on lanes 2 and 3 before filling the test area. Moreover test lane 2 was equipped with an earth pressure cell to measure the vertical earth pressure under the static and dynamic loading of the roller in a depth of 0.5 m.

Numerous tri-axial accelerometers were positioned along a line perpendicular to the direction of compaction in the centre of the test area on the highly compacted subgrade to measure the propagation of ambient vibrations.



**Figure 2.** Test layout of the experimental field tests.

### 2.2 Compaction device

A HAMM HD+90 VO tandem roller was used as compaction device. The roller comprises a total mass of 9380 kg and two drums of about 1900 kg vibrating mass each. The typical speed of the roller during compaction is 4 km/h.

Depending on the rotational direction of the eccentric masses the vibratory drum on the front operates with 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.

The drum on the rear of the roller is an oscillatory drum that uses tangential amplitude of 1.44 mm. The standard frequency of oscillation is 39 Hz.

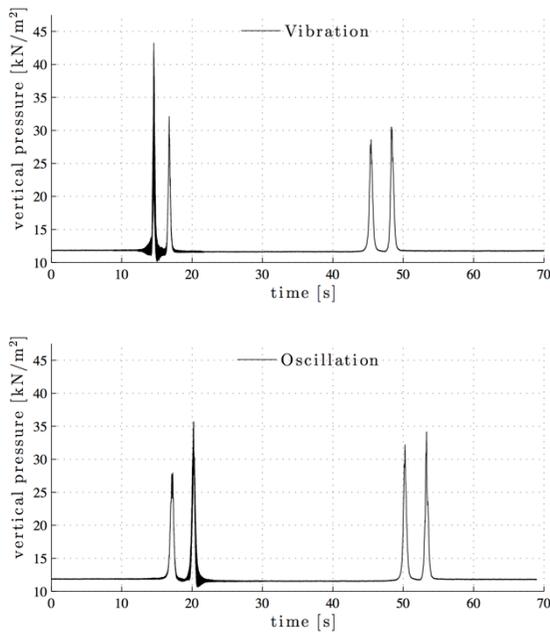
## 3 FIRST RESULTS OF THE EXPERIMENTAL FIELD TESTS

Subsequently first results of the experimental field tests are presented, which primarily focus on the differences between the vibratory and the oscillatory drum. Unless otherwise noted, the parameters for the small vibration amplitude were used for the vibratory drum. Each test run comprised a forward motion with one dynamically excited drum (vibration or oscillation) and a static backward motion.

### 3.1 Vertical earth pressure

The vertical earth pressure was measured between the level of the highly compacted subgrade and the compacted layer of loose sandy gravels and therefore in a depth of 0.5 m beneath the roller. Figure 3 shows the vertical earth pressure for two test runs. At the top the measured pressure over time for a test run with an active vibratory drum is depicted. The vibrating drum is clearly visible as significant first peak, which is followed by a smaller peak caused by the inactive oscillatory drum. The roller stops at the end of the test lane (after around 32 seconds) and moves backwards without any excitation of the drums (two smaller peaks at 46 and 49 seconds in Figure 3).

The measured earth pressure is very similar for the oscillatory test run (Figure 3 bottom) with a significant second peak caused by the dynamically excited oscillatory drum.

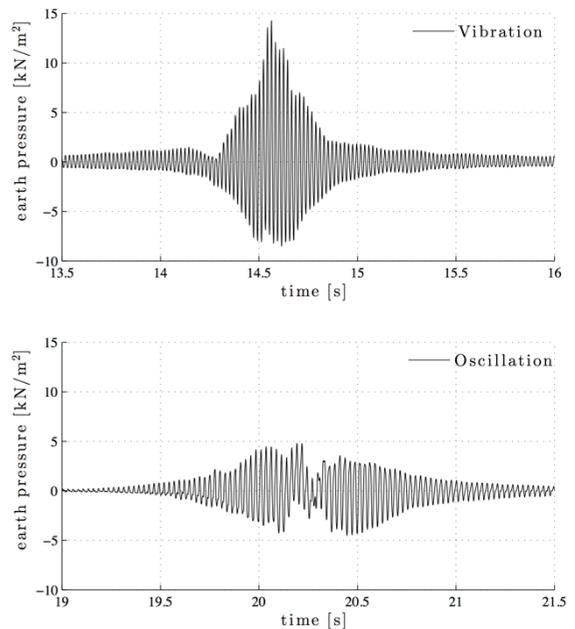


**Figure 3.** Vertical earth pressure: vibratory test run (top), oscillatory test run (bottom).

To point out the differences between the two types of excitation, the dynamic part of the vertical earth pressure for the vibratory and oscillatory test run is depicted in Figure 4. The static part of the vertical earth pressure is filtered for this comparison. Both

curves oscillate around zero and show the frequency of excitation.

In contrast to the earth pressure progression of the vibratory test run with its maximum at the passing time of the drum, the curve of the oscillatory test shows a node at the same time. The maximum values were measured shortly before and after the node, while the phase changes in the node. The fast forward-backward-rotation of the oscillatory excitation forces the drum to move forward and backward in its self-produced settlement depression. In each period of the oscillatory movement the drum rolls onto the bow wave in front of the drum and causes a vertical pressure component. This vertical component increases as the drum approaches the pressure cell, but decreases to a node in the pressure curve when the drum is situated exactly above the pressure cell. A similar behaviour as for the approach can be observed when the drum moves away from the pressure cell. However, with a phase change and caused by the rear wave.

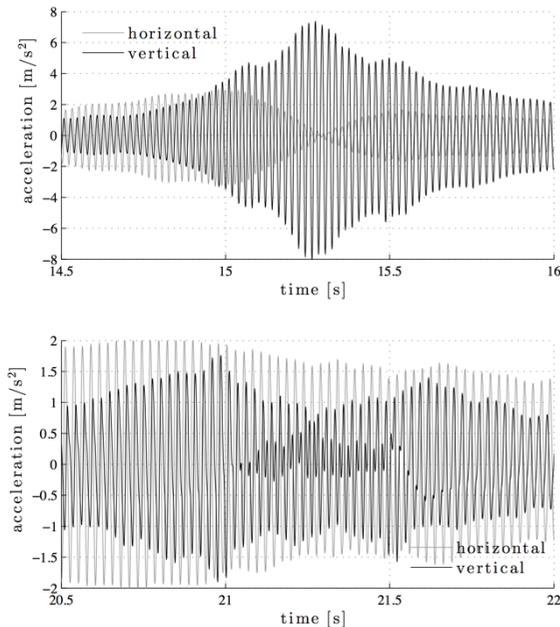


**Figure 4.** Dynamic part of the vertical earth pressure: vibratory test run (top), oscillatory test run (bottom).

### 3.2 Soil accelerations

The soil accelerations were measured in three axes as described in section 2.1. The horizontal accelerations in Figure 5 correspond to the accelerations measured in the direction of compaction (“x” in Figure 2). The horizontal accelerations perpendicular to the direction of compaction (“y” in Figure 2) are not depicted. The positive sign is defined downwards.

The comparison of accelerations of both types of excitation in Figure 5 shows higher values in vertical direction for the vibratory drum. The reasons for that are the type of excitation and the periods when the tests were performed. The vibratory test run was performed subsequently when the layer of sandy gravel was already compacted and therefore showed a stiffer reaction. For the vibratory drum the direction of dynamic loading matches the direction of the measured vertical accelerations, resulting in larger values in vertical direction. The vertical acceleration is a maximum when the drum is exactly above the accelerometer, while the horizontal component of the soil acceleration shows a node and a phase change at the same time. The dominant frequency of both components is the frequency of excitation (50 Hz).



**Figure 5.** Soil accelerations: vibratory test run (top), oscillatory test run (bottom).

The fast forward-backward-rotation of the oscillating drum causes mainly horizontal accelerations in the direction of compaction (Figure 5 bottom). The horizontal accelerations with almost constant amplitude show the excitation frequency. The vertical accelerations show a different behaviour. A continuous phase change can be observed as the oscillatory drum passes the accelerometer. The curve of the horizontal acceleration shows the formation of a secondary vibration as the drum approaches the sensor, which increases until the frequency of the vertical acceleration is twice the frequency of the horizontal acceleration or the excitation acceleration respectively. The secondary vibration decreases and disappears after the drum pass and the vertical and horizontal accelerations show the same dominant frequency again, however, with a reversed phase of the vertical accelerations. The explanation for the observed phenomena is the settlement depression under the oscillatory drum and the formation of bow wave and rear wave. One forward-backward-rotation corresponds to one period of horizontal movement and acceleration. Because of the upward movement of the drum onto the bow wave during the forwards motion and the upwards movement onto the rear wave during the backward motion, two periods in vertical direction occur during the same time of one period in horizontal direction. Hence, the vertical acceleration shows a double frequency of the horizontal acceleration.

## 4 MODES OF OPERATION

### 4.1 Vibrating rollers

Different modes of vibratory roller operation were first investigated by (Adam 1996). The observed modes depend on the vibration amplitude, frequency, roller speed and soil stiffness (Figure 6) and significantly influence the compaction process itself but also the lifetime of the roller.

### 4.2 Oscillating rollers

Depending on the friction coefficient between drum and soil, soil stiffness and roller parameters (Kopf 1999) identified similar modes of operation for oscillatory rollers, namely adhesion, one-sided slip and asymmetric slip/symmetric slip, which also were ob-

served during the author’s field tests and visualized by high speed cameras.

The static friction is not exceeded in the operation mode adhesion.

Due to the superposition of oscillatory excitation and roller travel, the static friction might be exceeded one-sided, resulting in one-sided slip.

The operation mode changes from one-sided slip to asymmetric slip and finally symmetric slip with increasing soil stiffness.

Depending on the soil conditions and compaction parameters a maximum compaction will be achieved after a certain amount of roller passes. The amount of slipping during one oscillation period increases until the state of maximum compaction (with the used compaction device) is reached and remains more or less constant from that point on. If the roller operator does not stop the work at this point the occurring slip between the roller drum and the soil increases the wear of the drum significantly, resulting in shorter lifetimes and higher costs. Therefore, the detection of slip and its ratio is of great interest for the optimization of the oscillatory compaction process and the minimization of the wear of the drum. An algorithm for monitoring and evaluating the oscillatory drum slip was developed and is presented in the following.

drum motion	interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed
periodic	continuous contact	CONT. CONTACT		yes	low	fast
	periodic loss of contact	PARTIAL UPLIFT		yes	↓	↑
		DOUBLE JUMP		yes		
		ROCKING MOTION		no		
chaotic	non-periodic loss of contact	CHAOTIC MOTION		no	high	slow

Figure 6. Modes of vibratory roller operation (Adam 1996).

## 5 SLIP INDICATOR FOR OSCILLATING ROLLERS

### 5.1 Theory and basic principle

The basic principle for the evaluation of the drum slip is based on the processing of the horizontal accelerations in the centre of the oscillating drum.

A perfect oscillatory motion does not cause any vertical or horizontal forces or accelerations in the

centre of the drum (e.g. gained with an uplifted well-balanced drum). The centre of rotation does not match the centre of the drum, as soon as the oscillating drum gets in contact with the soil; horizontal accelerations arise in the centre of the drum. The measurements show a sinusoidal curve with the frequency of the excitation in case of weak soils and a high friction coefficient between the drum and the soil. The Fast-Fourier-Transformation (FFT) of an ideal measurement curve has only one peak at the excitation frequency (Figure 7).

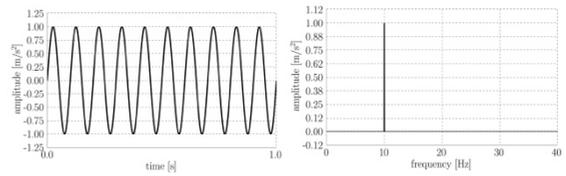


Figure 7. Signal of a sine in time domain (left) and frequency domain (right).

As the soil gets stiffer during compaction, the static friction is exceeded and the drum slips periodically on the surface of the soil, intermitted by phases of adhesive contact. The horizontal accelerations do not increase any further as soon as the static friction is exceeded, but remain constant. The idealized measurement curve then shows a capped sine with peaks at the excitation frequency  $f$  and its odd multiples  $3f$ ,  $5f$ , etc. in the FFT spectrum (Figure 8). The ratio of the FFT at the excitation frequency decreases the more the slip between drum and soil and the more the sine is capped, while the ratios of the higher frequencies increase.

Consequently, these characteristics can be used to indicate the operation mode of an oscillatory drum forming the basis of the so called slip indicator.

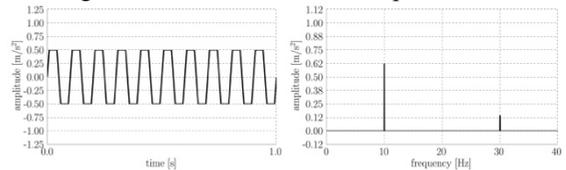
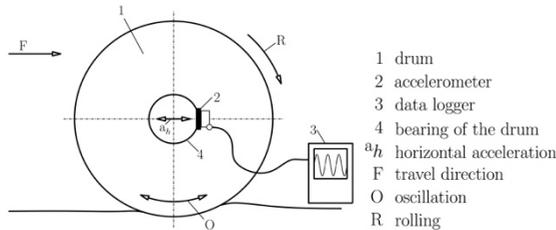


Figure 8. Signal of a symmetrically capped sine in time domain (left) and frequency domain (right).

## 5.2 Measurement and signal processing

The horizontal accelerations are measured on the bearing of the drum and recorded (Figure 9). The sampling rate of the recording is recommended to be at least ten times larger than the oscillation frequency.

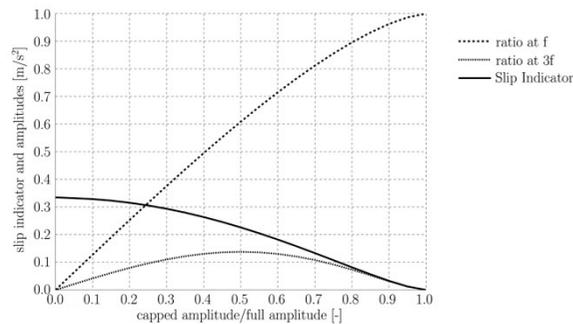


**Figure 9.** Measuring principle of the horizontal accelerations in the center of the oscillatory drum.

The recorded signal is evaluated in sections. Due to the FFT in the signal processing a time frame of  $2^n$  samples is assessed. The ratios of the FFT at the excitation frequency  $f$  and the first odd multiple  $3f$  are evaluated for each time frame. The slip indicator ( $SI$ ) can then be written as:

$$SI = \frac{A(3f)}{A(f)}$$

The evolution of the slip indicator is depicted in Figure 10. The ratio at  $f$  for a perfect sine is 100%, while the ratio at  $3f$  and the slip indicator are zero (right hand side in Figure 10). The slip indicator increases as the relation of capped and full amplitude decreases (from right to left in Figure 10).



**Figure 10.** Evolution of the slip indicator in dependence of the relation of capped and full amplitude.

The presented slip indicator is a suitable tool to estimate the slip between the drum of an oscillating roller and the ground surface. However, it is noted that a measured slip does not necessarily cause and increased wear of the drum. The magnitude of strains on the drum surface in the contact area between drum and soil has to be taken into account as well. Only in the case that shear stresses on the drum surface occur in combination with large slip values at the same instant a significantly higher wear of the drum surface appears.

## 6 CONCLUSION

In the presented study two types of excitation for dynamic rollers were compared, in particular vibratory and oscillatory drums. First results of large-scale in-situ tests were provided to outline their differences in functioning, mode of operation and loading the soil. Moreover, a new indicator for the evaluation of the operation modes of an oscillatory drum was introduced to distinguish slip from adhesive contact between the surface of an oscillatory drum and the soil.

## ACKNOWLEDGEMENT

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