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MODELLING AND SIMULATION OF HEAVY TAMPING DYNAMIC RESPONSE OF THE GROUND

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ABSTRACT: Heavy tamping is a deep dynamic compaction technique and has been increasingly used since beginning of the Seventies. The paper reports on in situ measurements and theoretical investigations referring to the decay of free soil vibrations caused by the falling weight after each impact. This behaviour is significant for the respective soil falling mass interaction and enables a site-specific optimisation of the heavy tamping technique. The field tests comprised acceleration measurements of the falling mass and the soil whereby the falling height was changed repeatedly. The decay of the amplitudes of free vibrations provided a damping coefficient and a damped natural frequency, which are used to determine the Poisson's ratio and the E-modulus of the ground after each impact from numerical calculations. Scope of the research project was to gain a reliable indicator for the degree of compaction of the soil immediately after each impact, hence a method for compaction control and documentation.

1. Introduction

Near surface soil compaction is usually performed by static and/or dynamic rollers comprising different kinds of exciters and drum shapes. Depending on the soil type and roller parameters for example: dead weight; static line load of the drum; drum amplitude; excitation frequency; roller speed; etc., the maximum compaction depth varies from about 0.15 m to 2.0 m. Thus, for soil improvement the depth is limited to relatively low values.

The success of dynamic roller compaction can be controlled by measuring the motion behaviour of the drum interacting with the ground during the compaction process. These so called "Continuous Compaction Control (CCC)" has proven to be an excellent technique to control, check, and documentation of the compaction over the processed area achieved by rollers (Adam, 1996, Brandl & Adam, 1997).

Deep compaction is a type of soil improvement whereby vibroflotation (displacement and replacement), heavy tamping and deep blasting techniques have proved especially successful. These methods usually reach to a depth of about 10 to 20 m, depending on ground properties, compaction equipment and input of compaction energy. With the "giga-machine" for heavy tamping (falling weight up to 200 tonnes, falling height up to 40 m) ground can be improved to a depth of up to 40 m, and the hitherto maximum vibroflotation depth is 60 m. Deep compaction techniques are used to improve natural soils and manmade fills, e.g. land reclaiming. For an intensive, deep-reaching compaction of old (municipal) landfills, heavy tamping is primarily useful. Vibroflotation producing granular columns or waste columns can also be applied (Brandl, 1997).

Experience and site observations have shown that deep dynamic compaction reduces settlements, accelerates the consolidation process, raises the bearing capacity of the ground, and increases significantly the liquefaction stability and earthquake resistance of soils and manmade fill. This is because dynamic loading and vibration induced particle re-arrangement of the ground to a high extent. Structures on improved soil showed significantly less earthquake damages than nearby buildings founded on ground without deep dynamic soil compaction. This could also be observed for shallow and deep foundations.

For vibroflotation technique on-line control systems are available measuring the maximum power consumption of the vibrator and its time history during the compaction process. An innovative approach takes into account the dynamic interaction between the vibrator and the soil and provides the spring stiffness of the soil and the damping coefficient. Unfortunately, only a prototype has been manufactured to date (Fellin, 2000).

So far, no on-line control system has been developed for heavy tamping compaction technique. In the following a new and innovative approach is presented, which has been based on both theoretical considerations and experimental investigations.

2. Heavy Tamping – Technology and Parameters

Deep dynamic compaction by heavy tamping, has been applied in Austria and Germany since the 1930s, but was initially limited to weights of about 10 tonnes and falling heights of about 10 m. Significant development started in the early 1970s with 20 to 25 tonnes dropping from heights up to 22.5 m, thus improving soft soils and peat for a highway junction in Austria (Brandl & Sadgorski, 1977). Meanwhile a great variety of crawler cranes, tripods, giga-machines, etc. has been used (Fig. 1), and heavy tamping may be modified in order to produce stone columns comprising a diameter of up to 2 – 4 m diameter.

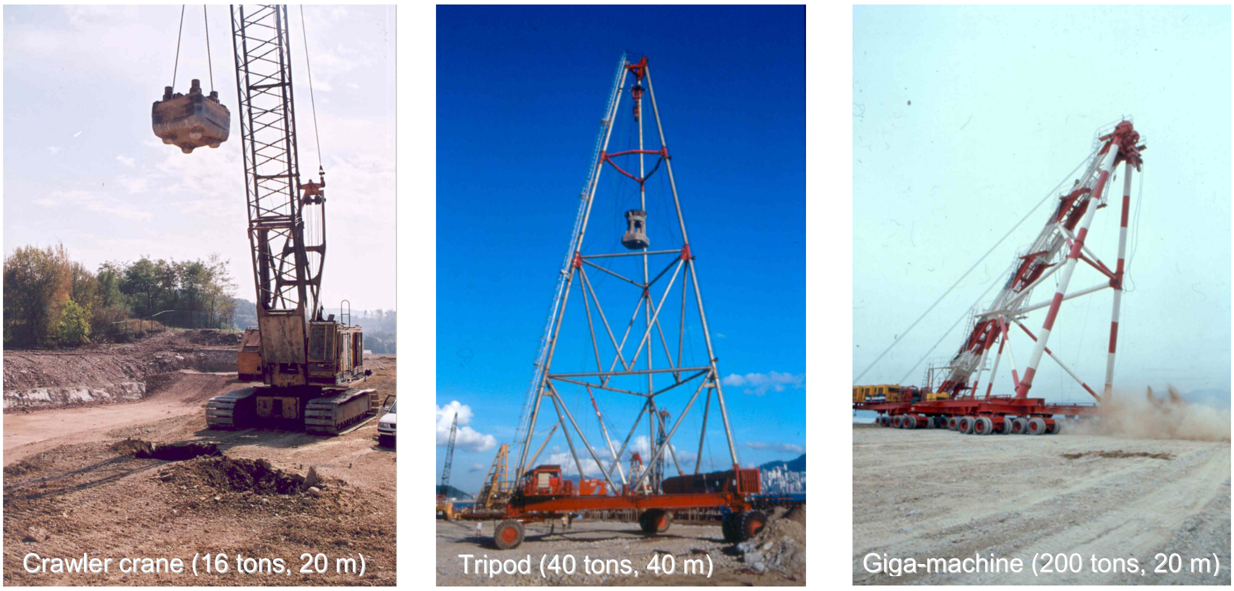


Fig. 1: Different equipment for heavy tamping.

Heavy tamping has been used for almost all soil types, even for wastes and under water. It produces temporary soil liquefaction and anticipates particle re-arrangement due to dynamic loading, and is therefore very suitable for ground improvement in seismic zones. Field observations showed that soils exhibit a substantially higher earth resistance after deep dynamic compaction/consolidation (heavy tamping) (Brandl & Sadgorski, 1977).

For design and compaction optimisation and control the following in-situ tests are commonly used in addition to conventional ground investigation:

Pressuremeter tests;

- Standard penetration tests (SPT) tests and other sounding methods;
- Measurement of pore water pressure;
- Measurement of settlement (average values or depth of compaction points, i.e. the holes created by the impacts);

- Spectral analysis surface wave method (SASW) or continuous surface wave technique (CSW). CSW has a deep-reaching capacity that makes a post-control of deep ground improvement or of a thick package of fill layers possible;
- Measurements of vibrations.

Fig. 2: Different falling weights (pounders) for heavy tamping.
Left: Steel pounder, middle: Concrete pounder, right: Flat steel pounder.

These tests are required for quality assurance, and they should be performed and interpreted in relation with the compaction energy (falling height, pounder weight, number of drops and passes); even the shape of the falling weight has a strong influence on the results (Fig. 2). E.g. flat weights of rather small mass are preferred for surface-near, “smoothing” (also called “ironing”) compaction, whereas heavy weights comprising a small cross section achieve a large depth of spot compaction.

The following construction parameters have a significant influence on compaction optimisation and propagation of vibrations:

- Mass and shape of falling weight (pounder);
- Falling height;
- Spacing and layout of the grid for compaction spots;
- Number of impacts per compaction point and number of passes (a pass usually compromises three to ten impacts);
- Sequence of compaction points with regard to geometry and time.
- In fine grained soil the following effects play an important role:
  - Temporary liquefaction during the impact and local disturbance of soil structure;
  - Compressibility of the material (depend on micro pores), especially in soft soils with organic components;
  - Increased permeability through created fissures by impacts;
  - Thixotropic recovery.

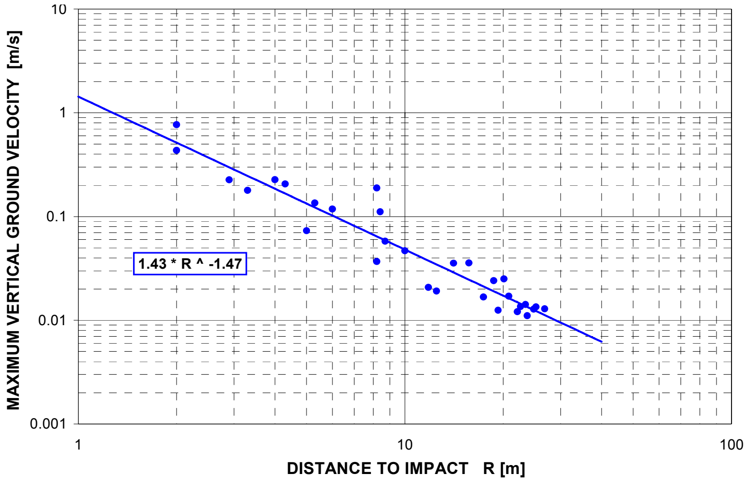


Fig. 3: Maximum vertical ground velocity versus distance to the compaction point (impact centre). Heavy tamping on soft waste material from ceramics and gypsum industry. Pounder of 16.5 tonnes from 15 m height.

Fig 4: Sensor for ground acceleration placed on a steel rod driven in the soil.

3. Measurements and analytical analysis of a single degree of freedom (SDOF) system

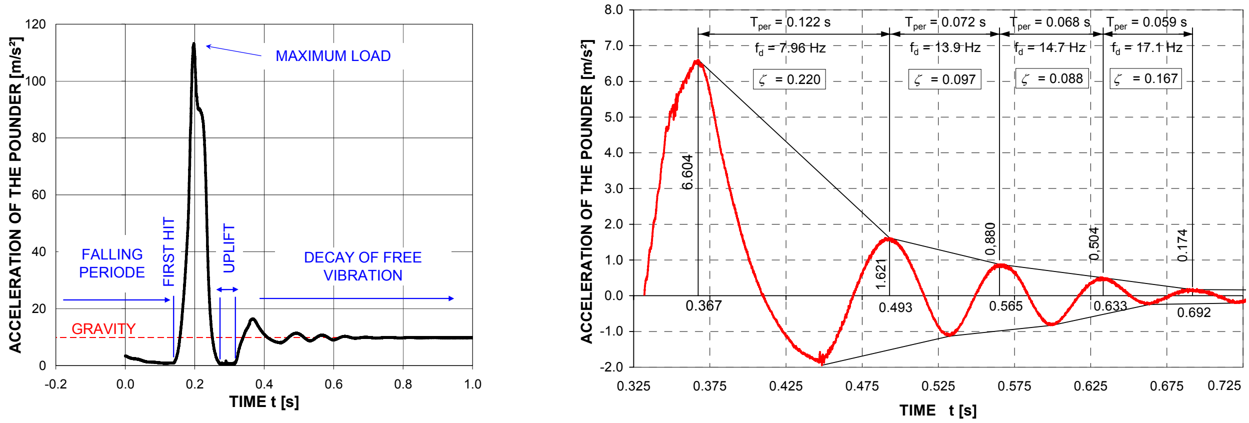
Due to the complex interaction of numerous influence factors recent research has been focused on the development of a process-integrated method that allows a continuous optimisation, control and documentation of the compaction. This novel system should represent an analogy to the roller-integrated continuous compaction control (Adam, 1996, Brandl & Adam 1997). Similar research has been performed for deep soil improvement by vibroflotation by using the vibrator also as measuring element. The basic idea of all these methods is to register the interactions between the compacting equipment and the soil that has to be compacted.

Hitherto, measurements of ground vibrations have been carried out in order to gain information on dynamic effects on sensitive structures and buildings from wave propagation caused by heavy tamping. Figure 3 shows a typical diagram illustrating the rapid decrease of maximum ground velocity with distance to the impact centre of a falling weight. Such correlations are especially important if heavy tamping is performed close to existing buildings, pipelines, etc., but they give no relevant information about the degree of compaction.

This can be achieved by measuring the acceleration of the falling weight, because this is proportional to the reaction forces of the ground. But these reaction forces include: soil compaction; replacement; liquefaction; excessive pore water pressures; local ground failure; plastic and elastic deformations, etc. Consequently, the reaction force is hardly suitable as a clear characteristic value required for a reliable compaction control. Contrary to that, the decay of free soil vibrations caused by the falling weight after each impact is characteristic of the soil – falling weight interaction and enables a site specific optimisation and quality control of heavy tamping (Fig. 5).

The basic ideas of this novel concept are as follows (Kopf & Paulmichl, 2004):

- Assuming an elastic decay of free soil vibrations under still increased pore water pressures represents an allowable theoretical approximation that can be solved similar to a viscously damped single degree of freedom (SDOF) system (Adam, 2003).
- Consequently, measuring the acceleration of the falling weight during the decay of free soil vibrations provides the damped frequency ω_d and Lehr's damping coefficient ζ, if a viscously damped single degree of freedom (SDOF) system is assumed. The undamped natural circular frequency ω is calculated as shown in Figure 6.



(a) (b)

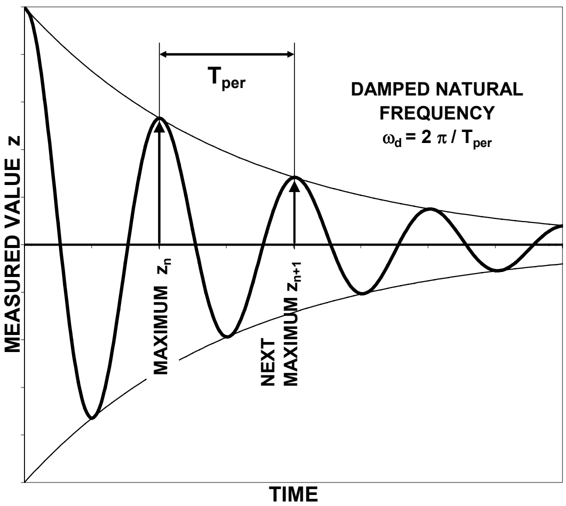
Fig. 5: (a) Acceleration of the pounder (diameter = 1.8 m, mass = 16.5 tonnes) after hitting untreated soil from a drop height of 1 m.
(b) Detail of figure (a): Decay of free soil vibrations. Dynamic parameters for an idealized viscously damped single degree of freedom (SDOF) system: T_{per} = periodic time, s; $f_d = \omega_d / 2\pi$ = damped natural frequency, Hz; ζ = viscous damping coefficient.

4. Numerical simulations

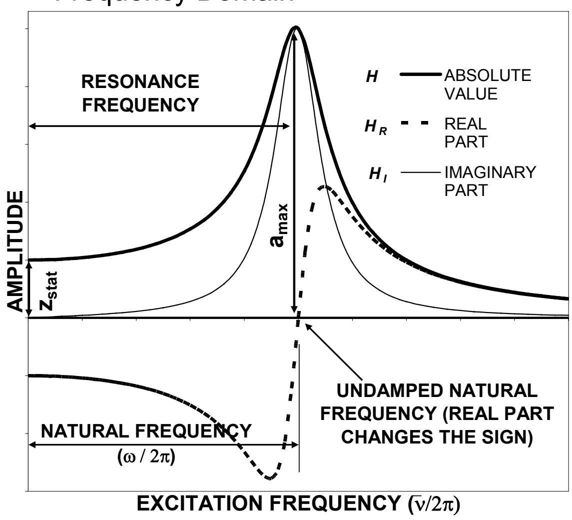
During the process of heavy tamping the soil is loaded below the original level with increasing numbers of impacts. The heavy pounder penetrates deeper and deeper into the ground. This changes the dynamic conditions of the system depending on several parameters. In order to quantify the specific effects extensive parameter studies were performed utilizing the boundary element method (BEM). This numerical method requires only the discretisation of the boundary (Banerjee, 1994) and is particularly suitable for linear-elastic halfspace problems. The assumption of linear-elastic soil behaviour is suitable for the present problem as the decay of the vibration after the compacting impact behaves as an elastic problem and so is deemed to provide sufficient accuracy. The pounder – halfspace system was simulated with the BEM in the frequency domain using the rotational-symmetric model according to Fig. 7. This computational model refers to in-situ measurements during full-scale tests. The penetration depth T is variable. In the case of no penetration of the pounder an analytically approximate solution is possible utilizing the SDOF-analogy. The so called Lysmer analogy relates the dynamic properties of the halfspace to a spring-damper element reducing the halfspace with an infinite number of degrees of freedom to a system with only one degree of freedom (SDOF system). The spring and damper coefficients of the Kelvin-Voigt body can be determined by the formulas of Lysmer (Lysmer, 1965) and Wolf (Wolf, 1994). Taking into account the known parameters k and c the equivalent SDOF system was solved in the frequency domain in order to check the reliability of the numerical simulation of the dynamic interaction system pounder – halfspace for T = 0 (Paulmichl, 2004).

For T > 0 approximations for the spring and damping coefficient are also available but they are limited to geometrical properties and the penetration depth. Therefore, numerical simulations with the Boundary element method (BEM) were carried out in order to analyse the decay of free soil vibrations. The system including the parameters according to Fig. 7 was solved in the frequency domain with the program GPBEST. The complex transfer function was determined by sweeping the frequency $\overline{\nu}$ of the harmonic unit load applied to the pounder. Material damping was neglected. Fig. 7 shows the complex transfer functions (real part, imaginary part, and absolute value) for T = 0 according to the BEM.

Time Domain



Frequency Domain



FORMULAS (free vibration):

logarithmic damping coefficient δ:

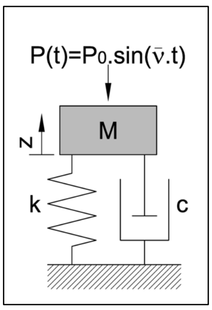
$$\delta = \ln\left(\frac{z_n}{z_{n+1}}\right)$$

damping coefficient after Lehr ζ:

$$\zeta = \frac{\delta}{2\pi\sqrt{1+\left(\frac{\delta}{2\pi}\right)^2}}$$

undamped natural frequency ω:

$$\omega = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$



FORMULAS (forced vibration):

Transfer function (absolute): $H = \sqrt{H_R^2 + H_I^2}$

$$H_R = \frac{\omega^2 - \bar{\nu}^2}{\left(\omega^2 - \bar{\nu}^2\right)^2 + \left(2\,\zeta\,\omega\,\bar{\nu}\right)^2}$$, real part

$$H_I = \frac{-2\,\zeta\,\omega\,\bar{\nu}}{\left(\omega^2 - \bar{\nu}^2\right)^2 + \left(2\,\zeta\,\omega\,\bar{\nu}\right)^2}$$, imaginary part

$$\chi_{max} = \frac{a_{max}}{z_{stat}} = \frac{1}{2\,\zeta\,\sqrt{1-\zeta^2}}$$, max. magnification

$$\zeta = \sqrt{\frac{1}{2}\left(1-\sqrt{1-\frac{1}{\chi_{max}^2}}\right)}$$, damping after Lehr

Figure 6: Overview of the mechanical properties of a single degree of freedom system (SDOF): Schematic plot and important equations of the free and forced vibration response in time and frequency domain.

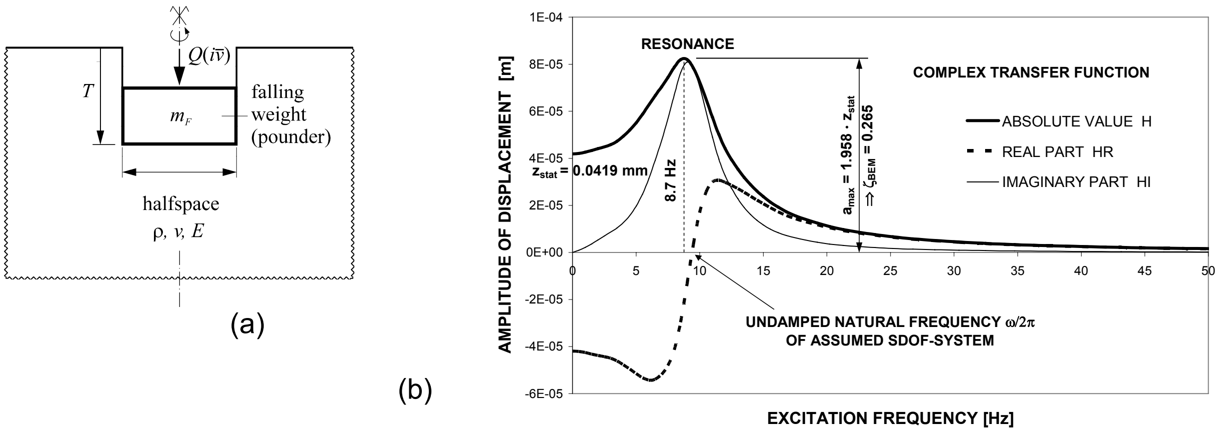


Fig. 7: (a) Mechanical model for the simulation with the boundary element method (BEM). (b) Transfer functions (real part, imaginary part, and absolute value) at the centre of the pounder from BEM analysis. Pounder: r = 0.90 m, mF = 16.5 tonnes, T = 0 m. Halfspace: ρ = 2.0 tonnes/m³, ν = 0.212, E = 16 MN/m².

Figure 8 shows the undamped natural frequency of the halfspace (corresponding to the undamped frequency ω / 2π of the SDOF-system) depending on the Young's modulus E and the Poisson's ratio ν. The simulation was performed for a falling weight used for in-situ measurements. The correlation describes – in a first theoretical step – the idealized state of the falling weight situated on the surface of the halfspace, hence T = 0. Figure 8 reveals that the natural frequency of the halfspace is widely proportional to $E^{1/2}$ and increases slightly with Poisson's ratio ν.

Numerical BEM calculations disclosed that Lehr's damping coefficient ζ derived from the SDOF-analogy depends only on Poisson's ratio and is practically independent of the E-modulus of the halfspace. This phenomenon could be found for all penetration depths T of the falling weight (pounder), whereby ζ varies with depth (Fig. 9a).

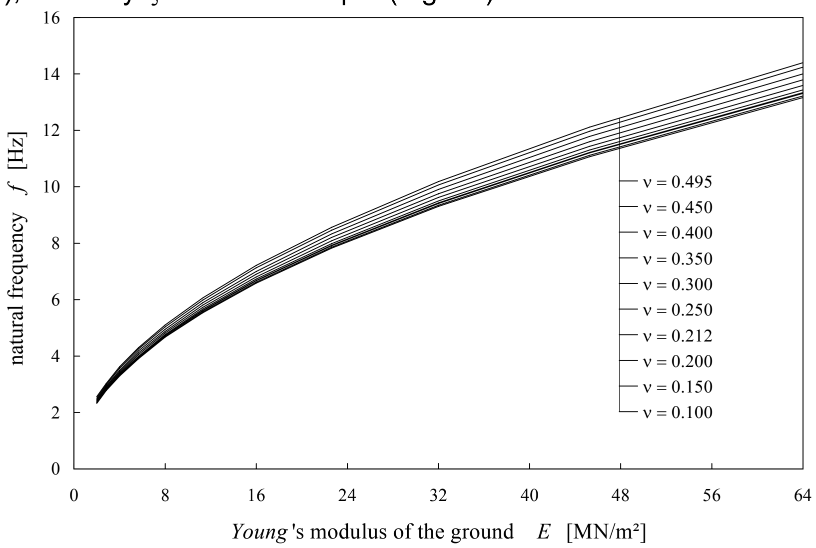


Fig. 8: Natural frequency of the halfspace versus Young's modulus E. Poisson's ratio ν as parameter. Curves for a pounder of 1.8 m diameter and 16.5 tonnes. No penetration into the ground (T = 0 m), no damping.

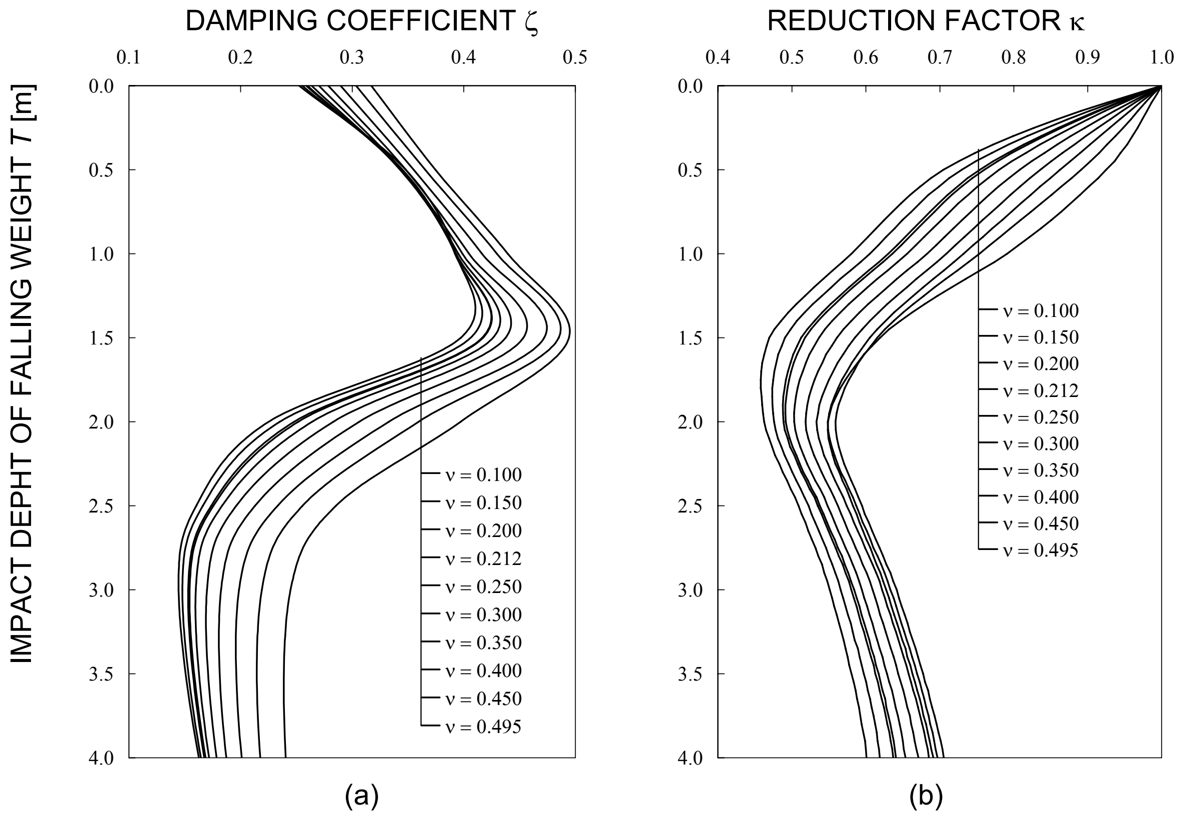


Fig. 9: Lehr's viscous damping coefficient ζ and the reduction factor κ versus penetration depth T of the pounder into the soil. Poisson's ratio ν as parameter. Curves for a pounder of 1.8 m diameter and 16.5 tonnes: Young's modulus of soil E = 16 MN/m², density ρ = 2.0 tonnes/m³; no damping.

The influence of the penetration depth of the pounder (i.e. the crater depth of the compaction point) can be described by a reduction factor κ, depending on Poisson's ratio (Fig. 9b). The curves include the pounder parameters (diameter, mass) and the soil parameters (density, *E*-modulus).

The theory and in-situ measurements make it possible to create a clear correlation between measured vibration parameters ($\omega/2\pi$ and ζ) and soil parameters (E, ν) of an idealized linear-elastic halfspace: Figure 8/left and the site-specific, known parameters T and ζ provide Poisson's ratio ν. Taking into consideration ν and the natural frequency $\omega/2\pi$ the *E*-modulus can be obtained from Figure 8 for the special case $T = 0$. Actually, the pounder penetrates into the ground, and this can be considered by multiplying the *E*-modulus for $T = 0$ by the reduction factor κ for $T > 0$ (from Fig. 9b). This theoretical approximation is valid because it could be proven that the lines of equal frequency (isolines) represent the axial-affine reproduction of only one mathematical function.

5. Practical approach for heavy tamping integrated dynamic compaction control

Based on the described theoretical and experimental investigations a practical approach is proposed to control the optimum tamping process and to check the actual parameters after each impact.

Fundamentally, the accelerations of the pounder have to be measured and transmitted to the data recording system. Therefore, a wireless data transmission system has proven to be suitable, in contrast to that a cable is error-prone due to the repeated impact-like loading.

Theoretical considerations discussed in this paper provide the basis for a method to determine the soil parameters from free vibrations of the pounder measured immediately after the respective impact. It is assumed that the soil behaves like a linear elastic halfspace during the free vibration phase, thus, the Poisson's ratio and the *E*-modulus can be derived from measurements.

Four steps are required for the achievement (Fig. 10):

- In a first step the damped natural frequency $\omega_d/2\pi$ and the damping coefficient after Lehr ζ are determined from the free vibrations according to Fig. 5b and Fig. 6a. Consequently, the undamped natural frequency ω is calculated according to the respective equation in Fig. 6a.
- In a second step Poisson's ratio ν can be estimated with sufficient accuracy from the damping coefficient after Lehr ζ and the actual penetration depth T of the pounder into the soil according to Fig. 9a.
- The relationship illustrated in Fig. 8 yields the *E*-modulus taking into account the Poisson's ratio ν determined in the previous step. However, this modulus is only true, if the pounder is situated exactly on the surface of the halfspace ($T = 0$).
- In a last step the "correct" *E*-modulus is calculated by multiplying the *E*-modulus determined on the surface by a reduction factor κ taking into account the penetration depth of the pounder into the soil ($T > 0$) according to Fig. 9b.

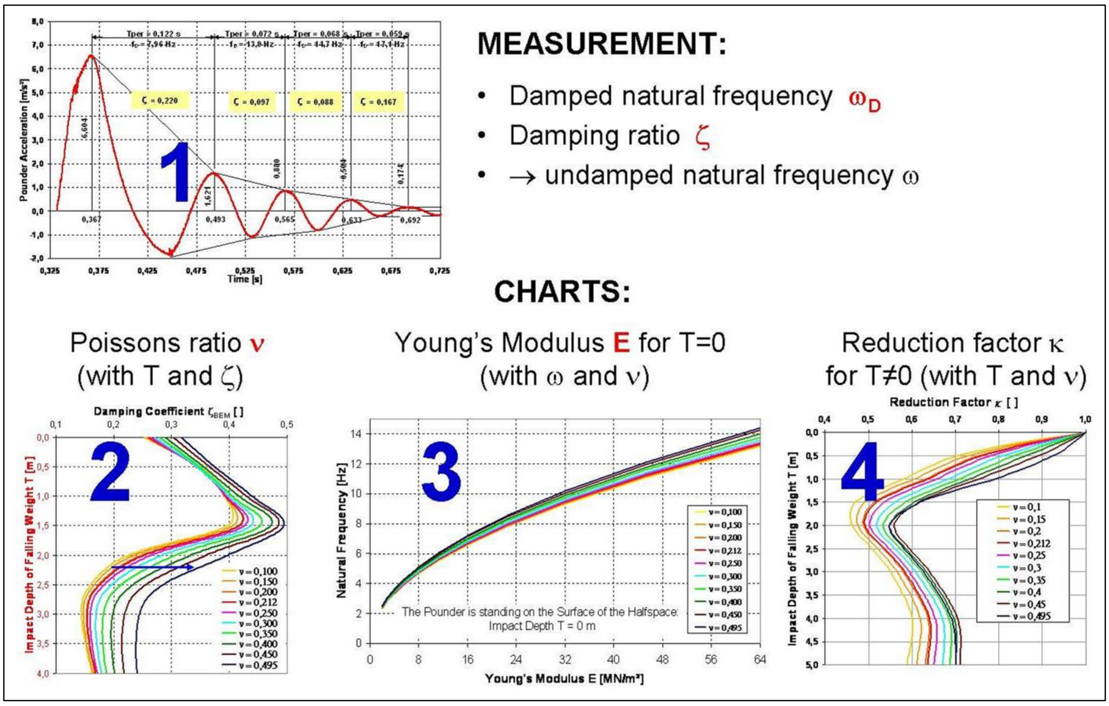


Fig. 10: Sketch of analysis procedure

Thus, it is possible to derive unambiguously two soil parameters (*E*-modulus and Poisson's ratio) from two vibration parameters (frequency and damping coefficient).

By means of the proceeding alteration of the soil parameters due to the pounder impacts the compaction achievement is documented. Consequently, this innovative monitoring method can be applied for on-line quality control, for optimisation of the compaction procedure, and as quick decision guidance in the case of strongly varying subsoil conditions. Last but not least, the entire working process can be automatically recorded and is available for a sophisticated quality assurance system.

6. Conclusions

Roller-integrated continuous compaction control of granular and mixed grained material placed in layers has become state of the art for high-quality earthworks since the Nineties (Adam, 1996, Brandl & Adam, 1997). Its fundamental idea, to use the compaction equipment simultaneously as measuring device, has a scientific challenge to develop an analogy for deep ground improvement by heavy tamping (deep dynamic compaction). The innovative method is based on acceleration measurements at the falling mass (pounder) involving the decay of free soil vibrations. Analytical analyses, numerical simulations and full-scale measurements on construction sites proved its practical applicability. This, recording the soil – pounder interaction enables a site-specific optimisation and continuous quality control for heavy tamping.

Literature

[1] Adam, C. 2003: *Computational tutorial in structural dynamics* (in German). Institute of Rational Mechanics, Vienna University of Technology, Austria.

[2] Adam, D. 1996: *Continuous Compaction Control with Vibratory Rollers* (in German). Ph.D. dissertation. Institute for Soil Mechanics and Geotechnical Engineering, Vienna University of Technology.

[3] Banerjee, P.K. 1994: *The boundary element methods in engineering.* McGraw-Hill, London.

[4] Brandl, H. & Sadgorski, W. 1977: *Dynamic stresses in soils caused by falling weights.* Proc. 8th Int. Conference on Soil Mechanics and Foundation Engineering, Moscow. 187-194.

[5] Brandl, H. 1997: *Waste columns for in-situ improvement of waste deposits.* Proc. Australia-New Zealand Conference on Environmental Geotechnics-Geoenvironment. Melbourne, Australia. Rotterdam: Balkema.

[6] Brandl, H. & Adam, D. 1997: *Sophisticated continuous compaction control of soils and granular materials.* 14th Int. Conference on Soil Mechanics and Foundation Engineering, Hamburg. 31-36.

[7] Fellin, W. 2000: Quality control in deep vibrocompaction. In: *Compaction of Soils, Granulates and Powders.* A.A.Balkema, Rotterdam. 133-144.