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Fading away vibrations during heavy tamping

Diffusion des vibrations lors du compactage dynamique

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ABSTRACT
Heavy tamping (deep dynamic consolidation/compaction) has been increasingly used since the early Seventies. The paper reports on in situ measurements and theoretical investigations referring to fading away vibrations of the falling mass after each drop. This behaviour is essential for the 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 drop height was changed repeatedly. The amplitudes of the fading away vibrations provided a damping coefficient. The numerical calculations involved numerous parametric studies and were compared to the measurement results. Scope of the research project was to gain a reliable indicator for the compaction degree of the soil immediately after each blow, hence a method for continuous compaction control and documentation.

RÉSUMÉ
Le pilonnage intensif (consolidation ou compactage dynamique) s'est développé fortement depuis le début des années 1970. Cet article rapporte les measures in situ et les développements théoriques sur l'amortissement des vibrations engendrées par la chute d'un pilon. Ces lois de comportement sont essentielles pour l'étude de l'interaction sol-pilon et permettent l'optimisation du compactage dynamique. Les essais in situ ont mesuré l'accélération du pilon et du terrain sous jacent, en function de la hauteur de chute du pilon. Les amplitudes, lors de la diffusion des vibrations, ont déterminé un coefficient d'amortissement. Les calculs numériques comprenant de nombreuses études paramétriques ont été comparés aux measures in situ. L'objectif de la recherché était de définer un paramétre fiable pour déterminer le degré de compacité immédiatement après chaque impact, et, par conséquent une méthode continue pour le contrôle et le suivi de la méthode.

1 GENERAL

Deep compaction is a sort 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" of heavy tamping (falling weight up to $m_F = 200$ tons, falling height up to $H = 40$ m) ground can be improved to a depth of up to 40 m, and the hitherto maximum of vibroflotation depth is 60 m.

Deep compaction techniques are used to improve natural soils and manmade fillings likewise, the latter especially in the case of land reclaiming. For an intensive, deep-reaching compaction of old (municipal) landfills, heavy tamping is primarily useful. Vibroflotation with granular columns or waste columns can also be used (Brandl, 1997).

Experience and in situ observations have disclosed that deep dynamic compaction increases significantly the liquefaction stability and earthquake resistance of soils and manmade fills, because dynamic loading and vibration induced particle re-arrangement of the ground is anticipated to a high extent. Structures founded on such soil improvement showed significantly less earthquake damages than nearby buildings standing on ground without deep dynamic soil compaction/densification. This could also be observed for shallow and deep foundations.

2 TECHNOLOGY AND PARAMETERS

Deep dynamic compaction by heavy tamping has been used in Austria and Germany since the 1930ies, but was at first limited to weights of about 10 tons and falling heights of about 10 m. Significant development started in 1972/73 with 20 to 25 tons dropping from heights up to 22.5 m, thus improving soft soils and peat for a highway junction (Brandl & Sadgorski, 1977). Meanwhile a great variety of crawler cranes, tripods, giga-machines, etc. has been used (Fig. 1), and heavy tamping may be also combined with other technologies (e.g. stone columns of 2 – 4 m diameter, i.e. "dynamic replacement").

Heavy tamping may be used for nearly all soils and other granular materials, even for wastes and under water. It anticipates soil liquefaction and particle re-arrangement due to dynamic loading and is therefore very suitable for ground improvement in seismic zones. Field observations disclosed that soils exhibit a substantially higher earthquake resistance after deep dynamic compaction/consolidation (heavy tamping).

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

- Pressuremeter tests (mainly);
- SPT tests and other sounding methods;
- Measurement of pore water pressure;
- Measurement of settlement (average values or depth of compaction points, i.e. the craters 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.

These tests are required for quality assurance and quality assessment likewise, 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 an influence on the results (Fig. 2). E.g. flat weights of rather small mass are preferred for surface-near, smoothing (ironing) compaction, whereas heavy weights with a small cross section achieve a large depth of point compaction.

Figure 1. Different equipment for heavy tamping.
left: Crawler cranes
right: Tripod
bottom: Giga-machine

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

- Mass and shape of falling weight (pounder);
- Falling height;
- Spacing and lay-out of the grid of compaction points;
- Number of blows per compaction point and number of passes (a pass usually compromises three to ten blows);
- Sequence of compaction points with regard to geometry and time.
- In fine-grained soil the following effects play a role:
  - Temporary liquefaction during the impact (impulse load) and local disturbance of soil structure;
  - Compressibility due to micro-bubbles, especially in soft soils with organic components;
  - Local stress constraints similar to a bent layered system of leaf springs;
  - Increased permeability due to created fissures;
  - Thixotropic recovery

Figure 2. Different falling weights (pounders) for heavy tamping.
left: Steel ponder with naps to increase influence depth
right: Heavy steel pounder structure
bottom: Flat steel pounder for final compaction, ironing the surface

3 MEASUREMENTS AND ANALYTICAL ANALYSES

Due to this complex interaction of numerous influence factors recent research has been focused on the development of an equipment-integrated method that allows a continuous optimization, control and documentation of the compaction. This novel system should represent an analogy to the roller-integrated continuous compaction control. Similar research is 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.

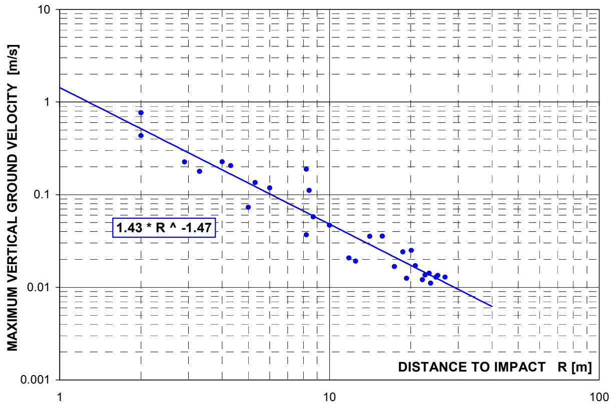

Figure 3. Maximum vertical ground velocity versus distance to the compaction point. Heavy tamping on soft waste material from ceramics and gypsum industry. Pounder of 16.5 tons from 15 m height.

Figure 3 shows a typical diagram illustrating the rapid decrease of maximum ground velocity with distance to the impact center from 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 gained by measuring the acceleration of the falling weight which is proportional to the reaction forces of the ground. But these reaction forces include all phenomena as soil compaction, replacement, liquefaction, excessive pore water pressures, local ground failure, plastic and elastic deformations, etc. Consequently, the reaction force is hardly suitable for clear characteristic values required for a reliable compaction control. Contrary to that, the fading away (decay) of free soil vibrations caused by the falling weight after each drop is characteristic of the soil - falling weight interaction and enables a site-specific optimization and quality control of heavy tamping (Fig. 4). The basic ideas of this novel concept are as follows (Kopf & Paulmichl, 2004):

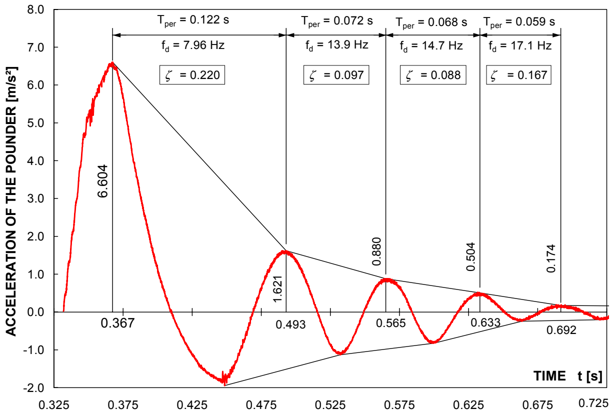

Figure 4. Decay of free soil vibrations after hitting untreated soil with a pounder (d = 1.8 m, m_F = 16.5 tons) from a drop height of 1 m.
Dynamic parameters for an idealized viscously damped single degree of freedom (SDOF) system: T_{per} = periodic time, s; $f_d = \omega_d / 2\pi$ = damped natural frequency, Hz; ζ = viscous damping coefficient.

Assuming an elastic decay (fading away) 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 (SDOFS) system (Adam, 2003).

The free vibration response z at any time $t = n \cdot T_{per}$ (Eq. 1a, e.g. upper turning point) and/or after vibration periods $T_{per} = 2\pi / \omega_d$ (Eq. 1b) measured later, are

$$z_n \equiv z\left(nT_{per}\right) = a_p e^{-\zeta\omega n T_{per}} \tag{1a}$$

$$z_{n+m_{per}} \equiv z\left[\left(n + m_{per}\right)T_{per}\right] = a_p e^{-\zeta\omega\left(n+m_{per}\right)T_{per}} \tag{1b}$$

where ω = undamped natural circular frequency, rad/s; ω_d = damped circular frequency, rad/s.

The ratio of the vibration responses at a distance of m_{per} periods is always constant, hence

$$z_n / z_{n+m} = e^{\zeta\omega m_{per} T_{per}} \tag{2}$$

The logarithmic damping coefficient is defined by

$$\delta_{m_{per}} = \ln\left(z_n / z_{n+m_{per}}\right) \tag{3}$$

and the damping coefficient after Lehr ζ (dimensionless) is

$$\zeta = \delta_{m_{per}} \Bigg/ \left(2m_{per}\pi\sqrt{1 + \left(\frac{\delta_{m_{per}}}{2m_{per}\pi}\right)^2}\right) \tag{4}$$

Consequently, measuring the acceleration of the falling weight during the decay (fading away) 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. From Eq. (5) the undamped natural circular frequency ω is calculated:

$$\omega = \omega_d \Big/ \sqrt{1 - \zeta^2} \tag{5}$$

4 NUMERICAL SIMULATIONS

During the compaction process of heavy tamping the soil is loaded below the original ground level with increasing numbers of blows. 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 a linear-elastic soil behaviour is suitable for the present problem as the fading away process of the vibration after the compacting blow can be idealised with sufficient accuracy as an elastic problem. The pounder-halfspace system was simulated with the BEM in the frequency domain using the rotational-symmetric model according to Fig. 5. 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 analytical approach 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 single degrees of freedom to a system with only on degree of freedom (SDOF system). The spring and damper coefficients (K and C) of the Kelvin-Voigt body can be determined by the formulas of Lysmer (1965) and Wolf (1994). With 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 $T = 0$.

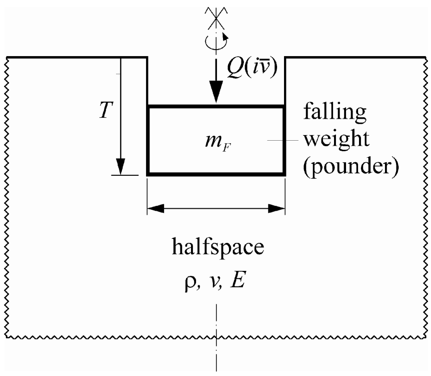

Figure 5. Physical model for the simulation with the BEM.

For $T > 0$ approximations for the spring and damping coefficient are also available but only with limitations (material properties, penetration depth). Therefore, numerical simulations with the BEM were carried out in order to analyse the decay of free soil vibrations. The system with the parameters according to Fig. 5 is solved in the frequency domain with the program GPBEST (Banerjee, 2001). The complex transfer function is determined by sweeping the frequency $\bar{\nu}$ of the harmonic unit load applied to the pounder. Material damping is neglected. In Fig. 6 the complex transfer functions (real part, imaginary part, and absolute value) for $T = 0$ according to the BEM are compared with the results gained from the SDOF-analogy. This comparison proves the reliability of the numerical solutions.

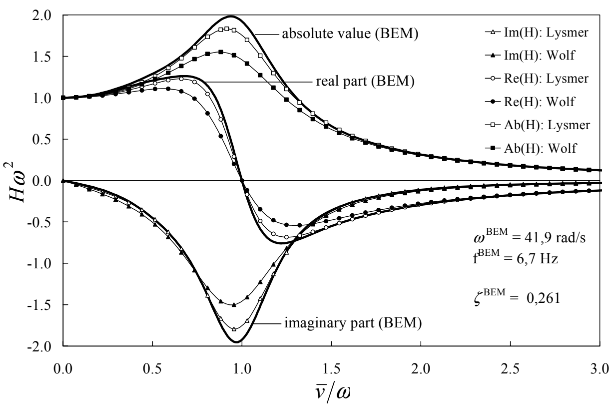

Figure 6. Transfer functions (real part, imaginary part, and absolute value) at the center of the pounder. BEM analysis and SDOF-analogy solutions. Pounder: $r = 0{,}90$ m, $m = 16{,}5$ tons, $T = 0$. Halfspace: $\rho = 2000$ kg/m^3, $\nu = 0{,}212$, $E = 16$ MN/m^2.

The transfer function of the euqivalent viscously damped SDOF-system is given by Eq. 6 (6a = real part, 6b = imaginary part, 6c = absolute value), the amplification function by Eq. 7 (Paulmichl, 2004).

$$H_R = \left(\omega^2 - \bar{\nu}^2\right)\chi_p^2 \tag{6a}$$

$$H_I = \left(-2\zeta_V \omega\bar{\nu}\right)\chi_p^2 \tag{6b}$$

$$H = \sqrt{H_I^2 + H_R^2} = 1 \Big/ \sqrt{\left(\omega^2 - \bar{\nu}^2\right)^2 + \left(2\zeta\omega^2\right)^2} \tag{6c}$$

$$\chi_p = \frac{a_p}{z_{stat}} = H\omega^2 = 1 \Bigg/ \sqrt{\left[1 - \left(\frac{\bar{\nu}}{\omega}\right)^2\right]^2 + \left(2\zeta\frac{\bar{\nu}}{\omega}\right)^2} \tag{7}$$

a_p = amplitude of the dynamic response, m; z_{stat} = static displacement, m; $\bar{\nu}$ = frequency of the harmonic load, rad/s; ω = natural frequency (undamped), rad/s; ζ = damping coefficient.

Inserting the resonance frequency (Eq. 8) in Eq. 7 (for the frequency $\bar{\nu}$) yields the maximum of the amplification function

(Eq. 9) from which the damping coefficient ζ can be determined (Eq. 10):

$$\omega_\chi = \sqrt{1-2\zeta^2}\,\omega \tag{8}$$

$$\chi_{p,\max} = a_{p,\max}/z_{stat} = 1\Big/\left(2\zeta\sqrt{1-\zeta^2}\right) \tag{9}$$

$$\zeta = \sqrt{\frac{1}{2}\left(1-\sqrt{1-\frac{1}{\chi^2_{p,\max}}}\right)} \tag{10}$$

Figure 7 shows the undamped natural frequency of the halfspace (corresponding to the undamped frequency $\omega/2\pi$ of the SDOF-system) depending on the Young's modulus E and 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 that the falling weight stands on the surface of the halfspace, hence $T = 0$. Figure 5 reveals that the natural frequency of the halfspace is widely proportional to $E^{1/2}$ and increases with Poisson's ratio ν.

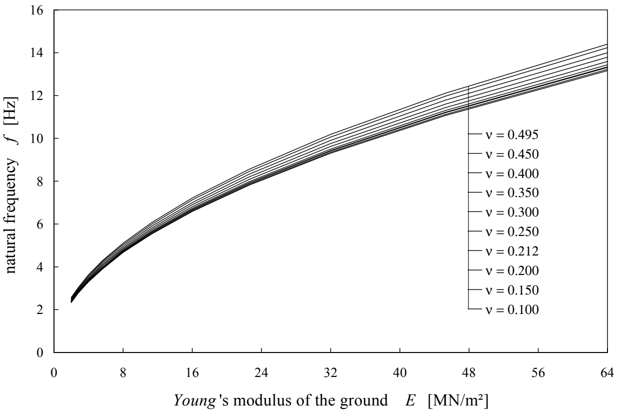

Figure 7. Natural frequency of the halfspace versus Young's modulus E. Poisson's ratio ν as parameter. Curves for a pounder of 1.8 m diameter and 16.5 tons. No penetration into the ground ($T = 0$), no damping.

Numerical BEM calculations disclosed that Lehr's damping coefficient ζ derived from the SDOFS-analogy depends only on Poisson's ratio and is practically independent of the E-moulus of the halfspace. This phenomenon could be found for all penetration depths T of the falling weight (pounder), whereby ζ itself depends throughout on depth (Fig. 8/left).

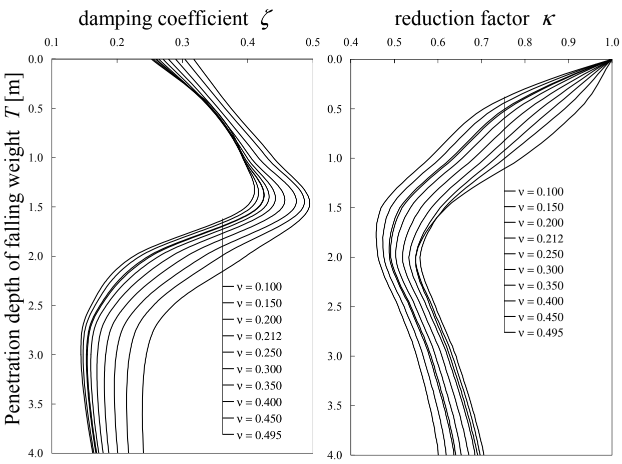

Figure 8. Lehr's viscous damping coefficient ζ and the reduction factor κ versus penetration depth T of the pounder into the soil. Poisson's ratio ν as parameter. Curves for a pounder of 1.8 m diameter and 16.5 tons: Young's modulus of soil $E = 16$ MN/m², density $\rho = 2.0$ t/m³; no damping.

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. 8/right). The curves include the pounder parameters (diameter, mass) and the soil density.

This 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. With this ν and the natural frequency $\omega/2\pi$ the E-modulus can be obtained from Figure 7 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. 8/right). This theoretical approximation is allowable because it could be proven that the lines of equal frequency (isolines) represent the axial-affine reproduction of only one mathematical function.

5 CONCLUSIONS

Roller-integrated continuous compaction control of granular material placed in layers has become state of the art for high-quality earthworks since the Nineties (Brandl & Adam 1997). Its fundamental idea to use the compaction equipment simultaneously as measuring device for immediate in-situ control was a scientific challenge to develop an analogous system for deep ground improvement by heavy tamping (deep dynamic compaction/consolidation). The innovative method is based on acceleration measurements at the falling weight (pounder) involving the fading away (decay) of free soil vibrations. Numerical simulations of the fading away vibrations during heavy tamping should be calibrated by an analytical approach. Within the frame of this research project good agreement could be obtained for sophisticated simulations using a range of initial and boundary conditions. Analytical analyses, numerical simulations and full-scale measurements on construction sites proved the practical applicability of this new method. Thus, recording the soil − pounder interaction enables a site-specific optimisation and continuous quality control of heavy tamping.

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