Innovative dynamic compaction techniques & integrated compaction control methods

Techniques innovantes de compactage dynamique et méthodes intégrées de contrôle de compactage

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ABSTRACT

The paper provides a state of the art overview of compaction technologies and moreover integrated vibration based measurement systems used on dynamic rollers and heavy tamping technique to continuously measure soil properties during and after earthwork compaction. Roller measurement values have evolved towards the estimation of more mechanistic soil parameters, e.g., stiffness modulus. Independent assessment of these measurement values has proven their efficacy. Heavy tamping is a deep dynamic compaction technique and has been increasingly used since beginning of the Seventies of the last century. The authors report on in situ measurements and theoretical investigations referring to the decay of free soil vibrations caused by the falling weight after each impact. The Rapid Impact Compactor is an innovative dynamic compaction device based on the piling hammer technology used to increase the bearing capacity of soils through controlled impacts. This ground improvement technique allied to dynamic compaction has been recently introduced in Central Europe. An integrated measurement system is currently under development.

RÉSUMÉ

Cet article fournit un état de l'art sur les technologies de compactage et, plus encore, sur les systèmes intégrés de mesure par vibration utilisés sur les rouleaux dynamiques et la technique de damage lourd pour mesurer en continu les propriétés du sol pendant et après les travaux de compactage. Les valeurs mesurées au rouleau ont évolué vers l'estimation de paramètres du sol plus mécaniques, comme, par exemple, le module de rigidité. L'évaluation indépendante de ces valeurs mesurées ont montré leur efficacité. Le damage lourd est une technique de compactage dynamique profonde et elle a été utilisée d'une manière croissante depuis les années mille neuf cent soixante-dix. Les auteurs rapportent des mesures in situ et des études théoriques concernant la décroissance des vibrations libres du sol provoquées par la masse tombante après chaque impact. Le Compacteur à Impacts Rapides est un appareil innovant de compactage dynamique basé sur la technologies des marteaux pour pieux, utilisé pour accroître la capacité portante des sols par l'intermédiaire d'impacts contrôlés. Cette technique d'amélioration des sols, alliée au compactage dynamique, a récemment été introduite en Europe centrale. Un système de mesure intégré est actuellement en cours de développement.

Keywords : earth works, ground improvement, soil dynamics, compaction, compaction control

1 INTRODUCTION

The quality of roads, highways, motorways, rail tracks, airfields, earth dams, waste disposal facilities, foundations of structures and buildings, etc. depends highly on the degree of compaction of filled layers consisting of different kinds of materials, e.g. soil, granular material, artificial powders, fly ashes and grain mixtures, unbound and bound material. Thus, both compaction method and compaction equipment have to be selected carefully taking into consideration the used material suitable for the prevailing purpose. Compaction process should be optimized in order to achieve sufficient compaction and uniform bearing and settlement conditions. Typical dynamic compaction technologies are based on harmonic excitation or on transient excitation and achieve different compaction depths:

(a) dynamic rollers (harmonic – surface near)
(b) heavy tamping (transient – deep)
(c) rapid impact compaction (transient – intermediate))

If compaction control can be included in the compaction process, time can be saved and cost reduced. Furthermore, a high-leveled quality management requires continuous control all over the compacted area, which can only be achieved economically by work-integrated methods. Modern dynamic compaction technologies like intelligent rollers, heavy tamping, and rapid impact compaction nowadays include integrated control techniques. Innovative approaches have been developed in the last years and will be briefly presented and discussed in the following.

2 ROLLER COMPACTION

2.1 *Roller technology*

Dynamic rollers like vibratory, oscillatory and vario rollers make use of a vibrating or oscillating mechanism, which consists of one or more rotating eccentric weights (Fig. 1). During dynamic compaction a combination of dynamic and static loads occurs. The dynamically excited drum delivers a rapid succession of impacts to the underlying surface from where the compressive and shear waves are transmitted through the material to set the particles in motion. This eliminates periodically the internal friction and facilitates the rearrangement of the particles into positions in combination with the static load that result in a low void ratio and a high density. Furthermore, the increase in the number of contact points and planes between the grains leads to higher stability, stiffness, and lower long-term settlement behavior.

The introduction of servo-controlled vibratory drum technology has catalyzed a new initiative termed *intelligent compaction*, where the vibratory force amplitude and/or frequency are automatically adjusted to improve roller performance and compaction. Currently, the so-called *intelligence* of intelligent compaction is limited. Most rollers now automatically decrease the vertical vibration force when jumping (double jump) mode is sensed. Further, some rollers (e.g., Bomag, Ammann) have the ability to automatically reduce

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the eccentric force amplitude when a user-defined threshold measurement value has been reached. In a broader sense, however, intelligent compaction is in its infancy. Considerable advances are anticipated in truly intelligent compaction over the next decade (Adam & Mooney 2008).

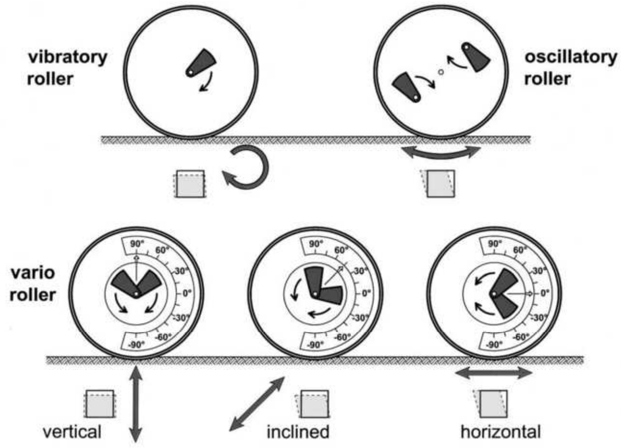

Figure 1. Dynamic rollers (vibratory roller, oscillatory roller, vario roller) and different kinds of excitation (drum types).

2.2 *Roller integrated continuous compaction control*

The roller-integrated continuous compaction control (CCC) is based on the measurement of the dynamic interaction between dynamic rollers and soil (Adam 1996). The motion behavior of different dynamically excited roller drums changes in dependence of the soil response. This fact is used to determine the stiffness of the ground. Accordingly, the drum of the dynamic roller is used as a measuring tool; its motion behavior is recorded, analyzed in a processor unit where a dynamic compaction value is calculated, and visualized on a dial or on a display unit where data can also be stored. Furthermore, an auxiliary sensor is necessary to determine the position of the roller or the localization is GPS-based. Control data are already available during the compaction process and all over the compacted area (Fig. 2).

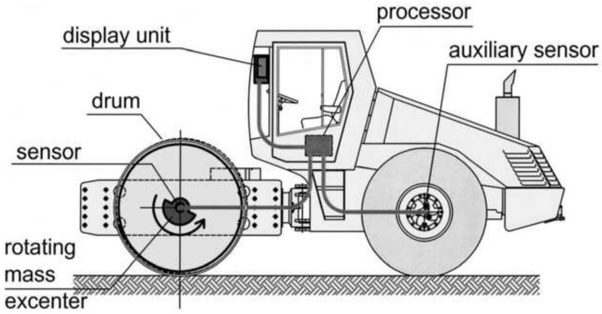

Figure 2. CCC principle; acceleration of drum soil interaction is measured at the drum, analyzed in a processor unit providing CCC data and displayed on a monitor; auxiliary sensor provides the actual position of the roller.

Four typical recording systems are available for vibratory rollers and vario rollers with vertical or any inclined excitation direction (except horizontal direction). All systems consist of a sensor containing one or two accelerometers attached to the bearing of the roller drum, a processor unit and a display to visualize the measured values. The sensor continuously records the acceleration of the drum. The time history of the acceleration signal is analyzed in the processor unit in order to determine dynamic compaction values with regard to specified roller parameters (Table 1) (Adam & Kopf 2004).

Table 1. Established CCC systems, CCC values and definitions.

CCC system	CCC value	definition of CCC value
Compactometer	**CMV** [ ]	acceleration amplitude ratio (first harmonic div. by excitation frequency amplitude) – *frequency domain*
Terrameter	**OMEGA** [Nm]	energy transferred to soil (considering soil contact force displacement relationship of 2 excitation cycles) – *time domain*
Terrameter	**E_{vib}** [MN/m²]	dynamic elasticity modulus of soil beneath drum (inclination of soil contact force displacement relationship during loading) – *time domain*
ACE	**k_B** [N/m]	spring stiffness of soil beneath drum (derived from soil contact force displacement relationship at maximum drum deflection) – *time domain*

3 HEAVY TAMPING

3.1 *Heavy tamping technology*

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 t and falling heights of about 10 m. Significant development started in the early 1970s with 20 to 25 t 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 and so on have been used (Fig. 3), and heavy tamping may be modified in order to produce stone columns comprising a diameter of up to 2–4 m. 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 owing 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 and Sadgorski 1977, Brandl 1977).

Figure 3. Different equipment for heavy tamping.

3.2 *Heavy tamping integrated continuous compaction control*

Owing to the complex interaction of numerous influence factors recent research has focused on the development of a process-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 (Adam 1996; Brandl & Adam, 1997).

Hitherto, measurements of ground vibrations have been carried out in order to gain information on the dynamic effects on sensitive structures and buildings from wave propagation caused by heavy tamping. 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. However, 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 not 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 optimization and quality control for heavy tamping (Fig. 4).

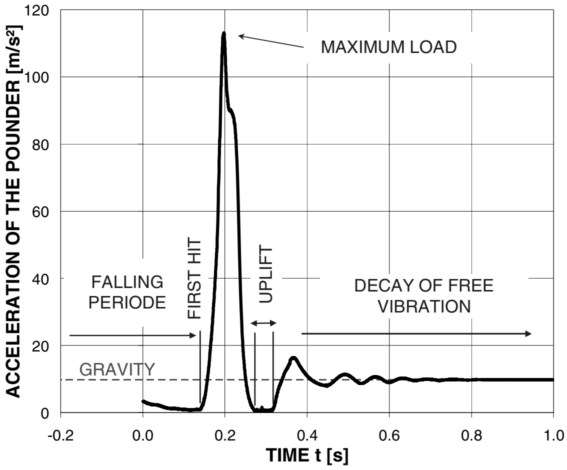

Figure 4. Acceleration of the pounder (diameter 1.8 m, mass 16.5 tonnes) after hitting untreated soil from a drop height of 1 m.

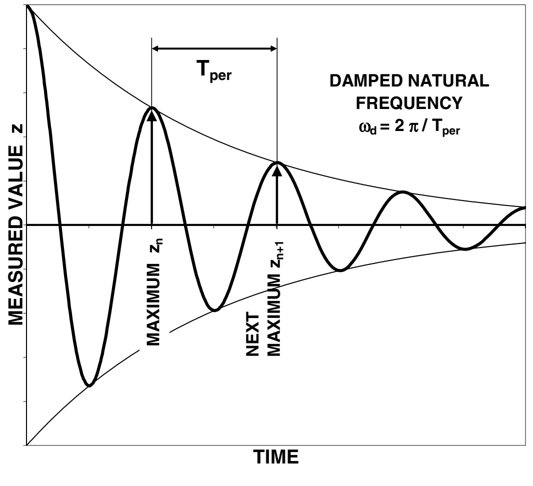

Figure 5. Decay of free vibration; mechanical properties of a single degree of freedom system (SDOF).

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

(a) 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 et al. 2007) (Fig. 5).

(b) 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

$$\zeta = \frac{\delta}{2\pi\sqrt{1+\left(\frac{\delta}{2\pi}\right)^2}} \qquad \text{with} \qquad \delta = \ln\left(\frac{z_n}{z_{n+1}}\right), \tag{1}$$

if a viscously damped SDOF system is assumed. The undamped natural circular frequency ω is calculated as follows.

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

Based on 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 proved to be suitable, whereas a cable is error-prone owing to the repeated impact-like loading.

Theoretical considerations (Adam et al. 2007) 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 and, therefore, the Poisson's ratio and the E modulus can be derived from measurements.

Four steps are required in order to achieve this.

(1) In a first step the damped natural frequency $\omega / 2\pi$ and the damping coefficient after Lehr ζ are determined from the free vibrations according to Fig. 5. Consequently, the undamped natural frequency ω is calculated according to the respective equation (2).

(2) 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. 6(2).

(3) The relationship illustrated in Fig. 6(3) 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).

(4) In a last step the 'correct' E-modulus is calculated by multiplying the E-modulus determined on the surface by a reduction factor k taking into account the penetration depth of the pounder into the soil (T > 0) according to Fig. 6(4).

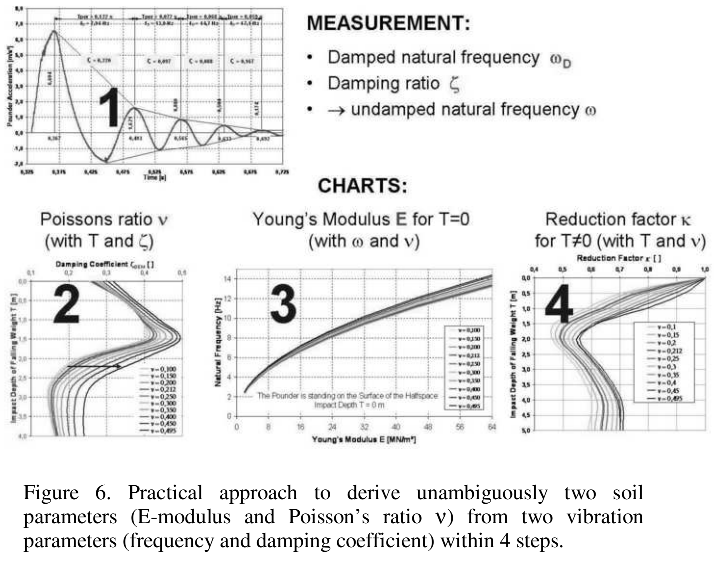

Figure 6. Practical approach to derive unambiguously two soil parameters (E-modulus and Poisson's ratio ν) from two vibration parameters (frequency and damping coefficient) within 4 steps.

4 RAPID IMPACT COMPACTION

4.1 *Rapid impact compaction technology*

The rapid impact compaction with the Rapid Impact Compactor (RIC) is an innovative method in the field of surface-near and intermediate-deep compaction techniques (Fig. 7). The RIC is a dynamic compaction device based on the piling hammer technology. Dynamic energy is imparted by a falling weight dropping from a controlled height onto a patented foot. The foot of the device remains in contact with the ground, thus the energy is transferred to the ground safely and efficiently.

Figure 7: Rapid Impact Compactor (RIC).

The RIC derived from the Rapid Runway Compactor that was originally developed in the early 90ies by BSP International Foundations Limited in conjunction with the British Ministry of Defence as a means of quickly repairing bomb craters in airfield runways. Subsequent research by the Building Research Establishment led to the development and design of a civilian variant mounted an excavator or crawler crane, a modified version of the BSP 357 Hydraulic Hammer. Thus, the Rapid Impact Technique could fulfil a niche between surface compaction by rollers, vibratory methods, and heavy tamping.

4.2 *Rapid impact compaction integrated compaction control*

Monitoring of the treatment process is extremely important for quality control and assurance purposes. At the beginning of improvement work it is necessary to establish a limiting energy input. Therefore a few test footprints are formed by driving until the penetration per blow becomes a negligible amount, e.g. 10 blows for 25 mm (final set).

The compactors are provided with a monitoring system. The compaction monitor is a kit of parts which can be coupled to the compaction device in order to record the performance of the hammer and the rate of ground improvement. The following parameters are automatically recorded during the compaction process and monitored from the RIC's cab with an on-board data acquisition system:

(a) blows per footprint
(b) depth of penetration
(c) energy input

The RIC employs an on-board computer to control impact set termination criteria, and to record critical data. So the machine is accurately controlled from excavator cab, and the degree of compaction is electronically monitored. The monitor can be set to halt impacting on a footprint once the design set is reached. Thus, wasting energy is avoided and performance and production rates can be improved. The stored data in the monitor can be downloaded to a PC and analysed, evaluated and printed (Adam & Paulmichl 2007).

The advantages of the monitoring and recording unit are:

(a) The ground can be improved to specified stiffness;
(b) The improvement can be carried out in an efficient way;
(c) The site compacted can be recorded on a on-board computer, thus the information of the compaction process can be analysed and any soft areas can treated again;
(d) The unit plugs directly into the compactor controls.

Finally, the RIC can also be used as a secondary site investigation tool. Significant changes in ground response can be identified recording the penetration at each footprint.

Currently, numerical and experimental investigations are performed in order to develop an integrated control system similar to heavy tamping in order to determine directly the properties of the soil during compaction with the RIC.

5 CONCLUSION

Soil compaction is usually performed by dynamic techniques whereby the dynamic excitation and depth effect is the limiting factor for the selection of the compaction method. Dynamic rollers are based on a harmonic excitation and are widely used for surface-near compaction of fill layers. Heavy tamping impacts the soil thus providing a transient loading causing deep compaction. Rapid impact compaction is based on a similar principle providing intermediate compaction depth.

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. 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. For rapid impact compaction a system is currently under development.

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