Five years of Impact Compaction in Europe – successful implementation of an innovative compaction technique based on fundamental research and field experiments

Cinq ans de compactage par impact en Europe – mise en œuvre avec succès d'une technique de compactage novatrice basée sur la recherche fondamentale et expériences sur le terrain

Adam D., Paulmichl I.
Vienna University of Technology, Austria

Adam C., Falkner F.-J.
University of Innsbruck, Austria

ABSTRACT: In the year 2007, the innovative Impact Compactor was widely introduced in Central Europe on the initiative of an Austrian company to compact and improve the ground. At the beginning, the application of the novel impact-like compaction technique was based on empirical data and experience gained on several construction sites. Soon after, a funded research project was initiated including both fundamental research and field experiments. The outcomes of the research work provided the basis for the optimized and economic application of this novel compaction method on-site. Since 2007, in numerous applications the Impact Compactor has been successfully employed for ground improvement for industrial, administrative and apartment buildings, bridges, bridge abutments, embankments, dams and dikes, and other civil engineering structures.

RÉSUMÉ : Le compacteur par impact pour l'amélioration des sols a été introduit en Europe Centrale en 2007, sur l'initiative d'une société Autrichienne. Au début de son utilisation cette technique novatrice de compactage et fondée sur des données empiriques et l'expérience acquise sur plusieurs chantiers. Peu de temps après, un projet de recherche a été lancé en se focalisant sur la recherche fondamentale et les expériences sur le terrain. Les résultats de ces travaux de recherche ont fournit la base d'une application optimisée et économique de ce procédé novateur de compactage sur site. Dans de nombreux projets, le compacteur à impact a été mis en œuvre avec succès pour l'amélioration des sols pour des projets des bâtiments industriels, administratifs et appartements, ponts, culées de ponts, remblais, barrages et digues et autres travaux de génie civil.

KEYWORDS: Impact Compactor, dynamic compaction, soil dynamics, ground improvement, earth works.

1 INTRODUCTION

1.1 *Background and history of the Impact Compactor*

The Impact Compactor was developed for the British military forces to compact and improve the ground. In the year 2007 the Austrian company TERRA-MIX introduced this device in Central Europe.

In the early days after implementation the application of the novel impact-like compaction technique was based on empirical data and experience gained on several construction sites. Later, a basic research project funded by the Austrian Research Promotion Agency (FFG) was initiated to quantify the effect of this innovative device, and to optimize its application. At the same time, a GPS-based data recording system for the documentation of the compaction process including stop codes as indication for maximum possible compaction was developed.

Since implementation, the Impact Compactor has proven to improve efficiently the ground for industrial, administrative and apartment buildings, bridges, bridge abutments, embankments, dams and dikes, and other civil engineering structures.

1.2 *Basic principle and setup of the Impact Compactor*

The Impact Compactor is a dynamic compaction device based on the piling hammer technology that is used to increase the load-bearing capacity of soils through controlled impacts. The general idea of this method is to drop a falling weight from a relatively low height onto a special foot assembly at a fast rate while the foot remains permanently in contact with the ground. The lately introduced compaction equipment aims at closing the gap between the surface compaction methods and the deep compaction methods, and permitting a middle-deep improvement of the ground up to a depth of 4.5 to 7.5 m (10 m) (Adam and Paulmichl 2007).

The Impact Compactor consists mainly of three impact components: the impact foot, the driving cap, and the hammer with the falling weight. The impact foot made of steel has a diameter of 1.5 m. Since the driving cap is connected loosely to the foot, only compression forces load the subsoil, which allows an efficient energy transfer. Impact foot, driving cap, and falling weight are connected to the so-called hammer rig. Falling weights of mass 5,000, 7,000, 9,000 or 12,000 kg are dropped from a falling height up to 1.2 m at rate 40 to 60 repetitions per minute. For further details see (Falkner et al. 2010).

Gravels, sands, silts, industrial byproducts, tailings material, and landfills can be successfully compacted by the Impact Compactor to increase the load-bearing capacity of foundations, to improve the ground bedding conditions for slabs, to reduce the liquefaction potential of soils, and to stabilize waste materials.

2 FUNDAMENTAL RESEARCH

2.1 *Numerical simulations*

Theoretical investigations comprised numerical computer simulations of the impact-type compaction effect, energy transfer into the soil, and wave propagation.

A theoretical study of the dynamic impact of the Impact Compactor on its environment was performed employing a simple mechanical model of the Impact Compactor-subsoil interaction system. Thereby, the falling weight was modeled as lumped mass, which hits the impact foot after a free fall. The initial velocity of the impact foot, which excites the underground, was derived assuming an idealized elastic impact between falling weight and the mass of the impact foot. The soil medium was modeled as homogenous, isotropic, and rate-independent elastoplastic halfspace based on Mohr-Coulomb theory with isotropic hardening. The axially symmetric impact foot made of steel rests on the surface of the halfspace. A sliding interface between the foot and the soil was adopted, i.e. only normal stresses are transferred between the foot and the soil. The numerical model takes advantage of the rotational symmetry of this subsystem, which is divided into a near-field and a far-field. The near-field was discretized by means of Finite Elements. Infinite Elements model the far-field in order to avoid wave reflections at the boundary between the near- and far-field, and to allow for energy propagation into the semi-infinite halfspace. The model and its parameters are described in more detail in Adam et al. (2010).

As an example, Figure 1 shows the peak velocity magnitude $v_{R,max}$ with respect to the distance of the compaction point for the subsoil condition silty fine sand after the first, third, fifth, and tenth compaction pass. The outcomes of this figure prove field observations that the pronounced increase of $v_{R,max}$ after each compaction impact leads to a parallel shift of the regression line, and thus, the arbitrary assumed limit value of 10 mm/s is shifted to a larger distance from the compaction point.

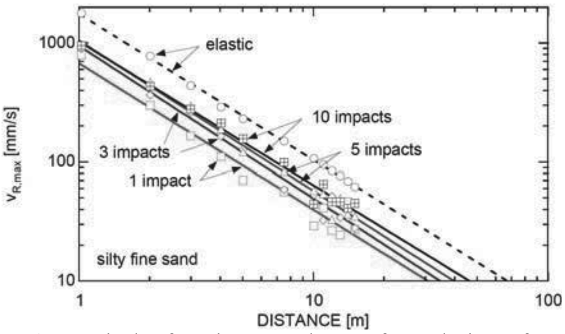

Figure 1. Magnitude of maximum resultant surface velocity as function of the distance from the impact foot after a specified number of compaction impacts applied to an elastoplastic silty fine sand.

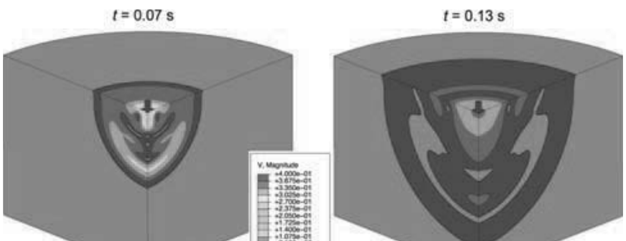

Figure 2. Distribution of the velocity magnitude at two specified instants after the first compaction impact. Elastoplastic silty fine sand.

Figure 2 shows the propagation of the velocity magnitude at two instants after the first impact is applied to the subsoil condition silty fine sand. Spherical propagation of the waves can be observed. Comparison of Figure 15(a) and Figure 15(b) prove that geometric damping leads to a rapid decay of the response amplitudes. According to Figure 15(b) the maximum peak velocities develop at the soil surface, because Rayleigh waves have the largest energy content. Furthermore, the faster propagating P-waves can be distinguished from the slower S-waves. According to the characteristics of P-waves in zones between compression and dilatation the velocities are zero.

The effect of compaction and the compaction depth have been investigated, because these properties serve to define the application fields of the Impact Compactor with respect to soil type and soil stratification. In numerical studies it was assumed that the equivalent plastic strain is the characteristic parameter for evaluation of the compaction depth. A threshold of 0.02 separates the compacted space from the non-compacted subsoil. After each impact in the compaction zone the soil properties were modified. Here, an isotropic hardening constitutive model was used for an engineering-like approximation of soil compaction.

Figure 3 shows the expansion of the equivalent plastic strains in a cross-section of homogeneous silty fine sand below the impact point after the first and tenth compaction pass. The colored area within the outer contour is considered as compaction zone. The largest equivalent plastic strains occur below the boundary of the compaction foot. The domains of equal plastic strains, i.e. the domains of equal degree of compaction, show the shape of a “stress bubble”. It can be seen that in this example the soil is compacted laterally and downwards with approximately the same magnitude. A thin surface layer shows as well distinct equivalent plastic strains, which are induced by Rayleigh waves. After the tenth impact the compaction depth is about 4.3 m.

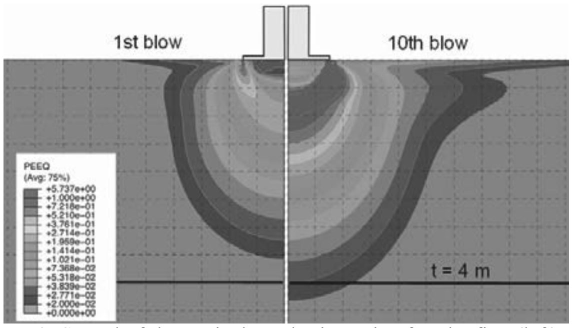

Figure 3. Spread of the equivalent plastic strain after the first (left) and after tenth compaction impact (right). Elastoplastic silty fine sand.

2.2 *Field experiments*

Field tests on different soil conditions were performed to verify theoretically derived outcomes. Moreover, they provide the basis for the optimized and economic application of this compaction method in the field.

Experimental results and field investigations confirm the trends of the presented numerical outcomes (see chapter 3).

3 DEVELOPMENT AND APPLICATION

3.1 *GPS-based recording system*

The Impact 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 cab with an on-board data acquisition system (see Figure 4):

- number of blows
- final settlement at the last blow
- total settlement (depth of the compaction crater)
- compaction energy
- average number of blows

In addition to these parameters a more novel device monitors electronically the coordinates of the compaction points, date, and time for each compaction point during the compaction process, and all data are documented via GPS controlled data acquisition (see Figure 4).

GPS-based data recording during the compaction process and the online display in the operator’s cab facilitates compaction control, an economic application of the compaction tool, and a work integrated quality control. Thus, local heterogeneities of the subsoil can be identified, and compaction with the Impact Compactor can be adjusted systematically. If necessary, additional compaction passes are conducted.

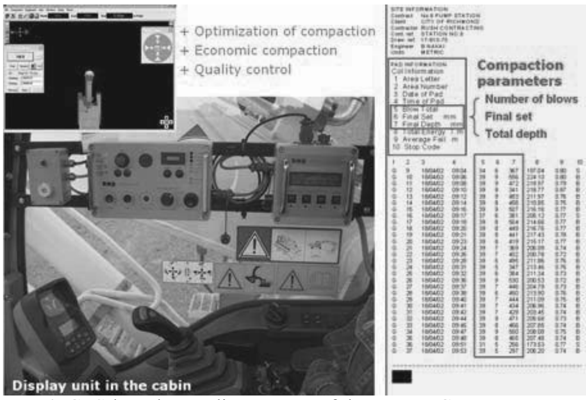

Figure 4. GPS-based recording system of the Impact Compactor.

3.2 *Parameter setting and quality control*

Optimization and control of compaction with the Impact Compactor is ensured by meeting the stop code criteria, GPS based compaction including work integrated documentation of the performance parameters for each compaction spot, and conduction of cone penetration tests and/or dynamic probing before and after compaction. During the compaction process the following stop codes are applied:

- stop code 1: total settlement (depth of the compaction crater)
- stop code 2: number of blows per compaction point
- stop code 3: final settlement of the last blow

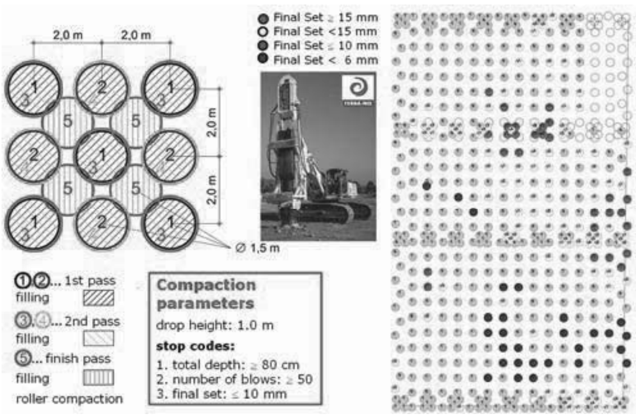

Figure 5: Compaction process (left) and compaction control (right).

The stop codes have to be verified and optimized on a test field that is located within the site (see Figure 5). In dependence of the subsoil conditions and the complexity of the project the calibration field can comprise up to three different compaction patterns and point grids. The compaction process at the test field is usually carried out by applying stop codes defined by a geotechnical expert based on the results and experiences from comparable sites. After the test compaction the treatment depth is determined and compared with the required compaction depth in order to find the suitable compaction point grid. The compaction pattern and point grids, the number of compaction passes and the stop codes are finally defined by the geotechnical expert.

The compaction depth is determined conducting cone penetration tests (CPT) and/or dynamic probing light, medium, or heavy (DPL, DPM, or DPH).

In Figure 6 the number of blows N_{10} determined by dynamic probing heavy and light before and after compaction is plotted against the depth. The dynamic probing heavy was performed in non-cohesive primarily sandy gravelly soil; the dynamic probing light was carried out in cohesive soil consisting of silts and sands. It can be seen that the depth effect of the Impact Compactor depends on the soil condition, and it varies from about 4 m (silts and sands) to 7 (8) m (sandy gravelly soils).

In cohesive soils of soft to stiff consistency dynamic probing heavy allows only a low number of blows independent of the degree of compaction. Consequently, for checking the compaction effect it is recommended to use dynamic probing light (DPL) or cone penetration tests (CPT) (Adam et al. 2010).

Typical depths of influence (treatment depth) are summarized in Table 1 in dependence of the soil type based on the results of numerous experimental investigations.

For quality control recorded compaction parameters are evaluated graphically. As an example, in Figure 5 (right) the "final set" (stop code 3) is used as control criteria, and the compaction points are hatched in blue, green, yellow or red color in dependence on the numerical value of the recorded "final set". It can be seen that another compaction pass had to be carried out on the red colored points. Consequently, this plot gives information on the compaction quality (whether the stop codes are met all over the site or not), and allows conclusions to be drawn about the subsoil quality before compaction.

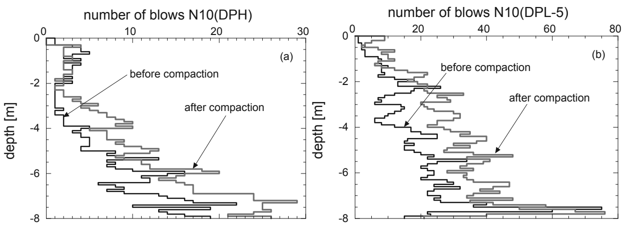

Figure 6: Dynamic Probing Heavy (DPH) in non-cohesive soil (left) and Dynamic Probing Light (DPL-5) in cohesive soil (right).

Table 1. Characteristic compaction depth for the Impact Compactor with a falling weight of 9,000 kg mass.

Type of soil	*Type of dynamic probing*	*Number of blows*	*Treatment depth*
Sa/Gr	DPH	$N_{10} > 20$	6 – 7.5 (10) m
si Sa	DPH	$N_{10} > 15$	5 – 6 m
sa Si	DPL	$N_{10} > 20$	4.5 – 5 m
Miscellaneous graded soils	DPL/DPH	$N_{10} > 15 / 20$	4.5 – 7 m

3.3 *Vibration emission and immission*

On numerous test sites the maximum surface velocity induced by the Impact Compactor as function of the distance were determined. The data acquisition tool MR2002DIN-CE (RED BOX) of the company SYSCOM was applied to monitor and record the vibrations. The velocities were measured in situ with tri-axial velocity transducers according to the German Standard DIN 45669 and saved with a data recorder. The velocity was measured in three orthogonal directions in the frequency domain of 1 to 315 Hz. The subsequent data processing was done with the software package VIEW 2002 (Ziegler Consultants). Subsequently, regression analyses were performed to obtain the magnitude of the maximum resulting velocity $v_{R,max}$ as function of the distance from the impact foot.

Figure 7 shows selected linear regression lines for different homogeneous ground conditions determined through free-field velocity measurements during impact compaction with a falling weight of 9,000 kg mass. It is seen that smallest peak velocity magnitudes develop during compaction of homogeneous loose sandy gravels. For this subsoil condition a coefficient of decay of about 1.8 is determined. Note that only one compaction pass was performed. Largest peak velocity magnitudes were measured during compaction of dense gravels. Compaction of sandy silts and gravelly silty sands led to peak velocity magnitudes in-between. The coefficient of decay of about 1.3 is practically identical for dense gravels, sandy silts, and gravelly silty sands. The results show that the peak velocity magnitude falls below the value of max $v_{R,max}$ = 10 mm/s, i.e. the limit value for buildings of the class no. III according to the Austrian Standard ÖN S 9020, at a distance of 11 to 34 m from the impact foot, depending on the subsoil condition and soil type. Based of hitherto experience the required minimum distance to buildings of class no. III is about 20 m. In comparison compaction of heavy tamping techniques induces resulting velocities of more than 10 mm/s at a distance of 30 m.

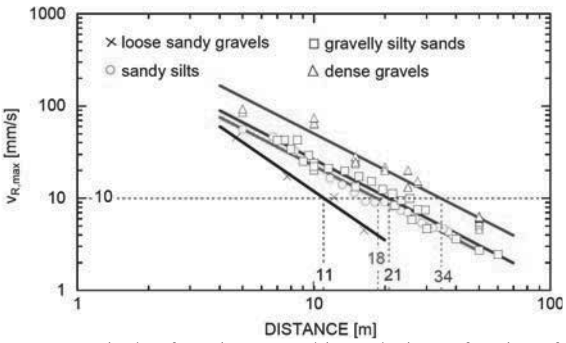

Figure 7. Magnitude of maximum resulting velocity as function of the distance from the impact foot. Measured values for different soil types.

4 SELECTED CASE HISTORIES

4.1 *Ground improvement for embankments and foundations*

In the last five years the standard application for the Impact Compactor was the ground improvement for embankments and foundations. Typical fields of application are:

- improvement of the ground in the embankment base
- compaction to increase the bearing capacity of foundations and/or reduce the liquefaction potential of soils
- improvement of the ground bedding conditions for slabs
- combined application with other compaction methods such as heavy tamping or deep vibro-compaction when large compaction depth is required, or lime stabilization of soft cohesive soils on top of the ground (Adam et al. 2010)

4.2 *Rehabilitation of flood protection dikes*

The efficiency of the Impact Compactor to improve existing flood protection dikes alternatively to e.g. the mixed-in-place method (MIP) was investigated by compaction of the core of a test dike (Adam et al. 2010).

The test dike was constructed on a gravelly ground, which is covered with a loess layer of about 0.75 m thickness. The core of the embankment was built layer-wise with a layer thickness of about 1 m. Each layer was only “pre-compacted” with a vibratory roller in order to simulate the weak compactness of existing old flood protection dikes. For one half of the embankment core sandy silt (loess) was used as filling material, for the other half silt (loam). The shoulders and slopes were constructed with sandy gravel (see Figure 8).

Optimization and control of compaction was realized by the following tasks and criteria:

- meeting the stop code criteria
- GPS-based documentation of the compaction parameters
- performance of dynamic probing heavy (DPH) before and after compaction
- performance of dynamic load plate test using the LFWD before and after compaction
- in-situ permeability tests

In the following selected results of dynamic probing tests are presented exemplary, which were carried out to determine the compaction depth. Figure 8 (right) illustrates the number of blows N_{10} over depth determined with dynamic probing heavy in the test section consisting of loess. It is obvious that the depth effect of the Impact Compactor is about 4.5 m. Figure 8 reveals that the upper zone of the gravelly ground beneath the embankment was compacted as well.

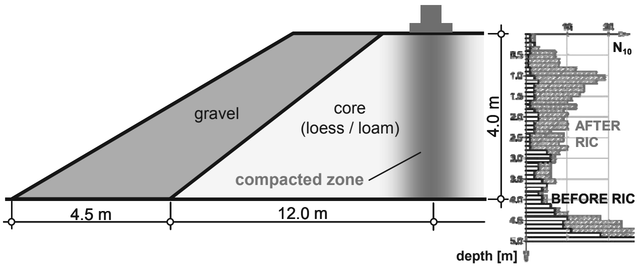

Figure 8. Section of the test dike (left) and Dynamic Probing Heavy in the loess (right).

5 CONCLUSION

In Central Europe the Impact Compactor was introduced in 2007. The novel compaction equipment provides a technically sound and economic method of improving the capacity of a wide variety of loose soils (silts, sands, gravels, cobbles, boulders) and fills. The effective treatment depth in soils is dictated by grain sizes and is typically in the range of 4.5 m (silt and sand) up to 7.5 m (10 m) depth (sand and gravel). Due to the numerous benefits, e.g. monitoring of the compaction process through a GPS-based recording system (on-board computer), reliability and safety in operation, quality assurance, versatility and working speed, the Impact Compactor is now a well established dynamic compaction method throughout Europe.

6 ACKNOWLEDGEMENTS

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