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RAPID IMPACT COMPACTOR – AN INNOVATIVE DYNAMIC COMPACTION DEVICE FOR SOIL IMPROVEMENT

Dietmar Adam, Vienna University of Technology, Austria
Ivan Paulmichl, Geotechnik Adam ZT GmbH, Austria

ABSTRACT: The Rapid Impact Compactor (RIC) is a dynamic compaction device based on the piling hammer technology used to increase the bearing capacity of soils through controlled impacts. This ground improvement technique, which is allied to dynamic compaction is called "Rapid Impact Compaction". 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 in contact with the ground at all times. The factors influencing the effectiveness of the compaction method are discussed in the present paper, and the results and outcomes of the field tests are presented. Finally, the benefits of the Rapid Impact Compaction are outlined.

1. Introduction

The compaction process should be optimized in order to achieve sufficient compaction and uniform bearing and settlement conditions. Commonly, three kinds of compaction techniques are used (see Figure 1):

- Dynamic roller compaction,
- Deep vibrocompaction techniques,
- Deep Dynamic Compaction (heavy tamping).

Soil compaction near the surface 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, the e.g., the dead weight the static line load of the drum the drum amplitude the excitation frequency the roller speed, etc., the maximum compaction depth varies from about 0.2 to 1.0 m. Thus, for soil improvement the depth is limited to relatively low values. The success of the dynamic roller compaction can be controlled by measuring the kinetic behaviour of the drum interacting with the ground during the compaction process. This so-called "Continuous Compaction Control (CCC)" has proven to be an excellent technique for the controlling, checking, and documenting compaction over the processed area achieved by the 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 a depth of about 10 to 20 m, depending on the ground properties, the compaction equipment and the input of the compaction energy. Ground improvement by Dynamic Compaction (DC) has been successfully employed throughout the world since the late 1960´s for densifying a wide range of natural soils and man-made fills. With the "giga-machine" for heavy tamping (a falling weight up to 200 tonnes, a falling height of 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 the intensive, deep-reaching compaction of old (municipal) landfills, heavy tamping is primarily useful.

Rapid Impact Compaction with the Rapid Impact Compactor (RIC) is an innovative method in the field of near surface and deep compaction techniques. The RIC is a dynamic compaction device based on 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.

The RIC derived from the Rapid Runway Compactor, which was originally developed in the early 1990´s by BSP International Foundations Limited in conjunction with the British Ministry of Defence as a means of quickly repairing bomb craters on airfield runways (BSP, doc 1). Subsequent research by the Building Research Establishment led to the development and design of a civilian variant mounted on an excavator or crawler crane, which is a modified version of the BSP 357 Hydraulic Hammer (BSP, doc 2). Thus, the Rapid Impact Technique could fill a niche between surface compaction by rollers, vibratory methods, and conventional DC (see Figure 1).

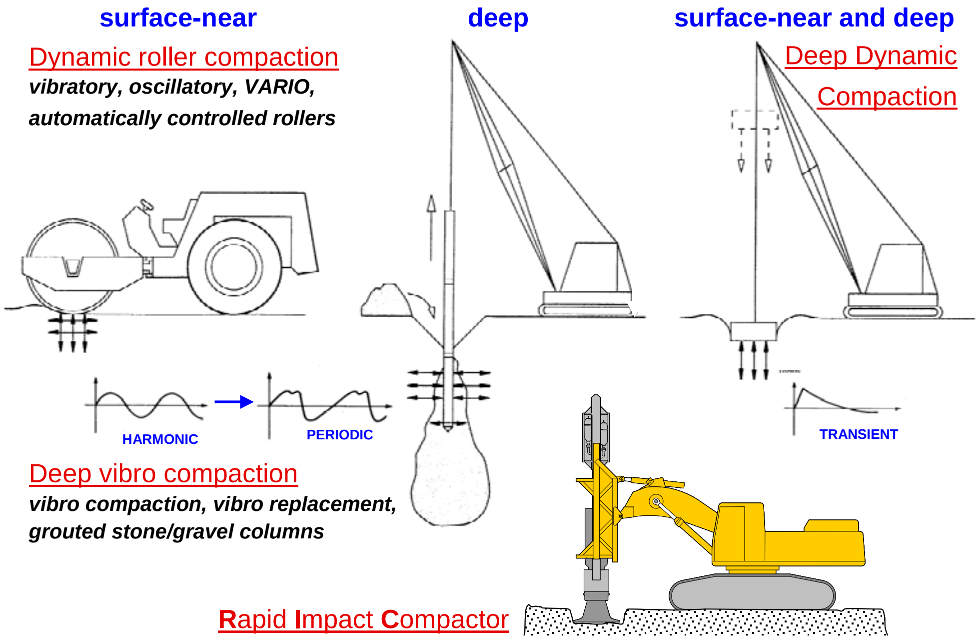


Figure 1. Dynamic compaction techniques.

2. Equipment and compaction method

Unlike the conventional DC, where a heavy weight is dropped from a great height only once or twice a minute, the general idea of this novel method is to drop a lighter weight from a relatively low height onto a special foot assembly at a fast rate, while the foot remains in contact with the ground at all times.

The RIC mainly consists of three impact components: the impact "foot", the driving cap and the hammer with the falling weight. The impact foot is a steel foot with a diameter of 1.5 m. It remains in contact with the ground the whole time. The driving cap connected to the foot allows for articulation. The impact foot, driving cap and falling weight are connected to a unit, the so-called hammer rig (see Figure 2).

(a) (b)

Figure 2. Impact foot (a), boom (b) and assembled rig (c) (Cooper, 2006)

(c)

The hammer device is mounted onto a track-mounted excavator through a universal boom assembly. The bushes of the boom are made to suit various models, and a fast reaction to new requirements is allowed. The rock-breaking circuits of the excavator are used for the hammer device. The different excavators in the 40-48 tonne class that match the complete rig are summarized in Table 1. Besides a complete rig that suits one of the mentioned excavators, front end equipment is also supplied, which can be mounted on a customer's base machine. At present three types of the device are available (see Figure 3): the RIC 5000, RIC 7000 and RIC 9000 (Note: The number indicates the mass of the falling weight in kg).

Table 1. Range of different excavators (Cooper, 2006).

Producer	**Model**
Caterpillar	345B
Daewoo	DH450
Hitachi	EX400
Kobelco	SK480
Komatsu	PC400
Hyundai	R450

(a) (b) (c)

Figure 3. Types of hammer devices available. (a) RIC 9000 mounted on a Kobelco SK480 (working in Iran), (b) RIC 7000 mounted on a Hitachi EX400 (operating in Canada), (c) RIC 5000 mounted on a Kobelco SK320 (working in China) (BSP web).

The following are some key operational features of the equipment:

- Drop weights with 5, 7 or 9 tonnes (depending on the size) are usually used.
- The drop height of the weight can be adjusted using an in-cab computer of up to 1.2 m.
- The RIC impacts the soil at a rate of 40-60 blows per minute.
- Energy is transferred to the soil through a 1.5 m diameter steel “foot” that rests on the ground surface.

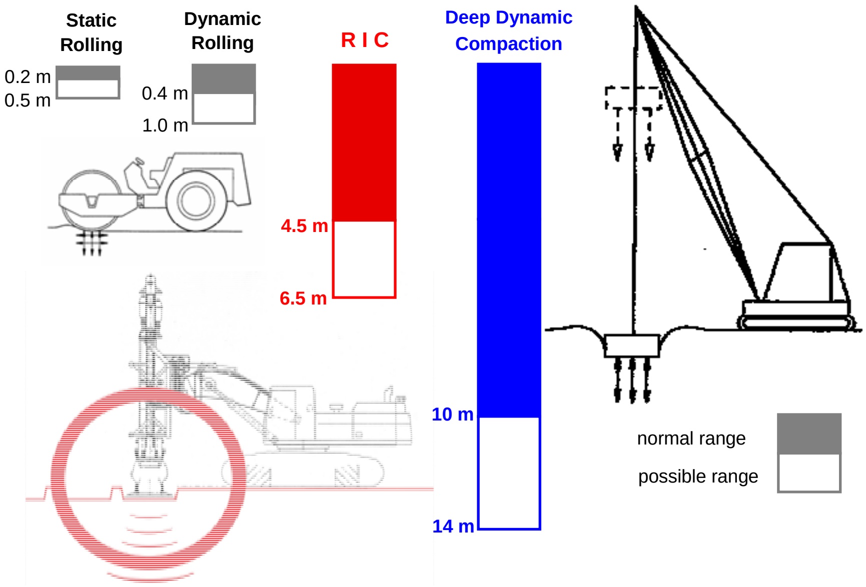


Figure 4. Compaction techniques. Comparison of the depth of compaction (Adam & Fürpass, 2007).

A comparison of RIC with other dynamic compaction methods with respect to the depth of compaction is given in Fig. 4 and Table 2. Thus, it appears that Rapid Impact Compaction is specifically aimed at the rapid treatment of large and small areas where a depth of treatment is required down to 3 to 10 m, as it was shown to be effective and economical at this range of depth

Table 2. Depth of compaction of different dynamic compaction methods.

Method	**Range of depth of compaction**
Static Rolling	0.2 – 0.5 m
Dynamic Rolling	0.4 – 1.0 m
RIC	4.5 – 6.5 (10.0) m
Dynamic Compaction	10.0 – 14.0 m

Dynamic Compaction (DC) imparts impact energy to soils or fills by dropping a large and heavy falling weight from a known height. With conventional DC the weight is typically 10 to 15 tonnes and the height 5 to 15 m. Thus, the energy per drop varies between 490 to 2,207 kNm. Assuming a frequency of one or two drops per minute, the power range is 0.5 to 4.4 MNm/min.

The RIC, on the contrary, imparts energy by dropping a 5 to 9 tonne weight from a relatively small height of 1.2 m at a blow rate of 40 to 60 times a minute. Depending on the ram weight, the maximum energy delivered per blow is 59 to 106 kNm. Although the energy per blow is small compared to the conventional DC, the rapid blow frequency amply compensates, resulting in a greater power that varies between 2.4 to 6.4 MNm/min. Thus, a much greater total energy input per unit area of a site can be achieved with RIC. Moreover, the energy transfer of the RIC is far more effective due to its foot which stays in contact with the ground during the impact sequence.

3. Treatment Design

Tests and observations from sites have confirmed that the Rapid Impact Compaction System is analogous to the conventional DC. Existing empirical data from the DC database can therefore be extrapolated for RIC. Mayne (1984) established a relationship between increased Standard Penetration Test (SPT) values (N_{SPT}) and the applied energy per unit area by evaluating data from DC projects (see Figure 5). The correlation between the Dynamic Penetration Super Heavy (DPSH) blow counts and the number of RIC blows per footprint according to Figure 6 shows that RIC produces similar results to that of the conventional DC. It can be seen, for example that, 35 blows from a 7 ton RIC unit imparts 167 ton metres/m^2 of energy into the ground, resulting in a DPSH blow count of 30 plus.

Experience has shown that an energy input of 150 ton metres/m^2 of treatment is typical for fills, while with granular materials, e.g. natural sands, the optimal energy requirement may rise to 250 ton metres/m^2 (BSP doc 1).

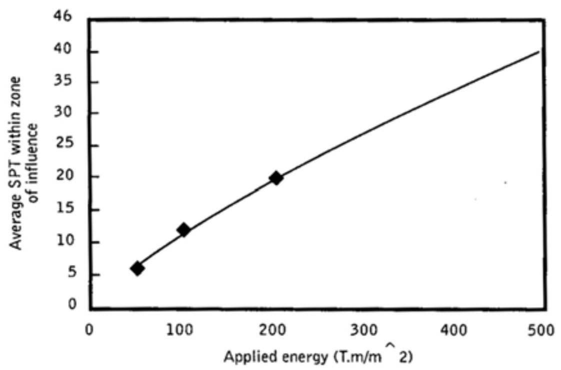


Figure 5. N_{SPT} vs. energy per unit area (DC).

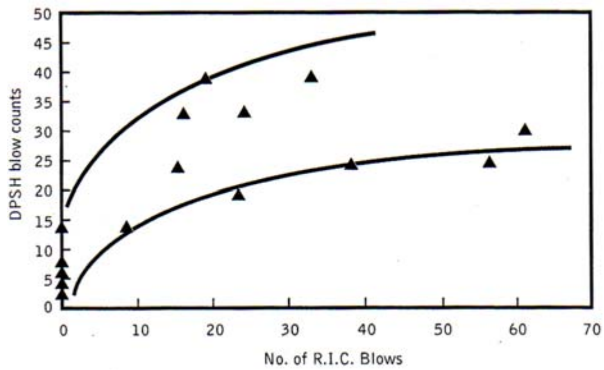
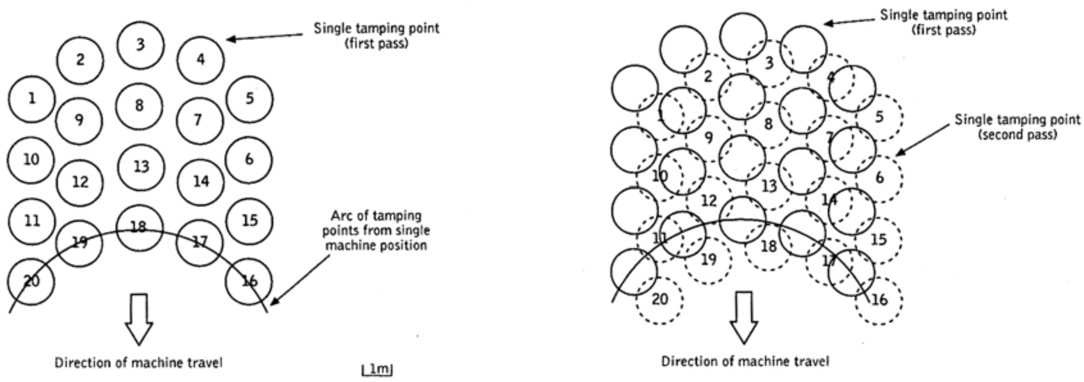


Figure 6. DPSH blow counts vs. number of RIC blows.

The layout of the impact points is generally based on an arc about the centre of rotation of the compactor carrier (hydraulic excavator or crane). The footprint positions are approximately at 2 m centres of the primary tamping and, if necessary, secondary tamping can be carried out the intermediate locations overlapping the primary points (see Figure 7). The treatment points can also be staggered within 9 m squares, whereas the ground has to be marked by grid lines (see Figure 8).

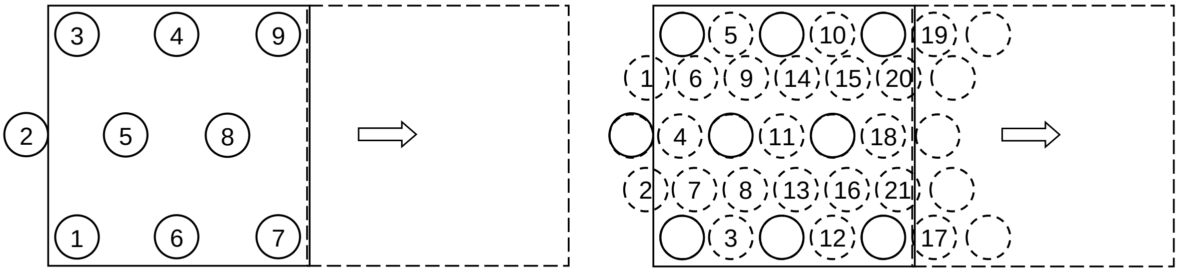
On completion of the Rapid Impact Compaction treatment the surface may be treated with a 1.8 m square tamping plate (ironing pass) or earthwork roller to compact the surface layer and create a more even finish.



(a) Primary treatment pass (b) Secondary treatment pass

Figure 7. Typical plan layout of tamping points. Sweep and track (BSP doc 1).

Where the surface of the ground to be treated is soft and easily sheared, a gravel-size aggregate layer with a thickness of 0.4 m is placed on the surface. Thus, the compaction effort is transmitted more efficiently into the underlying material.



(a) Primary treatment pass (b) Secondary treatment pass

Figure 8. Typical plan layout of tamping points. Staggered points within 9 m squares (Cooper, 2006).

4. Quality control and assurance

Monitoring of the treatment process is extremely important for quality control and assurance purposes. At the beginning of any 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 improvement of the ground. The following parameters are automatically recorded during the compaction process and monitored from the RIC's cab with an on-board data acquisition system (Figure 9):

- the blows per footprint,
- the depth of penetration, and
- the energy input.

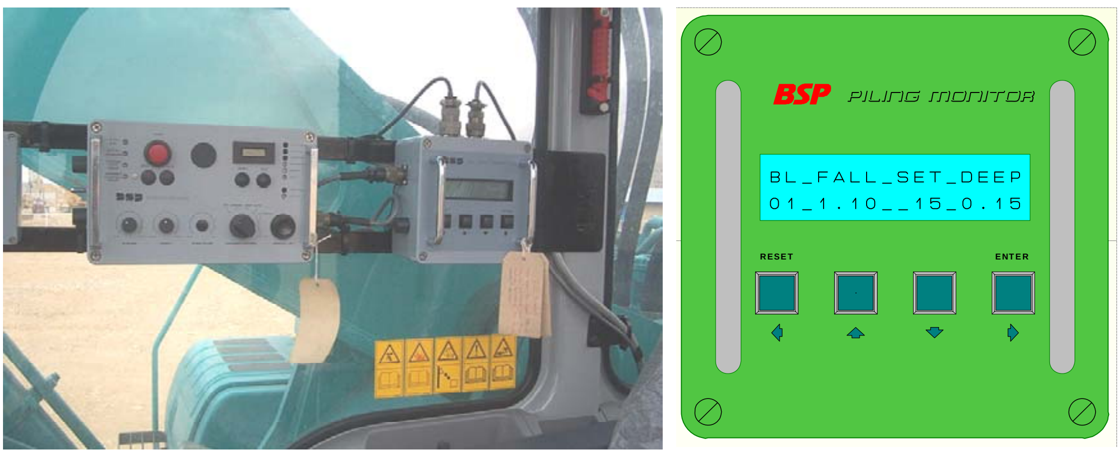


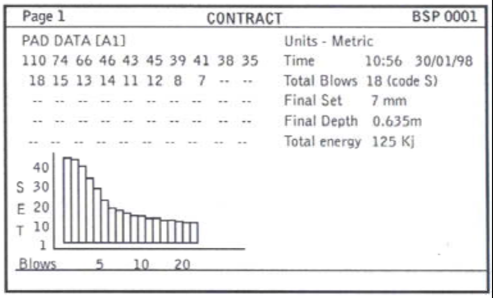
Figure 9. On-board computer in the cab of the RIC (Cooper, 2006).

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 the 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 data stored in the monitor can be downloaded to a PC and analysed, evaluated and printed (see Fig. 10).

The advantages of the monitoring and recording unit are:

- the ground can be improved to a specified minimum degree of stiffness;
- the improvement can be carried out in an efficient manner;
- the site compacted can be recorded on a on-board computer; thus, the information concerning the compaction process can be analysed, and any soft areas can be treated again;
- the unit plugs directly into the compactor controls.

Location	Date	Time	Blows	Final Set	Final Depth	Total Energy	Stop Code	Blows ->			
DRG01-G9	18/04/02	09:04	34	6	367	197.04	S	51	35	20	18
DRG01-G10	18/04/02	09:06	39	9	556	224.10	B	78	60	35	20
DRG01-G11	18/04/02	09:08	39	9	472	219.97	B	67	50	26	16
DRG01-G12	18/04/02	09:10	39	8							
DRG01-G13	18/04/02	09:12	39	9							
DRG01-G14	18/04/02	09:14	39	8							
DRG01-G15	18/04/02	09:16	39	9							
DRG01-G16	18/04/02	09:17	37	6							
DRG01-G17	18/04/02	09:18	39	8							
DRG01-G18	18/04/02	09:20	39	8							
DRG01-G19	18/04/02	09:21	39	8							
DRG01-G20	18/04/02	09:23	39	8							
DRG01-G21	18/04/02	09:24	39	7							
DRG01-G22	18/04/02	09:26	39	7							
DRG01-G23	18/04/02	09:28	39	6							
DRG01-G24	18/04/02	09:31	39	5							
DRG01-G25	18/04/02	09:32	39	6							
DRG01-G26	18/04/02	09:36	39	9							
DRG01-G27	18/04/02	09:37	39	7							
DRG01-G28	18/04/02	09:38	39	6							
DRG01-G29	18/04/02	09:40	39	7							
DRG01-G30	18/04/02	09:41	39	7							
DRG01-G31	18/04/02	09:42	39	7							
DRG01-G32	18/04/02	09:44	39	9							
DRG01-G33	18/04/02	09:45	39	8							
DRG01-G34	18/04/02	09:47	39	9							
DRG01-G35	18/04/02	09:48	39	8							
DRG01-G36	18/04/02	09:51	31	5							
DRG01-G37	18/04/02	09:53	39	5							



stop criterion defined by
Blows
and
Final Set respectively

Contract	NO.8 PUMP STATION
Client	CITY OF RICHMOND
Contractor	RUSH CONTRACTING
Contract Ref.	STATION NO.8
Drawing Ref.	17-610-75
Engineer	B.NAKAI

Figure 10. Data Presentation after PC download (BSP doc 1).

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

Level surveys of penetration associated with each print position should be recorded so that the volumetric change, i.e., the densification of the ground within the treatment depth, can be calculated. Penetration testing should be carried out before, during and after compaction in order to demonstrate the effectiveness and depth of the treatment. The following penetration tests are acceptable:

- standard penetration test (SPT);
- electric cone test;
- dynamic cone test (a testing rate of 1 per 400 m^2 is recommended).

Figs. 11 and 12 show typical examples of field measurements before and after Rapid Impact Compaction.

Besides the penetration test, load plate tests should be carried out to prove the degree of compaction by determining the deformation modulus of the compacted subgrade. Traditionally, soil compaction is assessed indirectly via the static deformation modulus, which is determined by means of the static load plate test. Instead, the dynamic load plate test with a Light Falling Weight Device (LFWD) can be carried out. This small device provides a dynamic deformation modulus of the soil layers. The simple operation of the device and the quick test implementation of only about 3 minutes per measuring spot allow for a significantly higher number of tests compared to the conventional static load plate test, and thus, a statistical evaluation is facilitated. The frequency of testing should be related to the uniformity of the ground conditions but should not be less than one test per 2000 m^2 treated. When using the Light Falling Weight Device, between 4 and 6 times as many tests compared to the static load plate should be carried out.

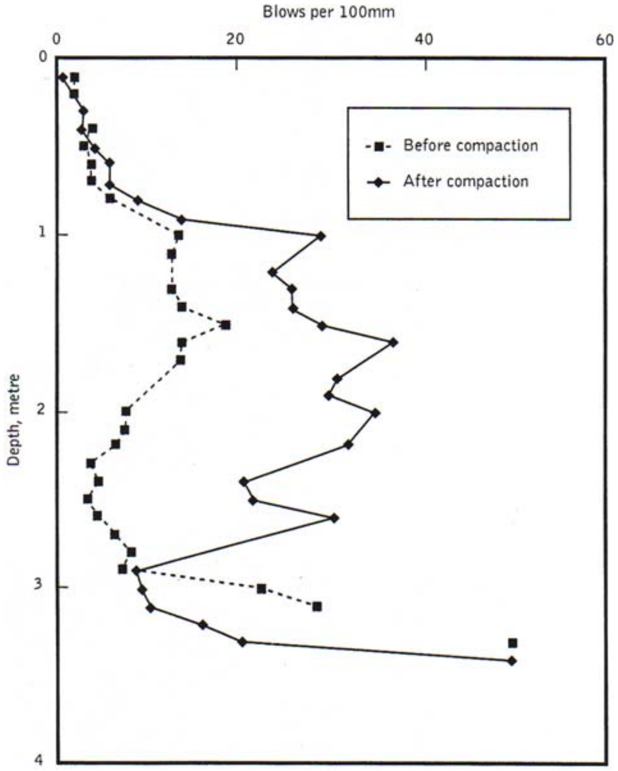


Figure 11. Improvement of wind blown sand and granular fill for wind turbine bases at Blyth (BSP doc 4).

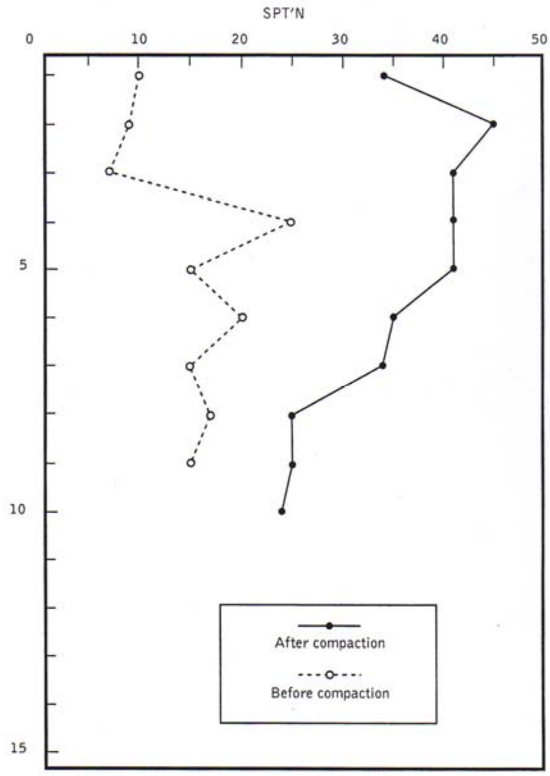


Figure 12. Improvement of sand, stone and brick fill for storage tank in Japan (BSP doc 1).

5. Effectiveness, safety and environmental considerations

Rapid Impact Compaction is used to improve the capacity of a wide variety of loose soils and fills to depths ranging from 1 to 6 m, including small sites. Thereby, the

- compactness of the packing (N values),
- soil stiffness (soil modulus, modulus of subgrade reaction),
- bearing capacity (friction angle, cohesion),
- settlement behaviour,
- uniformity of the soil parameters,
- weak zones identified

can be improved.

Typical areas of application could include projects such as low-rise structures like housing and schools, embankments, roads and pavement areas. Having the Rapid Impact Compactor mounted on a tracked machine gives it the versatility to move about in narrow and limited height spaces, such as within existing warehouses. With regard to its mobility, the RIC is able to be transported as a single unit, with the impact foot removed and the front end lowered horizontally on a flat-bed trailer. The machine can be ready to work just a few minutes after off-loading. If road restrictions apply, the unit can be easily split into two loads with the excavator travelling separately from the hammer. Re-assembly is achieved in less than two hours.

RIC has been successfully used to consolidate gravel, sands, silts, miscellaneous sand/silt/clay and industrial and mining waste fills. It can be applied

- to surface consolidation finally treating on upper strata after the traditional Deep Dynamic Compaction,

- to support foundations by increasing the bearing capacity and reducing settlement,
- to support floor slab by stiffening soils and creating uniform bearing conditions,
- to mitigating liquefaction by increasing the shear wave modulus, and
- to stabilizing waste.

Table 3. Variation in test results using a typical RIC 7000 (Cooper, 2006).

soil type	**N value after compaction**	**depth of effectiveness**
sand	N > 20 (typical N = 20 – 30)	6.0 m
silty sands	N > 15 (typical N = 15 – 20)	4.5 m
sandy silts	N > 10 (typical N = 10 – 15)	3.5 – 4.5 m
miscellaneous fills	N > 10	3.0 – 5.0 m

Load plate tests have shown improvements in soil stiffness of between 2 and 10 within the zone of influence. Bearing capacities from 1 m x 1 m pad foundations or 0.75 m wide strip footing ranging from 100 to 250 kPa have been achieved, depending on the soil (BSP doc 4). The rules of thumb regarding the effectiveness of the RIC 7000 subject to the soil type are given in Table 3.

The effectiveness of the method is influenced by the following factors:

- Soil type / grade:
  - Cohesionless soils densify more easily than cohesive.
  - The presence of silts/fine sand reduces the depth of effectiveness.
- Subsurface stratigraphy:
  - Underground obstructions reduce the compaction´s effectiveness.
  - Dense / soft layers inhibit the compaction beneath.
- Ground water level / moisture content:
  - Excess pore pressure should be allowed to dissipate.
  - Saturated ground can liquefy.
  - Bone dry surface layers can shear.
- Depth and thickness of a compressible layer:
  - It dictates the grid spacing and blow counts.

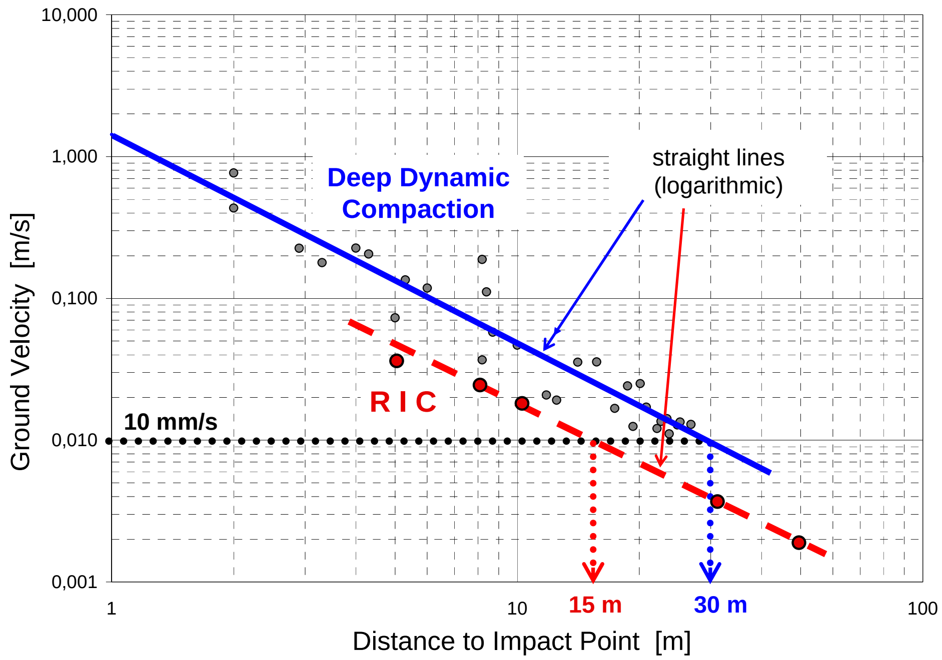


Figure 13. Ground vibrations induced with RIC in comparison with Deep Dynamic Compaction (Adam & Fürpass, 2007).

The RIC can be combined with Heavy Tamping applications where the depth of the fill is great, with stone columns at strategic foundation points, with lime-mixing on clay soils or with blast densification. It can also complement excavation and replacement techniques, surcharging or the ironing pass of traditional DC.

Other activities can take place in close proximity; since the tamping foot remains on the ground during the compaction process, there is no risk of flying debris and no danger from a falling weight as with conventional DC.

Vibration measurements have shown that at a distance of 30 m, the peak particle velocities typically vary between 1 to 5 mm/s (BSP doc 1, BSP doc 3). Vibrations induced with DC at the same distance are in contrast at an order of about 10 mm/s. With RIC, ground velocities of 10 mm/s occur at half the distance, i.e., about 15 m (see Fig. 13). The results to date indicate that without site specific testing, a safe working distance of the RIC to structures can be on the order of 6 m.

The highest air-borne noise levels are generated during the actual impact, with peak levels registering 88 to 92 dB(A) at 6 m on an open site. The equivalent continuous sound level (LEQ) ranges from 85 to 90 dB(A). Thus, a hearing protection zone of 8 m is recommended (BSP doc 1).

Conclusions

Rapid Impact Compaction provides a technically sound and economic method of improving the capacity of a wide variety of loose soils and fills. The Rapid Impact Compactor can work alone on some types of strata (effective treatment in the top layers of typically up to 6 m depth) or in conjunction with other ground improvement techniques, e.g., Deep Dynamic Compaction, where the strata´s depth or grain sizes dictates. Due to the numerous benefits, e.g., compaction control through an on-board computer, operation at safety, quality assurance, versatility and speed, the Rapid Impact Compaction system will become well-established in the dynamic compaction field. Further research, including theoretical, numerical and practical studies, is nevertheless essential to enhance the innovative compaction system.

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