13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)
 ISBN 978-0-9946261-0-3

Comparing the relative merits of dynamic compaction, rapid impact compaction and impact rolling

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ABSTRACT: This paper reviews compaction by dynamic means and discusses factors that influence the effectiveness of the following techniques: Dynamic Compaction, Rapid Impact Compaction and Impact Rolling, all of which have their particular application in ground engineering. Case study examples covering a wide range of projects and soil conditions, are included. The improvement depths for each of these dynamic ground improvement techniques are explored, with the results from the case studies compared with published information to help the reader make informed choices given similar soil conditions. Case studies that report the measured magnitude of ground vibrations are also presented to assist with the assessment of the potential source of nuisance to people or damage to surrounding structures.

1 INTRODUCTION

The knowledge that ground can be improved by dynamic effects has been utilised in various parts of the world for hundreds, if not thousands, of years. There is evidence from the Roman Empire, and early Chinese dynasties, where weights were dropped to compact the ground, and drawings showing a machine developed to drop weights for ground compaction in the Middle Ages (Munfakh, 2002).

In more recent times, we have progressed with Deep Dynamic Compaction (DC), Rapid Impact Compaction (RIC) and Rolling Dynamic Compaction or Impact Rolling (IR), which all offer different in-puts and outcomes. DC is generally applied by drop-ping a weight of 5 to 25t from heights as much as 20 to 25m, using a crane as shown in Figure 1.

Figure 1. Deep Dynamic Compaction equipment.

RIC, on the other hand, is a higher frequency of a 5 to 16t hydraulic hammer, dropping 0.8 to 1.5m, pounding a tamping plate 1 to 2.4m diameter, with the compactor being mounted on an excavator, as shown in Figure 2.

Figure 2. Rapid Impact Compactor.

IR is applied by 3, 4 or 5-sided non-circular modules weighing 6 to 12t, towed by a dedicated tractor at speeds of 10-12km/h, as shown in Figure 3.

Figure 3. The “square” (4-sided) Impact Roller.

DC and RIC are applied on a predetermined grid, usually with primary and secondary passes, while the IR is tracked multiple times over the site.

Table 1 is indicative of the production rates achieved by these means.

Table 1. Dynamic technique productivity.

Technique	Weight (t)	Drop Height (m)	F* (blows/min)
DC	5-25	<25	0.5-1
RIC	5-16	<1.5	30-60
IR	6-12	<0.25 (+kinetic energy)	90-120

* F = Frequency of application.

All dynamic treatment devices distort the ground surface to a greater or lesser degree, and support plant is required to fill craters, smooth undulations and, in some cases, to compact the top disturbed zone with a conventional circular drum roller.

Soil properties, including classification and consistency or relative density, and groundwater conditions are the most significant site-specific factors in addressing ground improvement options and the requirements for, and suitability of, dynamic techniques. Other factors include the proposed development layout, loadings, site modifications (e.g. cut and fill) and sensitive receptors (e.g. nearby structures and residents).

2 PRINCIPLES

2.1 *Overview*

Ground improvement by dynamic means manifests it-self as enforced surface settlement (Berry et al., 2000). It has been shown that there is little gain in ground improvement after the application of a certain quantum of energy.

Amongst the parameters of importance in the prediction of the depth of treatment due to dynamic processes are the mass, the impact area, drop height, impact velocity, soil stiffness, deceleration, energy and momentum.

Where ground does require improvement (e.g. where poor, soft or loose conditions mean that excessive settlements may occur), action is needed, and if it is deemed suited to dynamically densifying the soil, the decision on the method adopted will depend primarily on the desired depth of treatment, which is associated with loadings, dimensions and sensitivity of the proposed development.

2.2 *Decision tree*

The process to decide whether a site is suited to the application of a dynamic compaction technique is a step-wise exercise, with a decision tree as follows:

Is the site suited to dynamic treatment?

- No - seek an alternative option
- Yes - choose between DC, RIC and IR (or a combination thereof), considering:
  - Soils
  - Depth
  - Space
  - Neighbours
  - Costs
  - The size of the proposed development, loads and performance parameters.

The two critical aspects addressed in this paper are depths achieved using these treatments and the associated ground vibrations generated.

3 DEPTH EFFECTS

3.1 *Dynamic compaction (DC)*

The maximum anticipated depth of influence of DC, in relation to the energy applied, approaches 20m for an energy per blow of 1,000tm, while the majority of the data, reflecting an energy per blow of 200-500tm, indicate a depth limit of approximately 10-15m (BRE 2003). Table 2 summarises data from published case studies. It should be noted that the reported depth of improvement often reflects the specification, material variations at depth and the types of materials.

Table 2. DC improvement depths.

No.	Reference	Soil type	D* (m)
1	McIntosh & Barthelmess (2012)	Landfill	<14
2	Tarawneh et al (2017)	Sand	>8.0
3	van Impe & Bouazza (1996)	Landfill	>8.0
4	Serridge (2002)	Silty sand	>6.0
5	Serridge (2005)	Landfill	>6.0
6	Slocombe (2013)	Sand	>10
7	Slocombe (2013)	Loose/weak soils	<14
8	Avalle & Tabucanon (2012)	Sand	8.0

* D = Improvement depth.

3.2 *Rapid impact compaction (RIC)*

RIC has been found to be most effective on gravels, sands, industrial and mining wastes, municipal waste, and, in some cases, on silts. The presence of finer grained soils reduces the depth of influence. The depth and thickness of the compressible layer/s dictate the grid spacing and blow count. Table 3 summarises published data for sites on which RIC has been applied.

Table 3. RIC improvement depths.

No.	Reference	Soil type	D* (m)
1	Adam & Paulmichl (2007)	Sand	6.0
2	Adam & Paulmichl (2007)	Silty sands	4.5
3	Adam & Paulmichl (2007)	Sandy silts	3.5-4.5
4	Adam & Paulmichl (2007)	Miscellaneous fills	3.0-5.0
5	Berry & Narendranathan (2010)	Gravelly sand	>6.0
6	Serridge & Synac (2006)	Granular fills	4.0
7	Tarawneh et al (2017)	Sand (calcareous)	3.0-4.0

* D = Improvement depth.

3.3 *Impact rolling (IR)*

Scott et al (in print, ICE-GI) discuss the most critical variable in quantifying the depth to which an impact roller can improve ground: the soil type. The work of Scott et al uses an energy-based approach to combine the effects of soil type, module mass, drop height and towing speed to predict improvement depths for in-situ compaction that are in broad agreement with previously published data.

Table 4 summarises seven published case studies that have used a 4-sided 8t impact roller to improve ground in-situ, while an eighth case used the 12t 4-sided IR and a ninth case examines the effects of a 3-sided module. Table 4 confirms that a greater depth of improvement can be achieved in granular soils compared to cohesive soils; this trend is also applicable to the other ground improvement methods discussed in this paper. Improvement in clayey soils is contingent on the moisture content being low enough (e.g. below modified optimum), to minimise heave effects, while sands respond well even with a relatively shallow groundwater table (Hillman 2007).

Table 4. IR improvement depths.

No.	Reference	Soil type	D* (m)
1	Clifford (1978)	Sand	>2.5
2	Avalle and Young (2004)	Fill (clay)	1.0
3	Avalle (2004)	Fill (sand)	>2.0
4	Avalle and Mackenzie (2005)	Fill (clay)	2.0
5	Avalle and Carter (2005)	Sand fill over sand	3.0
6	Scott and Suto (2007)	Fill (gravelly clay)	1.5
7	Scott and Jaksa (2014)	Clayey sand fill over over natural clay	1.75
8	Hillman et al. (2007)	Sand (calcareous)	3.0
9	Chen & Lv (2017)	Sand (loose dry)	2.5

* D = Improvement depth.

3.4 *Depth summary*

Figure 4 presents a summary of the above information, as an update of a widely utilised diagram.

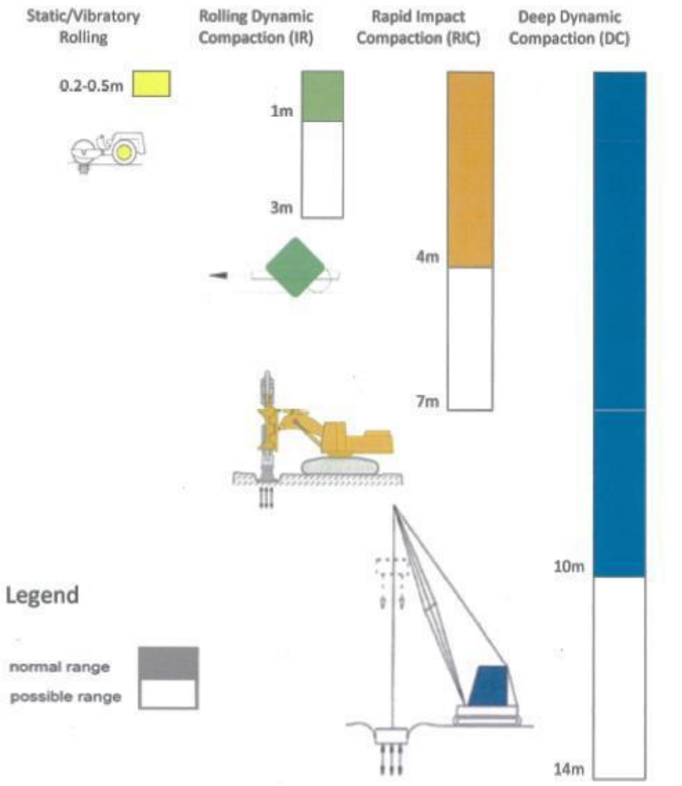

Figure 4. Comparative depth effects.

4 VIBRATIONS

4.1 *Dynamic compaction (DC)*

Ground vibrations, measured as Peak Particle Velocity (PPV), have been reported for several projects, a selection of which is shown in Figure 5. Their variation is a function of the type of material being compacted and the energy of compaction involved in the DC process.

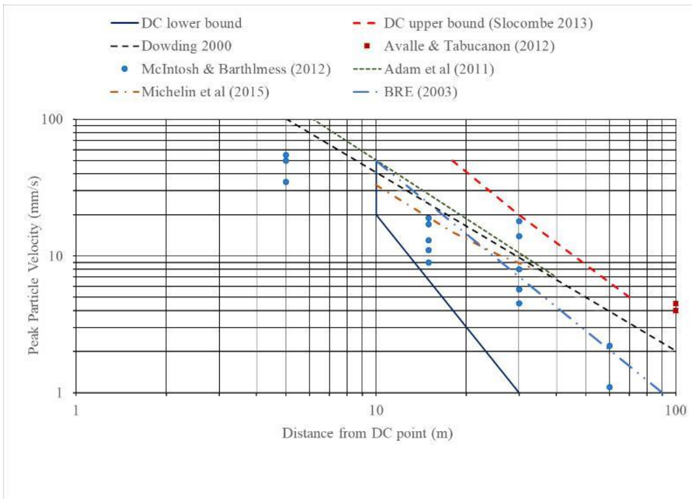

Figure 5. DC vibration decay.

4.2 *Rapid impact compaction (RIC)*

Measured ground vibrations due to RIC are shown in Figure 6.

Included with the data extracted from published information is a recently completed project in NSW. Ground conditions at this site comprised up to 1m of granular fill overlying sandy soils, with some intermediate clay at some locations. The vibration response to RIC can be seen to be similar, in general, apart from a case of a 9t hammer on dense gravels (Adam et al 2011).

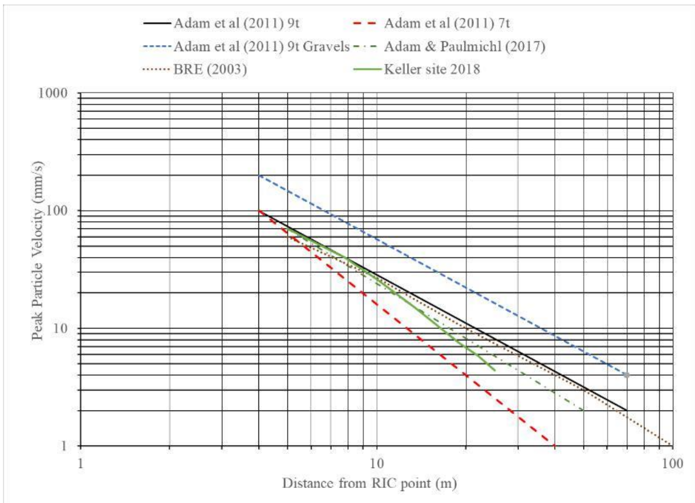

Figure 6. RIC vibration decay.

4.3 *Impact Rolling (IR)*

Ground vibrations induced by a 12t 4-sided impact roller were measured during an IR trial at a site known to consist of non-engineered fill. The site contained historical infrastructure that was sensitive to vibration and settlement, so a vital objective of the trial was to determine a minimum distance for IR to ensure that vibrations did not exceed 2 to 3mm/s PPV, commensurate with the risk of potential cosmetic damage to historic structures. Ground vibrations were measured using accelerometers recording acceleration in three orthogonal directions and at varying lateral distances from an impact roller. The measured accelerations were converted to PPV, an indicator of ground vibration damage.

The relationship between PPV versus distance is shown in Figure 4, where a linear trend in vibration decay can be observed (logarithmic scale on both axes). Avalle (2007) collated vibration data from 25 different sites that were compacted with an 8t 4-sided impact roller and produced results in a similar format. From this body of work, Avalle (2007) captured 85% of vibration results via the use of a simple expression for obtaining an initial estimate of the magnitude of PPV (measured in mm/s), equal to 100/D, where D is the distance in metres. Comparing the expression proposed by Avalle (2007) with the site data in Figure 7, it is evident that the proposed relationship provides a reasonable estimate of maximum PPV for distances exceeding 50m from a 12t 4-sided IR, but slightly less conservative for closer distances.

Whilst the rate of vibration decay is dependent upon a number of factors (such as ground conditions and towing speed of the roller), the heavier 12t module adopted in this trial was undoubtedly a contributing factor as to why greater values of PPV were measured in this case study compared with other sites that were compacted using an 8t IR as reported by Avalle (2007).

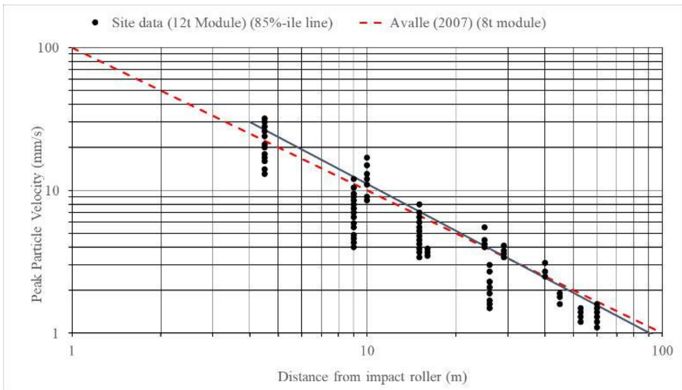

Figure 7. IR vibration decay (12t module cf. 8t module).

4.4 *Vibration comparison*

Vibrations induced by compaction can be a potential source of nuisance to people or damage to surrounding structures. Field measurements of the magnitude of vibration are useful to assess this risk. Each compaction method will achieve a given range in PPV depending on the site conditions.

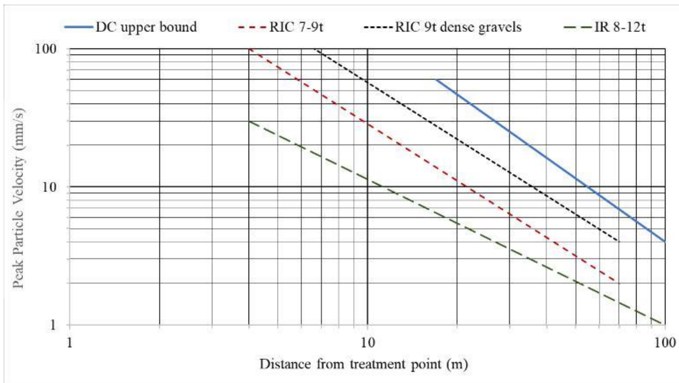

Figure 8. Comparison graph of dynamically induced vibrations.

A perusal of Fig. 8 indicates that DC is at the higher range in terms of PPVs; for example, at a distance of about 30m DC can generate a PPV of 15mm/s, whereas an IR of 8-12t may only generate a PPV of about 2.5mm/s.

5 CONCLUSIONS

Dynamic Compaction, Rapid Impact Compaction and Impact Rolling are three improvement techniques that all compact ground by dynamic means. The choice of the method requires an understanding of the depth of improvement that can be typically achieved; at some sites, more than one method may be appropriate as the target improvement depths of the three methods described can be complementary. For each technique, a number of published case studies are summarised to inform the reader of typical depths that may be achieved in similar conditions. Factors that affect whether a site may be improved using dynamic techniques are discussed. Vibration effects are often an important consideration; case studies that have monitored vibrations for particular ground and energy conditions give indicative relationships of vibration decay for each of the dynamic ground improvement techniques discussed.

6 ACKNOWLEDGMENTS

The authors acknowledge AW Edwards, the main contractor at the Alexandria site where recent vibration data was collected by Keller Pty Ltd during RIC works.

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