Ground Vibrations Induced by Dynamic Compaction and Rapid Impact Compaction

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ABSTRACT
This paper presents results of ground vibrations measured on two projects where ground densification was performed with both conventional Dynamic Compaction, using a crane, and Rapid Impact Compaction using an excavator mounted hydraulic hammer rig. The gathered results permit a normalisation method developed for Dynamic Compaction and an evaluation of the effects of soils type and working methods on resulting ground vibrations.

RÉSUMÉ
Cet article présente les résultats de mesure de vibrations pour 2 projets où des travaux de densification des sols à l'aide de compactage dynamique au moyen d'une grue et d'un atelier de compactage rapide par impacts ont été utilisés. Les données obtenues ont permis de vérifier une méthode de normalisation des données et d'évaluer l'effet des types de sol et des méthodes de travail sur le niveau de vibrations généré.

1 INTRODUCTION

The densification of loose soils by falling weights is an ancient method of improving ground. First known technical reference on the subject involved a site in Germany (Loos, 1936). This technique was later used on routine basis by late Louis Ménard at the end of the 1960's. Since then, Dynamic Compaction (DC) (also referred to as impact densification, heavy tamping and dynamic consolidation) has become an accepted method of site improvement. This method is used to treat foundation soils in order to increase the bearing capacity, reduce the settlements under service loads and mitigate the risk of liquefaction in loose saturated soils. The method consists of systematically dropping large weights on the ground surface to densify the underlying soils and repeating the operation on a grid layout over the surface. Weights typically vary between 10 and 25 tonnes with drop height of 10 to 30 metres. The use of +/- 15-tonne weights is common. Depths of improvement range typically between 9 and 12 metres.

Dynamic Compaction is typically economically and technically advantageous for reclaimed land, heterogeneous or granular fills and loose natural sand to sandy silt deposits. It is also used to form Dynamic Replacement (DR) stone pillars in soft ground (silty clay or peat) as a means to reinforce these soil types.

Dynamic compaction methods have been used for a variety of projects including buildings, streets, highways, airport runways and facilities, power plant facilities, dams, tank farms, dockyards, etc. It has also been used to reduce the volume of garbage in municipal dumps and also to collapse underground cavities/voids.

In the early 1990's, a device originally developed for the rapid repair of bomb craters on runways and airfields by the British Armed Forces became available to civil works. This device, until then known as the Rapid Runway Compactor, is marketed as a ground improvement technique under the name of Rapid Impact Compaction (RIC). This technique finds a niche between conventional roller compaction and conventional Dynamic Compaction. With this technique, a modified hydraulic piling hammer acting on an articulating circular steel base is used to densify soils through repeated impacts on the ground surface. The ram used is typically 7 to 9 tonnes and the adjustable drop height is typically around 1 metre. Although, the energy per blow is small relative to DC methods, the equipment permits application of energy at an average rate of about 40 blows per minute.

Typical depth of influence is about 5 to 6 metres in granular soil conditions like loose sand, although greater depth of improvement can be obtained in very favorable soil conditions. In silty soils, the depth of influence is reduced and improvement can usually be measured up to 4 to 5 metres.

Although Dynamic Compaction and Rapid Impact Compaction generate vibrations that are annoying to neighbors and potentially hazardous to nearby structures, the two techniques have many advantages in terms of cost, schedule and effectiveness. With less energy per blow, Rapid Impact Compaction is typically presented as a technique generating lower vibrations than the heavier tampers used with Dynamic Compaction.

This paper reviews the vibrations generated by these two techniques on specific projects where both techniques were used. Measured vibration levels are compared to each other in terms of energy per blow and distance from the source. They are also compared to safe levels of vibrations typically set by regulatory or municipal agencies.

2 DYNAMIC COMPACTION

Dynamic Compaction involves the use of heavy steel masses known as tampers or pounders typically weighing 10 to 20 tonnes, which are dropped in virtual free-fall from heights of 10 to 30 metres. Larger weights of 30 to 40 tonnes are occasionally used for more demanding/deeper applications. The largest weight ever used was a 172 tonne tamper built by Louis Ménard for the densification of the Nice airport in France in 1977 (Gambin, 1983). Figure 1 shows the Giga-Machine, as it was called, at work on the site of a future runway. Similarly, special devices have been built to permit drops of 40 metres. For the construction of the Peñitas Dam in Mexico in 1980 (Moreno et al, 1983), a special tripod capable of lifting a 40 tonne tamper to a height of 40 metres used for the densification of 15 metres of loose sand. Nevertheless, for the great majority of projects, specially adapted heavy crawler cranes are used. These cranes are usually limited to tamper weights of 25 tonnes and drop heights of 30 metres.

Figure 1. Giga-machine lifting a 172 tonne tamper at the Nice Airport (France).

Figure 2. 125 ton capacity crane and 15 tonne tamper used for the Peribonka Dam (Québec) foundation densification.

Figures 2 and 3 show specially modified crawler cranes more typically used for Dynamic Compaction operations. The DC rig shown in Figure 2 is lifting a 15 tonne tamper to densify the foundation of a dyke at the Peribonka hydro-electric dam site in northern Quebec. The rig in Figure 3 is lifting an ironing tamper, which is a low energy 10 tonne steel plate of 2.4 metres square.

Figure 3. Crane lifting an ironing 10 tonne tamper

Depth of improvement is typically in the range of 9 to 12 metres when tampers of 15 to 20 tonnes are dropped from 18 to 23 metre height (Mayne et al, 1983). Greater depths of improvement can be achieved with larger weights or greater drop heights. For a specific project, the specialty ground improvement contractor would typically select the most appropriate tamper weight and drop height combination to obtain the targeted ground improvement requirements specified for the site soils and loading conditions.

3 RAPID IMPACT COMPACTION

Rapid impact compaction involves the use of a specially adapted hydraulic pile hammer acting on a special articulated base or foot. The hammer is generally equipped with a 7 to 9 tonne steel weight dropped form a maximum height of 1.2 metres. The driving cap connected to the base allows articulation. The steel impact base has a diameter of 1.5 metres. This impact base remains in contact with the ground surface during the compaction operation.

Energy per blow is 25 to 40 times less than typical energy per blow used in Dynamic Compaction. To obtain significant improvement, the device must apply a much greater number of blows, which is facilitated by a rate of impact of about 40 blows per minute.

A hydraulic excavator base is typically used as a carrier for the RIC unit. Figure 4 shows the Geopactor RIC rig at work.

Rapid Impact Compaction can typically improve sandy soils to a maximum depth of 5 to 6 metres (Mohammed et al 2010). In sandy silt, the depth of improvement is typically in the range of 3 to 5 metres (Adam and Paulmichl, 2007).

Figure 4.Geopactor RIC rig at work in North Bay (Ontario).

4 GROUND VIBRATIONS

The impact of a falling weight with the ground surface causes vibrations. These vibrations can be potentially damaging to nearby building structures and sensitive equipment, as well as annoying to people. Consequently, proper monitoring of ground vibration levels and vibration frequencies must be undertaken to protect all interested parties. Vibrations caused from dynamic compaction and RIC operations are characterized by relatively low frequency waves.

The magnitude of ground vibration levels may be measured in terms of displacement (s), velocity (v) or acceleration (a). Often, harmonic motion is assumed when converting from one parameter to the other parameters. The relationship among peak values of harmonic waves may be expressed by:

$$a = 2\pi f v = (2\pi f)^2 s \qquad [1]$$

where f is the frequency of vibration.

Peak particle velocity (PPV) is generally used to define damage criteria for buildings/structures and annoyance levels to people, especially in urban environments. Peak particle velocity is the maximum vector sum of the particle velocities measured in the 3 principal axes (x, y, z) during an event.

Peak particle velocities are usually measured at ground level adjacent to the structure being monitored.

4.1 Damage Criteria

One of the most extensive studies of ground vibrations was made during the 10 year research program by the U.S. Bureau of Mines (USBM), (Nicholls et al, 1971). This study sets the threshold for safe ground vibrations at 51 mm/s (2 inch/s). This initial criterion did not account for the vibration frequency and USBM later replaced it by RI 8507 which takes vibration frequency in the 1-100 Hz range into account (Siskind et al, 1980). Figure 5 shows the revised criteria set by RI 8507.

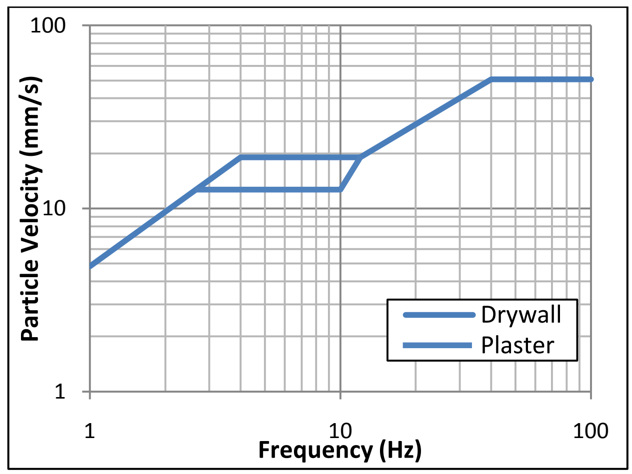

Figure 5. Safe criteria for one or 2 story houses as proposed by USBM RI 8507 (Siskind et al, 1980).

The RI 8507 study focused on one or two storey residential structures. These structures are typically built with a wooden frame and their natural frequency may be in the 5 to 20 Hz range. The resulting guidelines can be used to control the onset of cosmetic cracking, mainly cracks in dry-wall (gyproc) or plaster. According to Medearis (1976), natural frequencies of houses range from 8 to 18 Hz (one-story) and 4 to 11 Hz (2 stories). Amplification factors for houses can vary between 1.5 and 8, with 4.0 being typical (Siskind et al 1980). Since the vibrations are measured at ground level, effects of vibration amplification are taken into account with these criteria.

Table 1
Criteria of ground vibrations for structures

Type of structure	Criteria of ground vibrations (mm/s)
Commercial and engineered structures	102
Buried utilities, wells and pipelines	127

Masonry foundation	127
Concrete blocks wall	76
Mass concrete	254
Underground works	305

For other types of structure, specific vibration safe limits presented by Wiss (1968), Crawford and Ward (1965) and Siskind (2000) are of interest. They are summarized in Table 1.

Since the guidelines of RI 8507 accounts indirectly for soil-structure interaction, possible amplification due to resonance structural vibrations is included in the proposed criteria. These amplifications can raise the vibrations at the structure level by a factor ranging from 2 to 4 in low rise residential buildings. To correctly take the amplification factor into consideration, it may be more appropriate to monitor the vibrations at the structure level instead of at the ground level. In such case, a vibration criteria of 51 mm/s can be used (Svinkin, 2003).

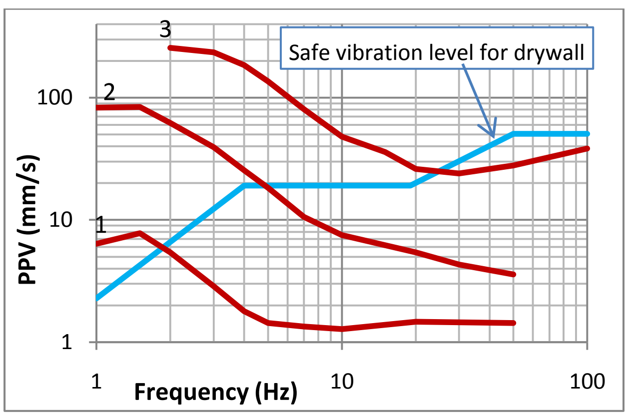

Figure 6. Human sensitivity to vibrations (Wright and Green, 1959) and safe level for drywall as per RI 8507 (Siskind et al, 1980).
Legend: 1 = Perceptible; 2 = Unpleasant to most; 3 = Intolerable.

4.2 Human Sensitivity

Regardless of the safe level of vibrations for structures/utilities, complaints or claims can be an issue at vibration levels much lower than the safe levels for structures. Humans can detect vibrations at levels that are much lower than those required to damage dry wall or concrete block structures. The sensitivity level of humans to transient vibrations varies for each person and with the duration of the vibrations. Human sensitivity to steady-state vibrations (vibratory roller/jack hammer) is much higher than for transient vibrations. For Dynamic Compaction, sensitivity to transient vibrations is more appropriate. The results of a study on the human perception of vibrations by Queen's University are summarized in the chart of Figure 6 in terms of particle velocity and frequency (adapted from Wright and Green, 1959).

As shown on this chart, at a frequency of 10 Hz, vibrations are perceptible at a PPV of 1.3 mm/s. They become unpleasant at 7.5 mm/s and are intolerable at 50 mm/s. At this frequency, the safe level for dry-wall cracking in houses is reported to be 19 mm/s.

4.3 Vibrations Caused by Impacts to the Ground

In blasting, vibration PPV is related to the scaled distance, which is defined as the distance divided by the square root of the weight of explosive used for the blast (Siskind et al, 1980). It is common to use a similar approach for Dynamic Compaction, where the weight of explosive is replaced by the energy per blow of the tamper mass. For preliminary estimates, Mayne et al (1984) proposed the following formula as a conservative upper limit to the ground vibration levels:

$$\text{PPV (mm/s)} \leq 70\left(\frac{\sqrt{W\,H}}{d}\right)^{1.4} \qquad [2]$$

Where W is in tonnes and H and d are in metres.

Mayne et al (1984) noticed that PPV measurements tend to increase with the number of blows imparted per compaction point as the materials become increasingly denser during the impacting process.

Equation 2 relates to the scaled distance concept commonly used in blast vibration monitoring, where both the distance and the amount of explosive are together on the abscissa of a log-log chart. Physically, there are no obvious reasons for the exponent to be the same for the distance and the square root of the energy. Mayne (1985) proposed a new approach where the PPV would be normalized by the impact velocity and the distance by the radius of the tamper. For a free falling body, the impact velocity is given by:

$$v_i = \sqrt{2\,g\,H} \qquad [3]$$

Where g is the gravitational acceleration and H is the drop height.

Based on vibration monitoring data from 12 different sites, Mayne (1985) proposed the following approximation:

$$\text{PPV} = 0.2\,\sqrt{2\,g\,H}\,(d/r_o)^{-1.7} \qquad [4]$$

Where d is the distance, from the point of impact and r_o is the radius of the tamper. PPV, g and H are in consistent units.

With this approach, Mayne (1985) could attain a better fit for his set of data.

5 VIBRATION MONITORING ON SPECIFIC PROJECTS

Over the years, a large database of vibration monitoring information has been accumulated both for Dynamic Compaction and Rapid Impact Compaction. Figure 7 presents vibration data gathered for ground improvement using either Dynamic Compaction or RIC methods, on a variety of sites. As shown on this graph, average values for RIC are lower than the average value for DC. Also, PPV for RIC shows a rate of attenuation that is faster than for DC. At larger distances from the impact point, vibrations measured for RIC are smaller for two reasons, the energy input is smaller at the point of impact and the rate of attenuation is greater.

To be able to account more specifically for possible effects of soil type, soil stratigraphy and groundwater level on DC/RIC vibration generation, vibrations were monitored on two projects where both a DC rig and a RIC rig were used to compact the same soils. The first project was an extension of an airplane hangar in Trois-Rivières (Québec) and the second was for the extension of an industrial building near Québec City. In both cases, the RIC was used to treat soils near the existing building, while a DC rig was used for the Dynamic Compaction of the remaining areas requiring treatment. This approach permitted the lower impact level of the RIC to be used close to the existing building and the economic and schedule benefit of the rate of compaction that can be achieved with a DC rig to reduce the overall cost and duration of the ground improvement.

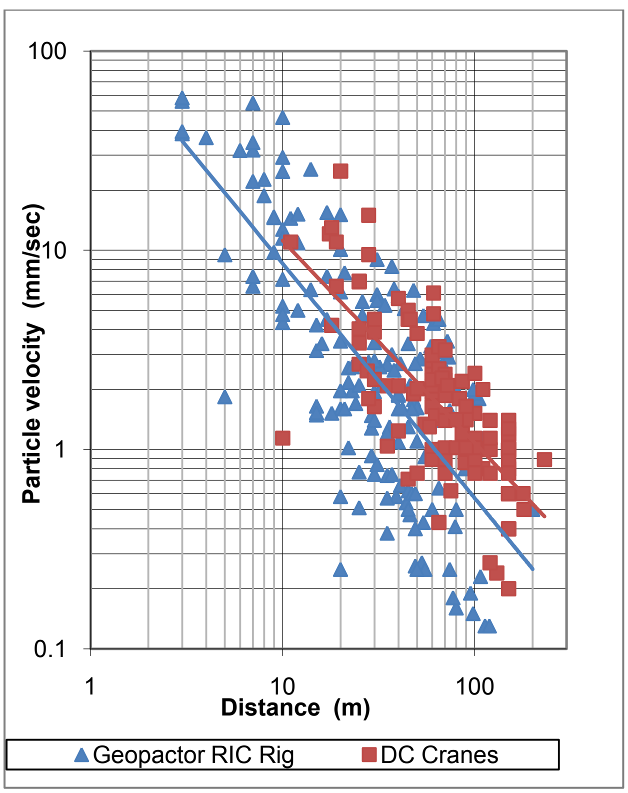

Figure 7. Vibration data for DC and RIC on various sites.

5.1 Trois-Rivières Airplane Hangar

Dynamic Compaction was required for the extension of an airplane hangar at the Trois-Rivières (Québec) Regional Airport. This building had been built when the National Building Code seismic resistance requirements were less stringent than they are today. For the extension, the ground had to be densified to respect the requirements of the 2005 Building Code.

This site was characterized by a thick deposit of fine sand with some silt to depths of more than 7 metres. The density of the sand varied from very loose to compact, with SPT N values ranging typically from 3 to 11. Groundwater was located at a depth of 1.7 metres.

To satisfy the requirements of the building code, soils had to be densified to obtain $N_{1,60cs}$ values greater or equal to 16.

To densify the soil under the area of the extension without risking damage to the existing building, a BSP RIC rig was used for compaction within 20 metres of the building, and a DC crane rig was used on the remainder of the site.

Figure 8. RIC rig working close to the existing hangar.

The RIC rig was equipped with a 9 tonne hammer acting on a 1.5 metre diameter base. With this equipment, the height of drop is adjustable between 0.2 and 1.2 metres. A John Deere 450 excavator is used as a carrier. Figure 8 shows the rig working within 2 metres of the existing building.

For the Dynamic Compaction, a DC crane was used to lift and drop a 12 tonne tamper. The height of drop varied between 12 and 18 metres. Figure 9 shows the crane at work at a distance of 30 metres from the existing building.

As a risk measurement procedure and measure of prevention against claims, an extensive pre-compaction building inspection was completed by an independent engineering firm. This same firm also monitored the vibrations during the compaction works.

Figure 10 shows the peak particle velocities measured on the site with the RIC and the DC crane as a function of distance from the impact point. There is a clear distinction between the two sets of data. Based on this data, if strict compliance with a safe level of vibrations of 20 mm/s was required, it would be possible to work at a distance of 10 m from the structure with a RIC rig, while it would be necessary to work at 20 m from the structure with a DC rig.

Figure 9. DC crane working away from the building.

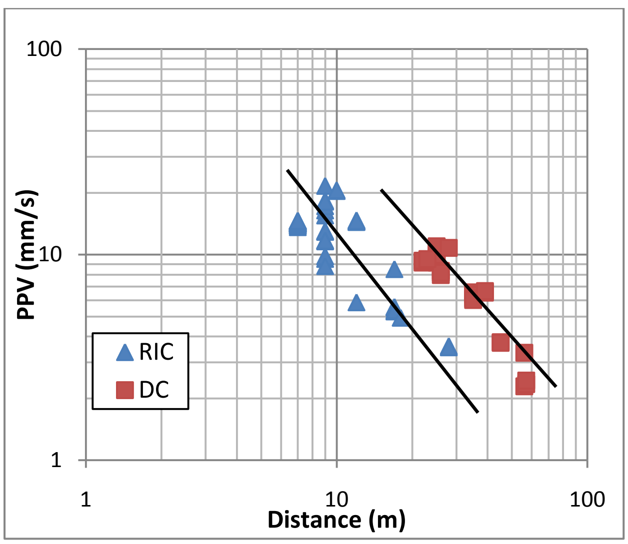

Figure 10. PPV measured for RIC and DC on the Trois-Rivières site.

Figure 11 shows the particle velocities and the vibration frequency for each rig. Vibration frequencies for the DC rig are generally between 5 and 10 Hz. For the RIC rig, frequencies are generally between 20 and 30 Hz. Since RIC frequencies are higher than the typical natural frequencies of houses, we can expect less vibration amplification and it can become possible to work closer to houses since the safe level of vibrations defined by USBM RI 8507 increases with increasing frequency.

Figure 12 shows the normalized data from Figure 10 with respect to Mayne (1985) who proposed normalizing vibrations with the velocity of the impact and the distance with the radius of the tamper. As shown on this plot, the data for the two rigs tend to form a straight line. Thus, vibrations generated by the RIC rig are smaller than those produced by the DC rig for two reasons; firstly the drop height is smaller and secondly the diameter of the RIC base is smaller than the width of the tamper.

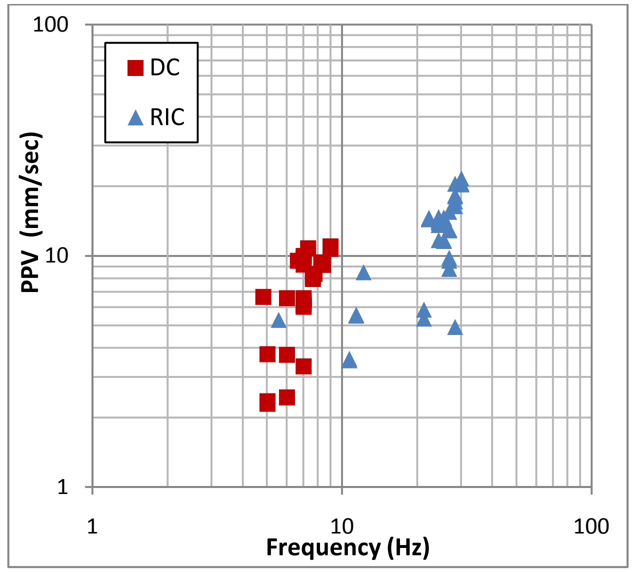

Figure 11 Distribution of the vibration frequencies for DC and RIC on the Trois-Rivières site

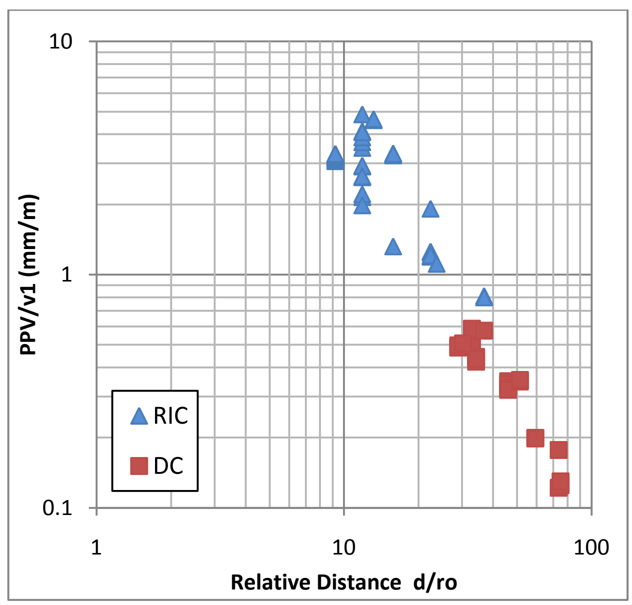

Figure 12 Normalized PPV as a function of normalized distance for RIC and DC on the Trois-Rivières site.

5.2 Québec City Industrial Building Extension

This building extension required that the in-situ soil be compacted to ensure uniform soil conditions over the foundation area. The site is underlain by a recent fill material composed of crushed stone that was placed without extensive quality control. The fill thickness varies between 2 and 6 metres and rests on bedrock. The area within 20 metres of the existing building was treated with a RIC unit equipped with a 9 tonne hammer and a 1.5 metre diameter base.

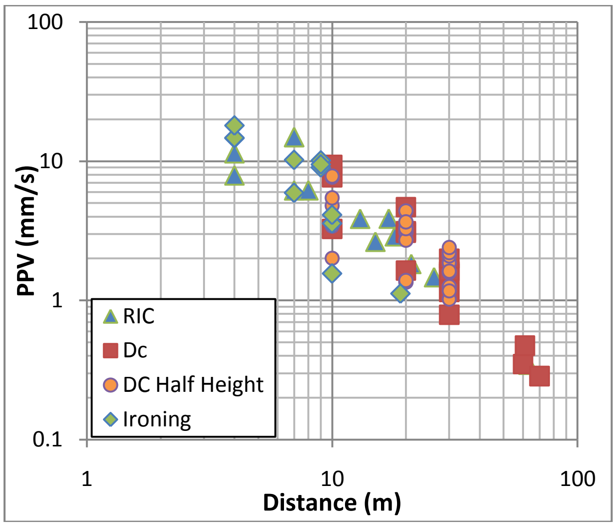

Figure 13. Vibrations measured for different energy per impact at Québec City site.

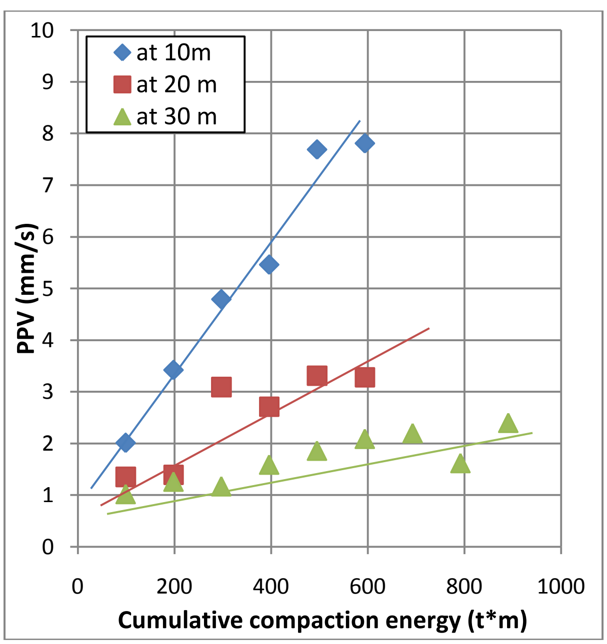

Figure 14. Effect of cumulative energy on the measured vibrations at 3 different distances for the Québec City site.

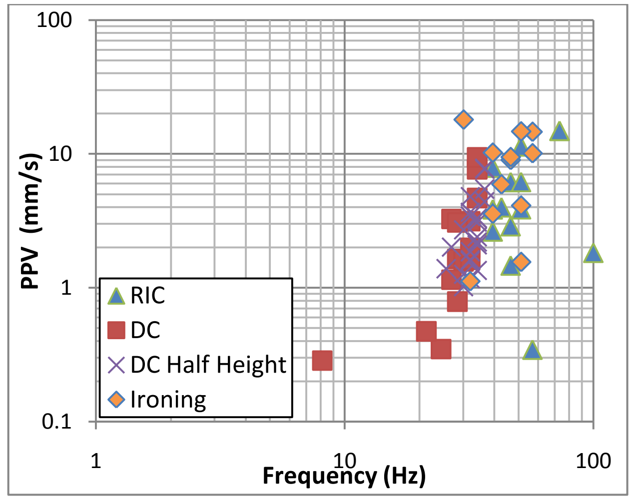

Figure 15. Distribution of the vibration frequencies for DC and RIC at the Québec City site

The remainder of the site was treated with a DC crane lifting an 11 tonne tamper from a nominal height of 18 metres. For the portion of the DC treatment area closest to existing structures, the tamper was dropped from half the full height (i.e. 9 metres).

Vibration monitoring was performed by an independent engineering firm who also conducted the pre-compaction survey of the nearby buildings.

Results of the vibration monitoring during the RIC and DC work are shown on Figure 13. As observed by Mayne et al (1984), the level of vibration tends to rise as cumulative energy is applied on a compaction point.

Figure 14 shows a significant increase in vibration as the number of blows at a specific compaction point increases. For the first blow, the vibration level was measured between 1 and 2 mm/s. After 6 blows the vibration level reached close to 8 mm/s at a distance of 10 m from the point of impact. The rise is less significant for points located at 20 and 30 metres from the point of impact, however they are still significant in relative terms.

Figure 15 shows the distribution of vibration frequency for the two compaction rigs according to the level of energy per blow. For DC tampers dropped from full height, frequencies are typically in the range of 25 to 35 Hz with similar values when the drop height has been reduced to half. For ironing using DC methods and for RIC, the frequencies typically are in the range between 40 and 50 Hz. Theses frequencies are significantly higher than what was measured at the Trois-Rivières site. This could be explained by the type of soil and the pre-treatment densities already existing at the Québec City site. Note that in both cases, the vibration frequency for DC is less than for RIC.

Figure 16 shows the same set of data normalized as proposed by Mayne (1985). Considering the number of drops (or the cumulative energy) on a single point had a significant effect on vibration levels on this site, it is difficult to compare the DC data with the RIC data since the cumulative energy on a given point was not measured during the vibration monitoring.

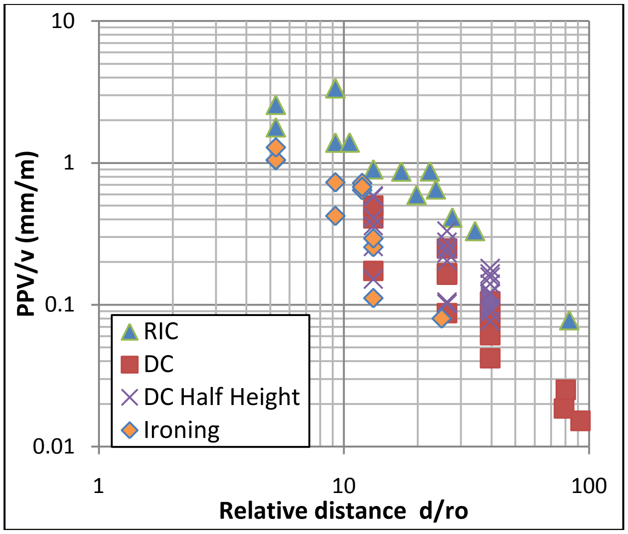

Figure 16 Normalized PPV as a function of normalized distance for RIC and DC at the Quebec City site.

6 CONCLUSIONS

The effects of Dynamic Compaction (DC) and Rapid Impact Compaction (RIC) methods are presented. Vibrations generated by these two compaction methods are compared for a variety of sites as well as for two sites where both techniques were used.

At equal distances, vibrations generated by the RIC methods are less than those produced by the DC method. This could be explained by the combined effect of smaller drop height of the hammer used in RIC and the smaller diameter of the tamper.

The data also shows that vibration frequencies produced by RIC are higher than those produced by the DC rig. Since RIC frequencies are higher than the typical natural frequencies of houses/structures, less vibration amplification can be expected making it possible to work closer to houses since the safe level of vibrations define by USBM RI 8507 increases with increased frequency.

The data gathered on the two DC/RIC projects also showed the importance of taking into account the cumulative energy applied on a point since vibrations tend to rise as the cumulative applied energy rises. Since projects performed with RIC rigs typically apply less energy per point than those completed with DC rigs, this could be another factor influencing the lower vibrations measured on RIC sites.

Finally, for compaction work close to existing buildings/utilities, the RIC equipment might be preferred to the DC rig since it generates lesser vibrations and higher frequencies. Further, RIC energy is applied in a more controlled manner, limiting the risk of exceeding target vibration levels.

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