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# Measurement of subsurface vibrations during sinkhole remediation by vibrocompaction, Alkimos, Perth, WA

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Vibrocompaction has been used successfully since the 1930s to compact loose cohesionless soils. Whilst there is information available for the attenuation of vibrations from construction plant at the ground surface, there is little or no published data for the attenuation of subsurface vibrations to allow assessment of potential effects on buried assets. This paper presents a vibrocompaction case study for improving loose cohesionless soils resulting from sinkhole features which formed directly over a tunneled Water Corporation asset. A vibrocompaction trial was carried out with a number of triaxial geophones installed at various depths to allow the attenuation of vibrations to be measured at different horizontal and vertical offsets. These measurements have been presented as well as some preliminary guidance for estimating the attenuation of subsurface vibrations from the vibrocompaction probe.

## 1 INTRODUCTION

The Quinns Main Sewer (QMS) is a DN2000 (2 m internal diameter and 2.45 m external diameter) reinforced concrete, HDPE plastic lined pipe (RCPL) which was constructed in 2008/2009. Tunneling methods (pipe jacking) were adopted for construction of the sewer over the majority of the alignment, utilising a dual mode earth pressure balance/slurry tunnel boring machine (TBM). Unfortunately records of grouting around the annulus of the pipe could not be recovered.

Sometime after its construction and prior to redevelopment of the land in 2016/2017, two sinkholes were identified during a walkover survey above a section of the QMS. A geotechnical investigation was subsequently completed by Golder Associates Pty Ltd (Golder) for the Water Corporation (Water Corp) with the main aim of identifying an increase in sinkhole risk over and above that of sinkhole risk due to natural karst that could occur. The more detailed objectives included defining the extent of ground impacted by each sinkhole, as well as assessing the risk of further sinkholes forming along the alignment.

The investigation comprised a desktop study of aerial imagery, a walkover survey and intrusive Cone Penetration Testing (CPT). Three areas at risk of sinkhole formation were identified along the 1.1 km long section. Recommendations were subsequently made for remedial measures to densify the sands and enable the proposed land development to proceed with an appropriately low risk of sinkhole formation.

Several remediation methods were considered and based on the site constraints and an initial cost study, a combination of vibrocompaction and ‘excavate and replace’ was proposed. This paper discusses the use of vibrocompaction near the QMS alignment.

## 2 BACKGROUND

The natural ground conditions are typical of much of the Perth coastal zone, comprising dune sand, mainly Safety Bay Sand of aeolian origin with some residual sand leached from Tamala Limestone. Laboratory testing indicated that sands were poorly graded (SP) and contained less than 5% fines.

CPT tip resistance in these sands was generally between 10 MPa and 15 MPa (medium dense to dense) but tip resistances of up to about 25 MPa (very dense) were also recorded. A decline in tip resistance to as low as about 2 MPa was often recorded in the 1 m thick layer of sand immediately above the limestone. This is a common natural occurrence around the interface between the sand and the Tamala Limestone and is quite distinct from the potential effects of disturbance due to tunneling.

Limestone was interpreted to be present in CPTs when a sharp increase in cone tip resistance or a rapid change in inclination occurred.

CPTs were completed both over the centreline of the sewer pipe as well as at offset distances from the centreline of typically 2.5 m. The objective was to assess the depth to limestone and identify loose sand zones along the alignment. A typical geological section is shown in Figure 1. A zone of ‘uncertainty’ of +/- 2 m from rock head is shown between the sand and limestone to allow for natural relief and variability.

CPTs at known sinkhole locations were used to provide a typical sand strength profile in sinkhole areas (between <0.5 MPa and 4 MPa). This typical sand strength profile for sinkholes provided a means to estimate the extent of existing sinkholes along and offset from the sewer alignment centreline, as well as the presence or absence of additional previously unidentified sinkholes.

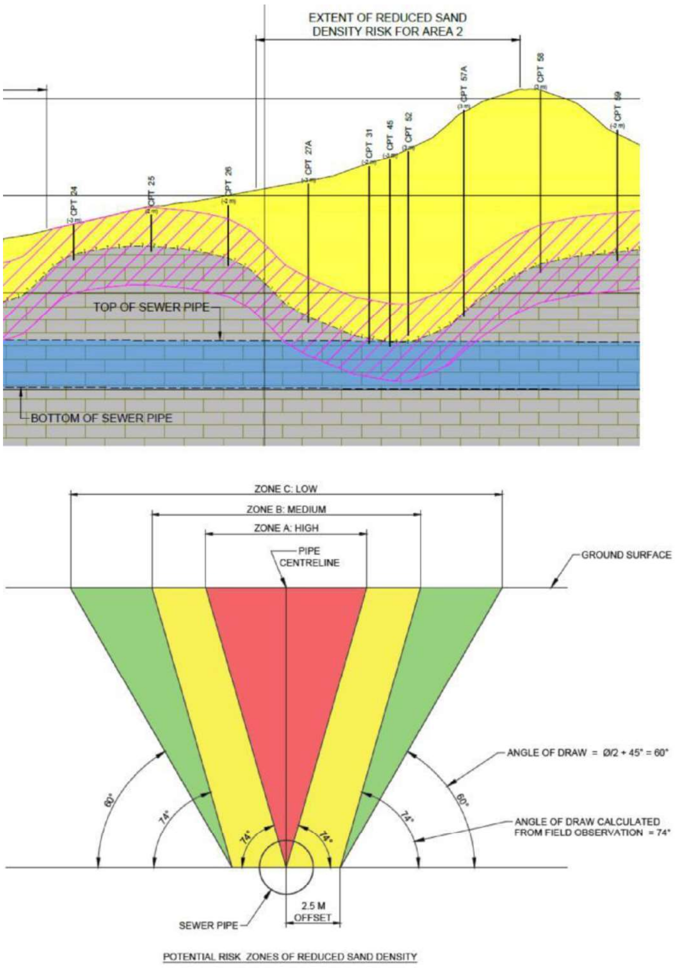


Figure 1. Typical Geological section (top) and Zones at risk (bottom) – associated with “mixed face” conditions

Based on the investigation completed, sinkhole development appeared to be associated with locations where mixed limestone/sand conditions occurred between the level of the QMS invert and crown. This would have given rise to mixed face conditions during tunneling which appears to have resulted in ground loss. The method for defining zones at risk of containing is shown in Figure 1.

Migration of the void to surface can occur either immediately or over time, resulting in loss of sand density and formation of a depression at the surface that forms a sinkhole. If the void is small or deep relative to the surface, it is possible that the volumetric loss can be accommodated by the overlying sand and a surface depression may not necessarily occur. In this scenario there will be a loss of density for some distance in the sand above the void, but this loss of density may not immediately extend to surface. The loss of density results in looser material that could densify and settle at a later date under static load, vibration or due to downward percolation (infiltration) of water from rainfall, soakwells and compensation basins. Densification of the sand could in turn result in surface subsidence and distress to structures and pavements located over such areas.

The angle between the plane of draw and the horizontal is often called the angle of break or the angle of draw. The angle of draw is a function of the strength properties of a soil and is best evaluated using field observations. Depending on whether it is assumed that the draw point for sinkhole development is at the top, middle or bottom of the sewer pipe, interpretation of CPT data suggested that the angle of draw in the dune sand is between approximately 74° and 77°. An angle of draw of 74° originating from the centre of the pipe was adopted.

Based on the conclusion that sinkholes were most likely to develop where the TBM was in mixed face conditions, the CPTs were concentrated in areas where sinkholes had already developed, as well as areas where the first pass of probing suggested potential for mixed face conditions at the level of the QMS. On this basis three risk areas were identified for treatment, including locations where sinkholes had already formed.

A total of eight options for ground improvement were considered, and vibrocompaction was judged to be most suited to the conditions, mainly due to the significant depth to the crown of the pipe.

The main risk of using this method was the potential for damage to the sewer pipe and to other underground services and any structures in the vicinity. In the final analysis two of the risk areas were treated using vibrocompaction, and one risk area was treated by ‘excavate and replace’ due primarily to the proximity of a gas main.

## 3 VIBROCOMPACTION -GENERAL

### 3.1 *Vibrator*

Vibro-treatment/compaction is a ground improvement process whereby the in-situ soils are improved or densified by the use of a vibrator at depth. The vibrator is a long, heavy tube enclosing eccentric weights, driven by an electric motor. The vibrator is connected to a source of electric power and a high-pressure water pump. Extension tubes are added as necessary, depending on the treatment depth, and the whole assemblage is suspended from a crane.

Keller has been at the forefront of the development of vibrators for soil treatment. The first vibrator for the densification of in situ sands was developed in 1935.

Table 1 shows the specification for the S300 vibrator used in the Alkimos project which is shown in Figure 2.

Table 1. Specification for S300 Vibrator

| | |
|---|---|
| Frequency | 30 Hz |
| Centrifugal Force | 230 kN |
| Amplitude | 20 mm |
| Motor Capacity | 120 kW |
| Motor Voltage | 380 V |
| Motor Speed | 1775 rpm |
| Service weight | 2450 kg |

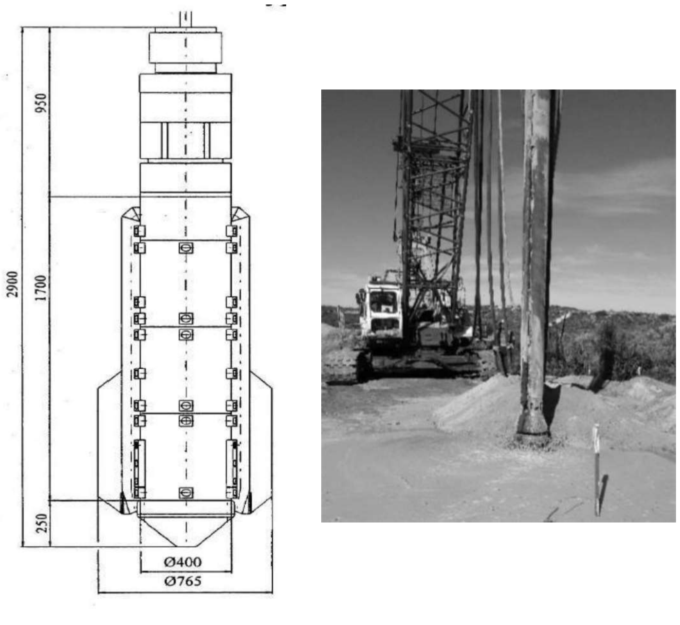


Figure 2. S300 Vibrator and Compaction plant

## 3.2 *Vibrocompaction process*

Vibrocompaction is typically suitable for treating sands with a fines content of less than 10%. The spacing of probes is designed to ensure that the zones of influence overlap sufficiently to achieve minimum requirements throughout the treated area using either a triangular or square probe grid.

The vibrator penetrates the ground under a combination of vibration and high-pressure water jetting which liquefies the soils surrounding the vibrator and assists in the penetration process. When the required depth is reached, the water pressure is reduced, and the vibrator is pulled up in short steps progressively compacting the surrounding soils at each step.

This process is repeated up to the ground level, leaving on completion, a column of very dense material surrounded by material of enhanced density. The degree of compaction achieved at a particular point depends on the properties of the soil being treated, the amount of time spent at each compaction step and the distance from the vibrator. The vibrocompaction process is illustrated in Figure 3.

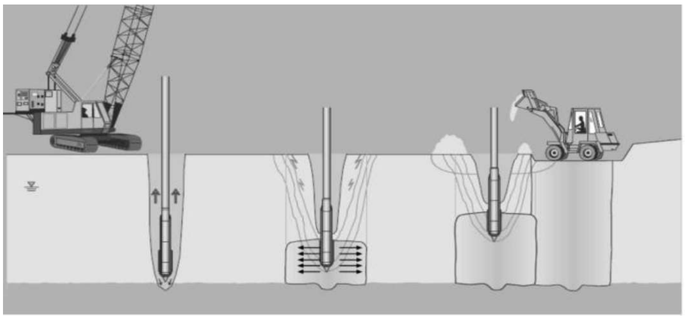


Figure 3. Vibrocompaction Process

## 4 VIBROCOMPACTION OF MAIN WORKS

### 4.1 *Specification*

At the QMS site, a density performance specification for ground improvement was specified based on returning the density to “ambient” natural ground conditions (unaffected by any tunneling induced ground movement). The criteria were set to be a tip resistance of not less than 5 MPa at 1 m below ground level increasing linearly to 10 MPa at 8 m depth.

Plan extent of improvement areas were defined by the medium and high-risk zones identified during the investigation. The depth of treatment was specified from 1 m below ground level to within about 1.5 m of the crown of the pipe. This depth was to be confirmed by a site trial prior to construction proper to limit peak particle velocity (vibration) at the pipe based on advice from the pipe designer.

### 4.2 *Layout and method*

The final probe layout was based on a 2.5m triangular grid. The general method of compaction at each probe location followed the procedure described above and pre and post compaction CPTs were carried out to assess performance

Minor modification to the adopted compaction methodology, in the form of additional retrieving of the vibrator to the ground surface after reaching its final depth, was carried out to create a larger annulus and allow material to flow past a partially cemented layer identified at some locations and provide material for compaction.

Monitoring of the compaction process was carried out using the Keller M5 computer, mounted inside the crane. The printouts of vibroprobes, which record the time, achieved compaction in amperage, were made available for the engineer to assess the result and make modifications to the compaction procedure where necessary. These printouts, together with a summary sheet, were submitted to Water Corp daily forming part of the quality control plan for the treatment work. The M5 unit and printout are presented in Figure 4.

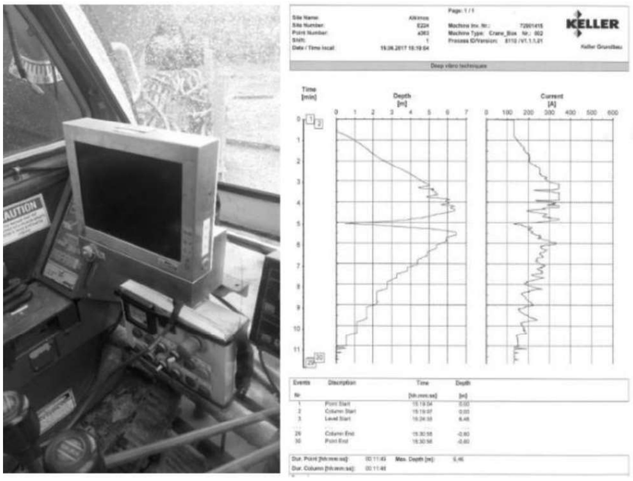
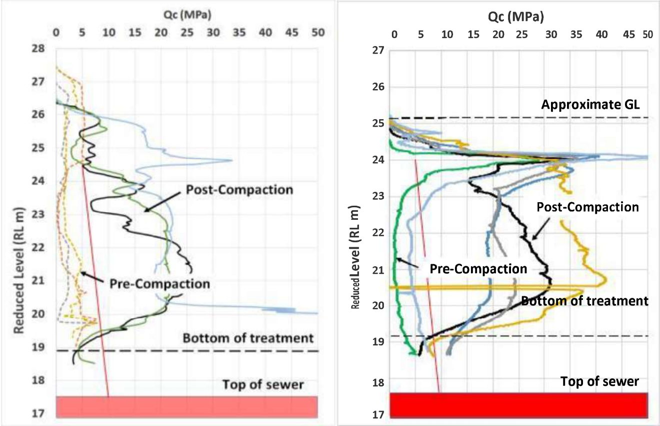


Figure 4. M5 Computer with Typical Vibrocompaction Printout

### 4.3 *Pre/post compaction testing*

Verification of the treatment work was carried out using CPTs. 1 test for every 25 $m^2$ of treated area was specified. Testing was generally carried out after a minimum 24 hour “resting” period following the treatment process.

From the results shown in Figure 5 it can be seen that the qc values recorded have typically been increased to more than double that prior to compaction. The adopted compaction methodology was able to deliver improved material over the entire depth of treatment.



Figures 5. Results of pre and post compaction CPTs

## 5 GROUND BORNE ATTENUATION OF VIBRATIONS

### 5.1 *Estimate of vibrations*

Whilst the benefits of vibrocompaction are obvious as a ground improvement technique, there was a significant risk of damage to the sewer due to ground-borne vibrations from the vibroprobe during the remediation works. With respect to the effects of ground vibrations on structures, ground vibrations are commonly quantified in terms of peak particle velocity (PPV) and the PPV is often used to set the potential damage criteria for structures as a result of vibration. In order to prevent significant damage to the sewer, the pipe designer defined an allowable PPV of 50 mm/s at the pipe.

Whilst there is some information available for the attenuation of vibrations from construction plant at the ground surface, there is little or no published data for the attenuation of subsurface vibrations to allow assessment of potential effects on buried assets. The application of the available empirically-based relationships resulted in estimates of a PPV of 50 mm/s at between about 1 m and 3 m offset from the proposed vibratory source and a PPV of 25 mm/s at between about 2 m and 7 m offset from the proposed vibratory source.

To refine these estimates a site trial was incorporated into the vibrocompaction works with triaxial geophones installed at various depths, to allow the attenuation of vibrations to be measured at different horizontal and vertical offsets from the vibroprobe during treatment. The trial was also used to assess the effectiveness of the proposed trial layout and revisions were made to the layout where necessary for the main works.

### 5.2 *Vibrocompaction Trial*

The layout of the vibroprobes and geophones is shown in Figure 6. Vibroprobes were arranged at 2.5 m centres in a triangular pattern. Three triaxial geophones supplied by Texcel Pty Ltd were installed, at depths of 2 m (near surface), 5 m and 8 m (nominal top of limestone) to enable measurement of the free field attenuation of vibration at three discrete depths for various horizontal offsets during the vibrocompaction process.

The geophones were installed in 100 mm diameter boreholes. A 2.5/1/0.3 (water/cement/bentonite) grout was tremied from the base of the borehole to 0.5 m above the tip of the geophone with sand filled from this level up to ground level.

The triaxial geophones were configured to record vertical, transverse and radial vibration although the vector sum of the three directions has been presented in this paper. Vibrocompaction was carried out to about 1 m above the limestone (about 7 m depth).

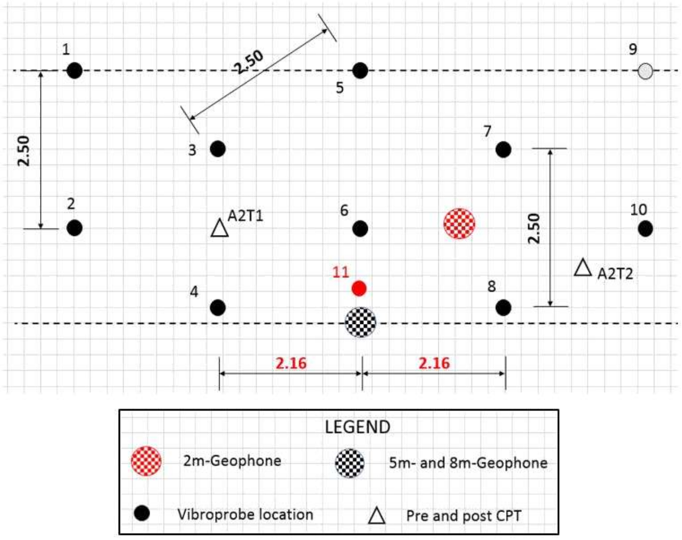


Figure 6. Layout of Vibrocompaction Trial

### 5.3 *Trial Results*

Figure 7 shows the maximum vector sum PPV measured by each geophone during the vibrocompaction process (during vibrator penetration and then during the subsequent compaction phase for each vibroprobe) against horizontal distance of the vibrator from the geophones.

Figure 8 plots the velocity (vibration) over time at the 5 m geophone against progress at a single vibrocompaction probe location (vibroprobe T11 which was about 0.7 m horizontal offset from the geophone). The PPV measured when the vibrator tip was at a depth of 3.0 m and 3.5 m (i.e. 2.0 m and 1.5 m above the geophone) during the penetration and compaction, were of interest to allow the assessment of the termination depth of the vibroprobe above the QMS pipe, such that the notional PPV was within the allowable PPV set by the pipe designer (50 mm/s).

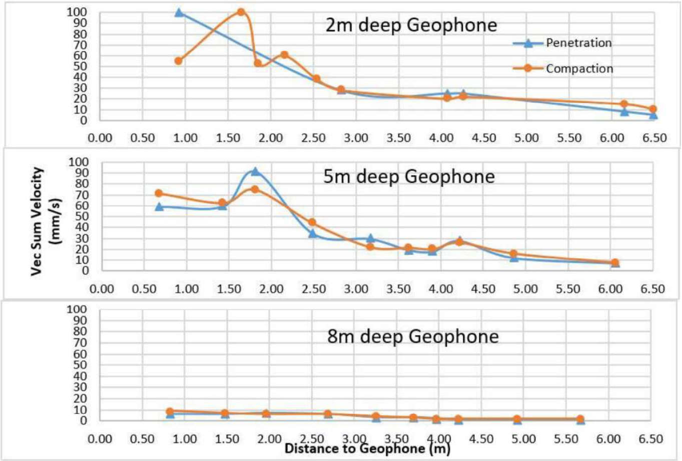


Figure 7. Maximum Vector Sum Velocity (or PPV) vs Horizontal Distance of Vibrator from Geophone

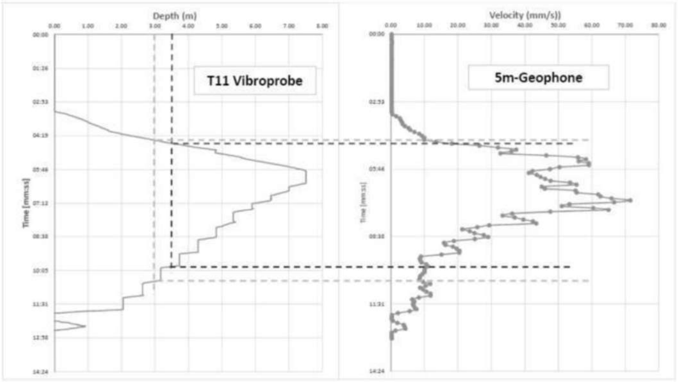


Figure 8. Plot of T11 Vibroprobe (0.7 m offset) progress against simultaneous vibration at 5m Geophone

### 5.4 *Observations from Trial*

The following observations were made regarding the vibration monitoring:

- Vibrations recorded by the 8 m geophone were less than might be expected when compared to the 2 m and 5 m geophones (see Figure 7). This was considered likely to be due to lower amplitude vibrations in the limestone in which this geophone was installed and the grout mix in which the geophone was installed being less stiff than the surrounding limestone and having a further damping effect.
- The relatively low overburden pressure for the 2 m geophone was considered likely to contribute to a less consistent correlation of vibration with horizontal offset.
- The data from the 5 m geophone was considered most reliable for use in setting the termination depth of the vibrocompaction probe.
- Vibrations generally diminish with horizontal distance from the vibrator/geophone (Figure 7) although there are some inconsistencies which likely reflect variations in the ground density.
- The maximum recorded velocities occur when the vibrocompaction probe tip is about 1 m below the level of the geophone (Figure 8) which coincides with the approximate level of the vibration source within the probe.
- A termination depth for the vibroprobe tip of 1.5 m above the QMS pipe was adopted based on the results of the trial. Recorded vibrations at this vertical separation (see Figure 8 and Figure 9) were less than 25 mm/s for all horizontal offsets during the trial, which provided some factor of safety against the vibration limit of 50 mm/s provided by the pipe designers.

### 5.5 *Vibrations monitoring during the main works*

Geophones were installed at a depth of approximately 0.5 m above the crown of QMS pipe at selected locations as a final check to ensure vibrations were within the maximum vibration criteria for the QMS pipe. All measurements at the geophones (installed 0.5 m above the QMS so with a minimum vertical separation from the probe of 1 m) were less than 40 mm/s, slightly elevated from those that would be predicted from Figures 8 and 9 but within the vibration criteria (50 mm/s) set for the pipe a further 0.5 m below the geophone.

## 6 CONCLUSIONS AND RECOMMENDATIONS

### 6.1 *Vibrocompaction*

Vibrocompaction has proved to be a successful technique for this project, for improving ground which had been disturbed due to tunneling in difficult mixed face (sand and limestone) conditions.

The post compaction results show an increase in the cone resistance (qc) values of at least a factor of two. The compaction specification was met at all locations tested.

### 6.2 *Attenuation of vibrations*

Whilst literature is available for the attenuation of vibrations at ground surface for a variety of sources including vibrocompaction plant, very little literature documenting the measurement of vibrations below ground was found to be available. The trial was therefore important for setting the safe offsets from the pipe. Based on the results of the trial, a vertical separation of 1.5 m was adopted for vibrocompaction above the pipe including some margin of safety.

Figure 9 below presents the consolidated results of the trial including some preliminary guidance for the range of velocities (vibrations) which might be expected at three horizontal offsets from the vibrocompaction probe, varying with vertical separation of the tip of the vibrator above the receptor (including data for the vibrator tip at the same level and below the receptor).

It must be noted that these values are specific to the following key variables and should be used with caution:

- Keller S300 Vibrator (refer to Table 1)
- The ground conditions, which comprised medium dense to dense sand overlying limestone at about 8 m depth.

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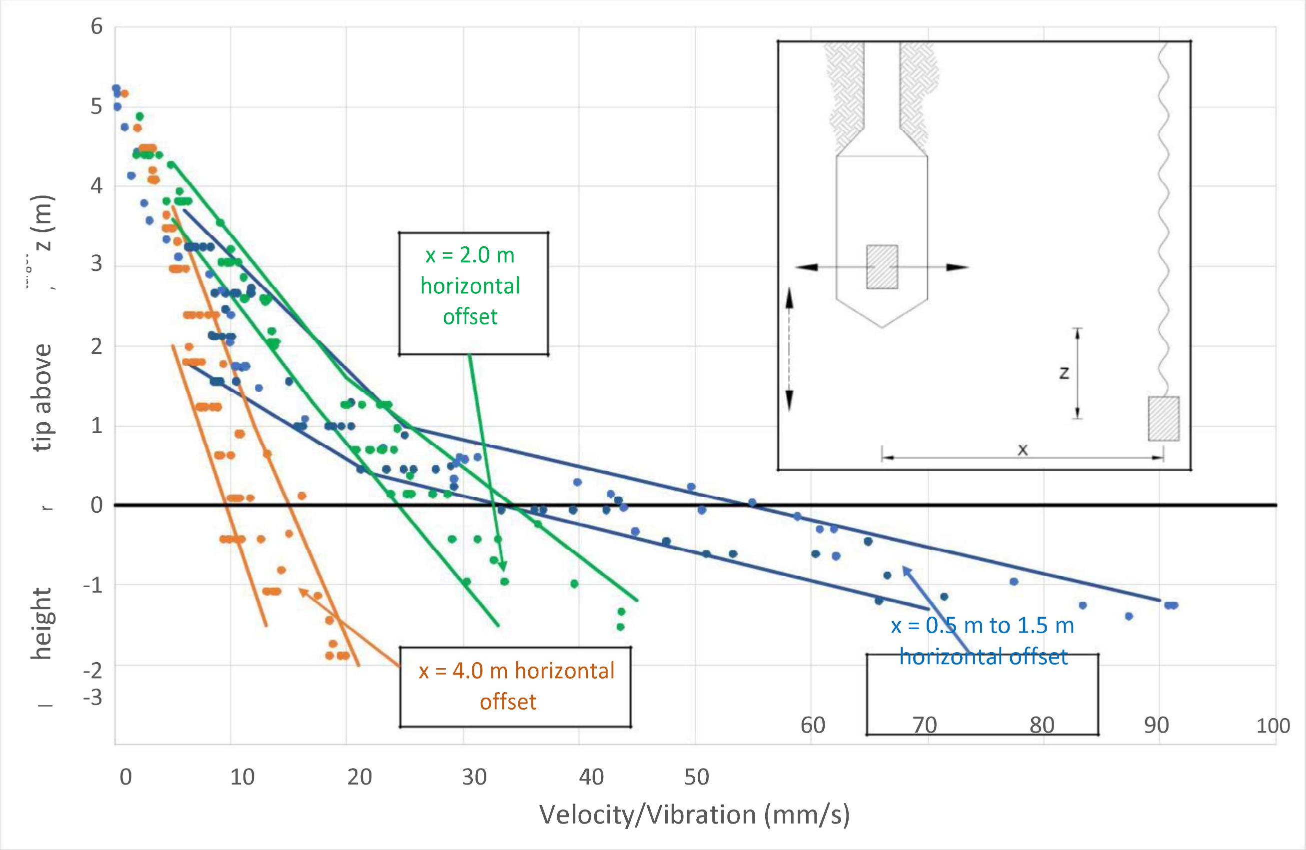

Figure 9. Range of velocities (vibrations) for varying horizontal offset and vertical separation above receptor