Ground Vibrations and Deformations Associated with Stone Column Installation

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ABSTRACT
The paper presents the results of ground monitoring during the installation of stone columns in granular soils in the Lower Mainland of British Columbia and discusses the levels of ground vibrations and surface settlement associated with this particular ground improvement technique. Data from two study sites are presented and compared with existing published data.
El articulo presenta los resultados de monitoreo durante la instalacion de columnas de peidra en suelos granulares en la provincia de British Columbia, Canada. Se presentan datos de dos sitios y se evaluan los resultados basado en informacion publicada en la literatura tecnica.

1 INTRODUCTION

With recent developments in urban environments, many projects are being constructed adjacent to existing infrastructure. In particular, transportation projects can significantly impact pre-existing infrastructure due to the often-extensive development corridors. Structures are commonly to be built on less-than-ideal ground with the result that some form of ground improvement is required to provide the necessary support. Ground improvement may require solutions ranging from standard driven or cast-in-place piles to specific treatment of the ground by densification/improvement methods.

In seismic areas, densification of granular soils is commonly required to avoid the potential impacts associated with liquefaction. Numerous ground improvement methods exist that effectively densify the in situ soils to avoid strength and stiffness reductions due to pore pressure increase during seismic shaking. Vibro-replacement, or the installation of stone columns in the ground, is a commonly used method in the Lower Mainland of British Columbia.

During the vibro-compaction process, a cylindrical probe is vibrated into the ground to a specified depth and then slowly withdrawn. The probe or vibroflot initially liquefies the surrounding soil and forces the soil out in a generally radial direction. The void left as the soil moves out is subsequently filled by soil from above as the probe is lifted up the profile. The soil that falls into the void below the probe is densified by re-penetrating the probe over successive depth intervals.

During the vibro-replacement process, the void that is formed by the vibrating probe is filled with coarser granular material that can be either added at ground surface (top-feed) or at the tip of the probe (bottom-feed). Figure 1 shows schematically the formation of a stone column using the top-feed method. Stone columns are usually installed on a triangular or square grid (Figure 2). The spacing between the stone columns, b, depends on the ground and probe characteristics and the densification required.

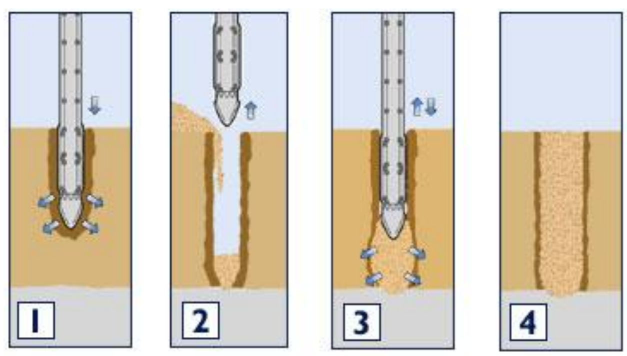

Figure 1. Top-feed procedure for stone column installation (Keller Foundations)

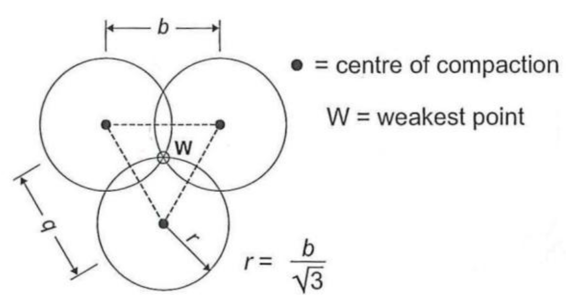

Figure 2. Typical triangular stone column installation grid.

The methods and equipment for vibro-compaction and vibro-replacement have developed over the years but the basic principle remains unchanged. Horizontal vibration of the probe is achieved by the rotation of an eccentric weight around a vertical axis and the dynamic horizontal forces are applied directly to the surrounding soil. The vibrator is suspended from a crane and lowered into the ground as the soil softens under the weight and vibration of the probe. The length of the vibrator is typically between 3 m to 4.5 m and weights range from 30 kN to 60 kN. Motors in the probes are generally electric or hydraulic. The width or double amplitude of the vibrator can vary from 10 mm to 50 mm at the nose when the probe is suspended in air with no lateral confinement. When the vibrator is inserted into the soil, the ground response may cause a reduction in the amplitude of vibration and dampening of vibration. One of the key objectives during any densification project is to maintain adequate vibration levels in the ground. Water and/or air injection is also used to facilitate the insertion of the probe. Field measurements (Achmus et al. 2007) indicate that the vibrators generally achieve better ground densification at frequencies of about 30 Hz.

In order to monitor the performance of the probe, the specialist operator usually monitors the following parameters that reflect how the probe is responding to the ground conditions:

- the depth of the vibrator as it is lowered and raised through the soil profile;
- the amperage (or oil pressure) as a measure of the energy imparted to the soil and the change produced by densification;
- the operational frequency of the probe;
- air or water pressure used when jetting.

As part of the design process, a trial densification program may be specified to ensure that the specific equipment to be used for the ground improvement can achieve the required levels of densification. During this trial program, it is also possible to monitor ground displacements and vibrations at distances away from the probe in order to evaluate the potential impact that ground densification may have on existing structures. Densification trials are a useful addition to the design process since the densification that may be achieved in a soil is dependent on both the soil and probe characteristics.

Soil characteristics may include initial density, grain size, shape and grading characteristics, fines content, specific particle gravity, depth (stress level) and permeability. Probe characteristics that influence densification are frequency, amplitude, acceleration, out-of-balance forces and duration and timing of re-penetration stages (Kirsch and Kirsch, 2010).

2 VIBRATIONS / DEFORMATIONS ASSOCIATED WITH STONE COLUMN INSTALLATION

2.1 Groundborne Vibrations

As the probe is inserted into the ground, the generation of shear waves in the ground gives rise to vibrations that radiate from the probe and can be felt at the ground surface. The levels of vibration are usually categorized in terms of the peak particle velocity (PPV) of the waves. In vibro-replacement, the vibrating probe generates a mainly horizontal vibration pattern and typically operates at frequencies of 30 to 50Hz. Given the number of interrelated variables, no explicit relationship exists allowing the magnitude of PPV to be predicted for a given source and ground conditions; hence various empirical relationships have been developed based on limited case studies. Commonly, the PPV is measured at the ground surface, although for specialized situations, the PPV can be measured at any depth. Published data generally correlate the magnitude of the PPV at the ground surface to specific levels of discomfort or damage that people or infrastructure may experience when affected by vibrations. Various national design codes and regulations provide guidance on acceptable levels of vibrations that structures can comfortably experience without undergoing damage or distress.

Kirsch and Kirsch (2010) report that Achmus et al. (2007) recorded vibration data at 20 different construction sites using four different Keller probes and developed a relationship between the measured PPV_G (at the ground surface) and the radial distance in meters from the probe, r. Based on the energy of vibration E, given by:

$$E = W/f \qquad [1]$$

where W is the power of vibrator in kW and f is the frequency in Hz.

The PPV_G can be obtained from:

$$PPV_G \text{ (mm/s)} = k(E)^{0.5}/r \qquad [2]$$

where k is an empirical factor developed from field vibration measurements and r is the radial distance from the probe. The peak particle acceleration can be obtained from:

$$PPA \text{ (mm/s}^2) = 2\pi f(PPV_G) \qquad [3]$$

TRL Report 429 (2000) proposes the following empirical expression for predicting the peak particle velocity in relation to the installation of vibrated stone columns:

$$PPV_G = k_c/r^{1.4} \qquad [4]$$

where k_c = 33, 44 and 95 for a 50%, 33% and 5% probability, respectively, of the vibration level being exceeded. This empirical relationships was subsequently adopted by BS 5228-Part 2-2009 for distances between 8 m and 100 m from the stone column location. However, the variation of PPV would appear to be better related to the direct distance between the point on the ground surface and the tip of the probe.

CIRIA Technical Note 142 (1992) examined 10 vibro-compaction case studies and proposed a series of attenuation lines where PPV_G was plotted against scaled distance ($E^{1/2}/r$), where E is in Joules. In the study, a distinction was made between measurements made on the ground and those made on adjacent structures, since the readings on structures were generally lower.

2.2 Densification Induced Settlement

Little information is available to evaluate the effect of ground movements due to vibrating probes. It is generally held that ground displacements will be limited to a distance from the probe equal to the final depth of the ground improvement (Kirsch and Kirsch 2010). It is also generally believed that ground deformations can be minimized by sequencing the densification such that the probe locations move progressively towards any structure(s) that may be impacted and by implementing effective control of the backfill during vibro-replacement. (This may be true for the level vibration, but we have found the opposite effect occurs for deformation levels. We have observed that the cumulative damage at non-densified locations was increased as the probe moved towards the location. Once the point was densified, the cumulative damage was less, but the vibration increases due to the increased stiffness of the ground.)

Case study reported damage to structures in the vicinity of vibratory works may also be attributed to differential settlement as a result of densification of the surrounding ground (Greenwood 1991). In general, there is less known/reported regarding the zone of influence of densification induced settlement. However, empirical measurements indicate that a PPV_G exceeding 13mm/s at the ground surface is necessary to cause the ground to settle under the influence of vibrations (Greenwood 1991). Furthermore, the data suggest that for a probe with an energy rating of 75-90kW, the soil experiencing such velocities would typically exist within about 10-12 m from the vibration source.

2.3 Outline of Stone Column Trials

For a major highway project in the Lower Mainland of British Columbia, stone columns were to be used to densify embankment and bridge foundations. The stone column layout determined necessary to achieve the design objectives was based on 20-m long columns on a triangular grid at a spacing of 2.75 m, center-to-center. The stone column diameter was specified as 0.9 m which gives a 10% replacement ratio.

A stone column trial section was established at several locations to evaluate the design and the performance of the equipment to be used by the contractor. As well as evaluating the ground response to the densification treatment, a monitoring program was undertaken to record both vibrations and ground movements associated with the installation of the stone columns. The results of the vibration and displacement monitoring are the focus of this paper. The densification results are not considered.

The stone column trials were performed at two separate sites. The soil conditions at the two sites are very similar, as indicated by the CPT soundings on Figure 3. Both sites have up to 5 m of fill and interbedded sand/silt layers at the existing ground surface, underlain by up to about 30 m of sand/silty sand. At both sites the existing ground is sensibly flat.

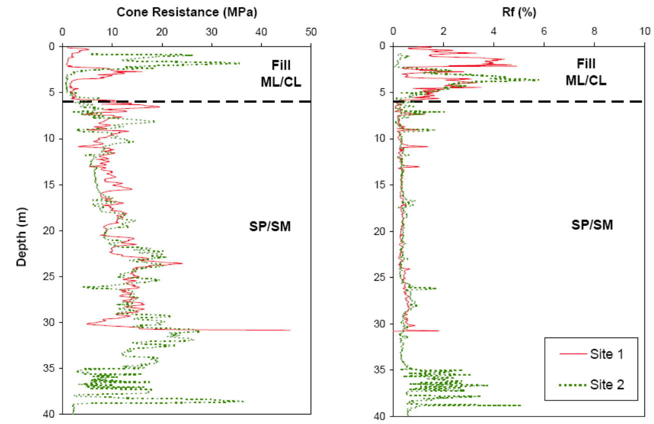

Figure 3. CPT soundings and soil profiles

The layout of the stone columns to be installed during the monitoring program at Site 1 is indicated on Figure 4 and on Figure 5 for Site 2. At Site 1 only ground vibrations were monitored, while at Site 2 both vibrations and surface settlements were recorded. A total of 19 stone columns were installed at Site 1 and 37 stone columns at Site 2. All stone columns were formed using the dry bottom-feed method and an electric vibroflot. Limited jetting was used, primarily to control surface water.

A V-23 vibroflot owned and operated by AGRA Foundations was used during this study. The probe is 3.3 m long with a diameter of 350 mm under the wear plates. The vibroflot weighs 2,350 kg and has a maximum double tip-amplitude of 23 mm. The 145 kW electric motor operates at 1800 rpm, with a maximum centrifugal force of 300 kN.

Ground vibrations were monitored using four Instantel vibration monitors. At Site 1 the vibration monitors were installed at fixed locations and not moved during the trial. At Site 2, the monitors were moved around the work area to evaluate the variation in the vibration levels with distance away from the probe. Also at Site 2, the settlement monitoring points were moved around the site, particularly since the individual points were lost once the stone column being installed was next to the monitoring location.

2.4 Results of Vibration / Deformation Monitoring

Typical results of peak particle velocity measured at the ground surface for a representative number of stone column installations are presented on Figure 6. The 19-column array layout is indicated on the figure as well as the location of the column actually being installed in relation to the four vibration monitoring points A, B, C and D. The lightly shaded circles indicate the already-installed column locations. The dark circle is the location of the stone column being installed while the measurements were being taken. The peak particle velocity at the ground surface (PPV_G) in mm/s measured in the direction of the stone column location is plotted on the y-axis against time on the x-axis. Time is measured from the start of stone column installation and is synonymous with depth of the probe. The measured PPV_G values include those associated with initial insertion of the probe and the re-penetration as the stone is compacted in the hole.

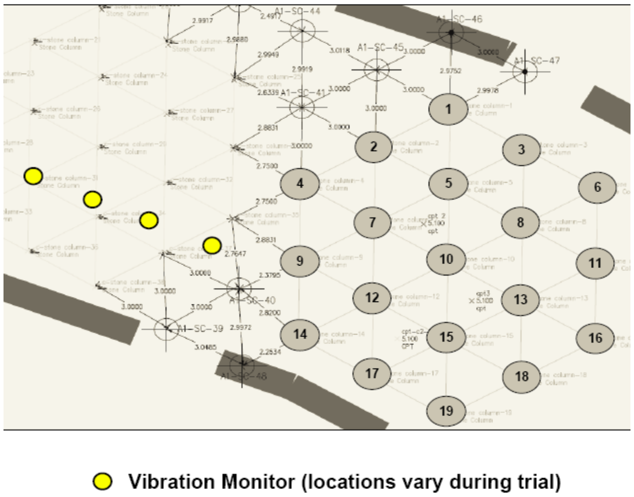

Figure 4. Stone column layout at Site 1

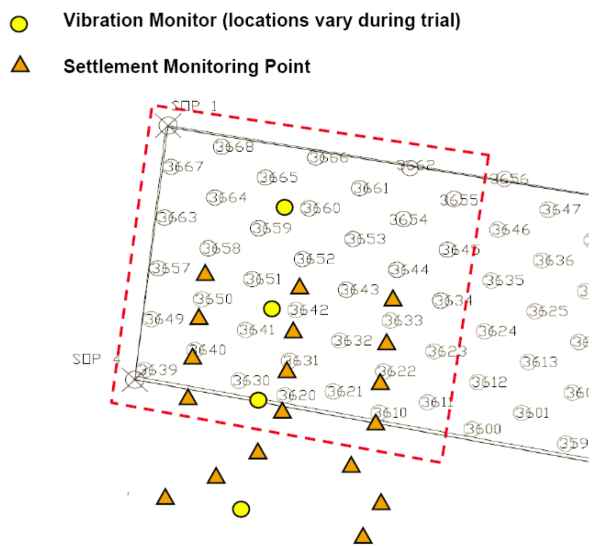

Figure 5. Stone column layout at Site 2

Figure 6a presents the results for the stone column location closest to the measuring points. Apart from the near-surface values, once the probe has penetrated the surface and is contained within the soil, the vibration levels are generally low, generally similar for all probes, and less than 5 mm/s. The measured vibrations appear to be uniform across all four gauges. It is easy to imagine the energy from the probe being radiated in all directions in the relatively homogeneous soils.

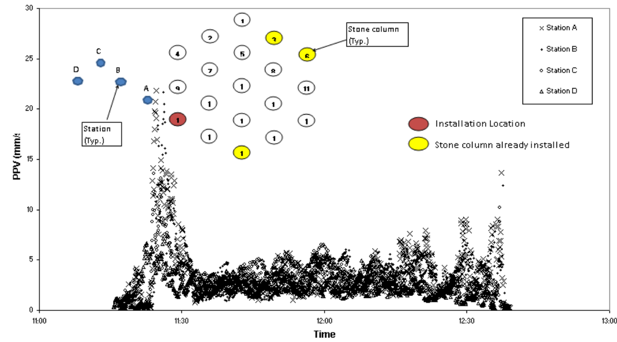

Figure 6a. Vibrations measured on column 14

Figure 6b indicates the measured vibrations at the middle location on the edge of the hexagonal array immediately next to the location in Figure 6a, but this time the surrounding stone columns have already been installed, forming a denser confinement barrier adjacent to the column being installed. The measured PPV data on Figure 6b indicate that much higher levels of vibration are transmitted to the monitors compared to the data in Figure 6a. The PPV_G measurements are about 15-25 mm/s for the probes nearest the column and reduce to about 5 mm/s for the locations furthest from the stone column. Finally, Figure 6c presents the result of measurements from a column located in the middle of the array. PPV_G measurements as high as 25 mm/s were recorded, although average values range from 10-25 mm/s for monitor A to less than 3 mm/s for monitors C and D.

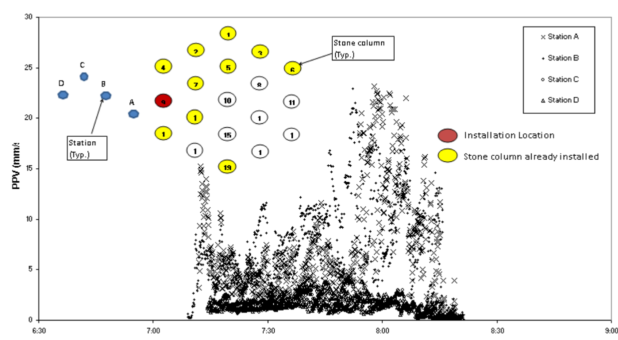

Figure 6b. Vibrations measured on column 9

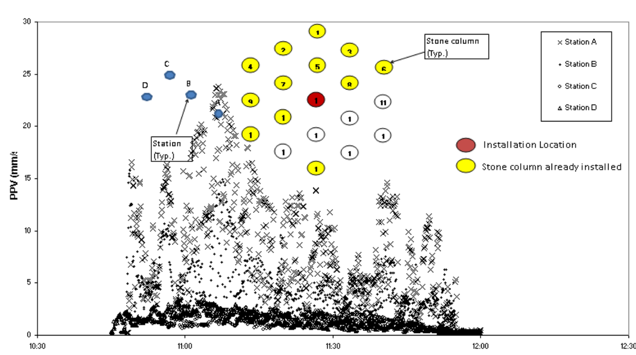

Figure 6c. Vibrations measured on column 10

The variation of PPV with plan distance for both sites is summarized on Figure 7. The k_c factor was estimated to vary between 80 and 300. The scatter in the data varies from about +/- 10 mm/s at small distances to about +/- 2 mm/s at larger distances. An outlier of what are higher levels of vibration was noted between distances of 8 m to 12 m at Site 1. This correlates to a specific area in the stone column array and may result from localized effects. Site 1 data do generally plot towards the upper side of the Site 2 data.

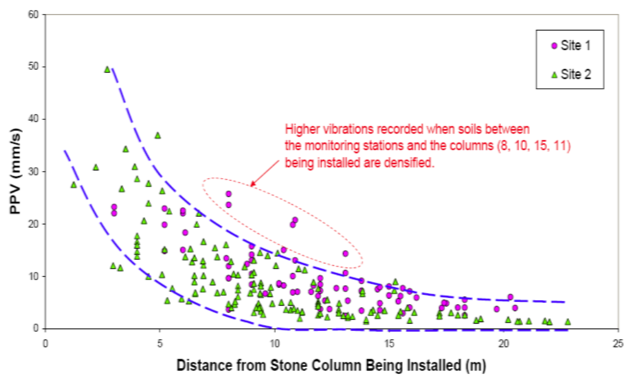

Figure 7. Variation of ground vibration (PPV_G) with distance from stone column being installed

The data on Figure 6 present the results from three individual stone column installations. However, the general data trends discussed above hold for all the other stone columns installed. Importantly, the data suggest that in situations where stone columns have been inserted between the point of vibration and an existing structure, the increased stiffness of the ground (due to the densification) may give rise to increased levels of vibration at the structure. However, this increase can also be evidenced when the stone column being installed is located between a zone of improved ground and the measuring point. In this situation, the vibrations may be reflected back from the improved ground and amplified towards the measuring point.

The PPV_G data have also been plotted over the published data presented in BS 5228-2 (Figure 8). The data generally plot at an upper bound limit across the entire range of distances and better correlate with ground measurements. Measurements made on pipes and structures presented on Figure 8 are lower than ground measurements. The better correlation with the upper bound data on Figure 8 is also considered to be related to the higher levels of energy input to the ground since the stone columns monitored during this study were installed specifically to ensure densification of granular deposits. It would appear that much of the published data relates to stone columns installed for ground improvement achieved by reinforcement/replacement, with lesser degrees of densification (and hence lower energy requirements).

The recorded ground settlement data associated with stone column installation are summarized on Figure 9. The trend in the data would suggest that the settlement induced by stone column installation is essentially negligible at distances of 10 m or more (>10 diameters) from the center of the stone column being installed. At distances of less than 5 times the stone column diameter, vertical settlements may range from 10-60 mm. However, the actual measured settlements may be very sensitive to the order the stone columns are installed (in relation to the monitoring point) and also the specific site conditions.

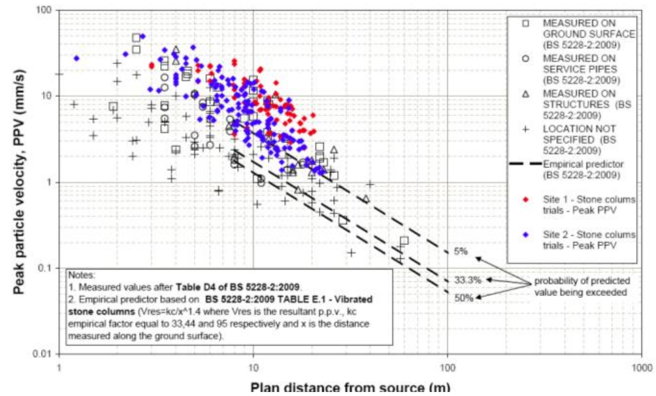

Figure 8. Comparison of vibration data from study sites with data published in BS 5228

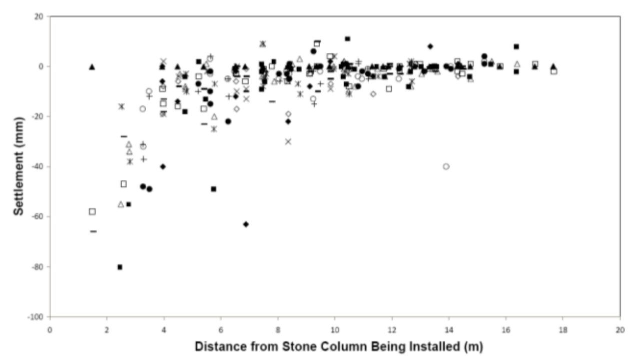

Figure 9. Variation of ground settlement with distance from stone column being installed

3 CONCLUDING COMMENTS

The results of PPV_G and settlement measurements at distances from a vibrating probe used for installation of stone columns have been reported in the paper. The results are in general agreement with published data except that the vibration levels are higher than previously published. It has been suggested that this may be due to the increased densification required at the two study sites compared to that at the sites of the published data. At both the sites reported herein, the densification was designed to minimize the impacts of design earthquakes ranging from 475-year to 2,475-year events. Additional studies have been performed in the area to evaluate the effect of stone column installation on accumulated vertical settlement, lateral ground movements and pore pressures.

Damage levels are usually referenced to PPV_G values and these generally correspond to the application of a limited number of cycles. During the installation of stone columns for liquefaction mitigation, a great number of stone columns may be installed within a small area. Hence, the cumulative effect of the vibrations as each stone column is installed, may be significant.

At a third site, pneumatic and vibrating-wire piezometers were installed to monitor pore pressures adjacent to stone column installation. The maximum pore pressure build-up in the granular layers was recorded as less than 20% of the overburden pressure ($\Delta u/\sigma'_v$) at a radial distance of 3 m. Generated pore pressures dissipated quickly with time, facilitated by the presence of the recently-installed stone column.

Ground settlements were also measured at the surface and at depth using Borros anchors. Settlements measured at both the surface and at depth demonstrated, up to a certain distance, a definite increase in ground movement as the number of columns was installed. The maximum ground settlement for a monitoring point at the center of a typical 2.75-m triangular array increased from 100 mm after installing one column to about 420 mm after completing the four surrounding columns located at the same radial distance. The total accumulated settlement decreased exponentially with radial distance from the densification point. At a distance of 10 m, the maximum recorded cumulative settlement was found to be less than 50 mm. The maximum cumulative ground surface settlement at the center of the 66-column array was about 700 mm.

Inclinometer measurements at the site indicated that the lateral ground movement is greatest at the ground surface and decreases with depth, for any distance from the stone column installation point. The total lateral movement is also cumulative and depends on the specific stone column installation sequence.

The measurements recorded during stone column installation would suggest that this particular method of ground improvement may significantly impact structures in the vicinity of the stone columns. Consequently, special measures may be required to avoid potential impacts to new or existing structures. Depending on the structures that may be impacted, the cumulative effects of stone column installation would suggest that a minimum offset distance between the nearest stone column and the structure should be about 10 m. It should be noted, however, that the measured vibrations and ground displacements are likely to be very site-dependent. For example, on another site we have measured ground displacements associated with stone column installation at distances within 5 column diameters as large as 700 mm.

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