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Rectifying an Excessive Vibration Issue in Shallow Foundation with Permeation Grouting: A Case Study

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ABSTRACT Large vibrating machines are integral part of industrial facility. This paper describes a case study of excessive vibration encountered in a machine foundation, as well as the corresponding rectification works. The vibrating machine was built on shallow foundation sitting on compacted sand fill layer. The self-weight of foundation is 8 times more than the equipment weight. The shallow foundation itself has a dimension of about 7.0 x 1.7 x 1.7 m. The vibrating machine frequency (which sits above the foundation) is 450 rpm, with a relatively large impulsive cyclic load. The paper first explores the potential root cause of the vibration issue. Thereafter, considerations for the rectification works are described; in this case, a permeation grouting technique using low-viscosity cement grout is chosen. The work method for this ground improvement works, including the completion criteria are also presented. Post-improvement vibration measurement indicates that the measured vibration is within the acceptable vibration limit, indicating a successful improvement work.

KEYWORDS Machine foundation, excessive vibration, block foundation, simplified method, ground improvement, permeation grouting

1 INTRODUCTION

The foundation of dynamic equipment (typically a vibrating machine) is not only subjected to static load due to the foundation and equipment self-weight, but also dynamic loads from the vibration of equipment. Even with the advent of sophisticated engineering software, the design of vibrating machine foundation is still considered a complex task. Therefore, many engineers still use the simplified method summarized in a compendium written by Richart et al. (1970), which is now an inclusive part of standard machine foundation textbook such as Arya et al. (1979), Das and Ramana (2011), Irsyam et al. (2018).

The historical development of the machine foundation is well described by Gazetas (1983), with notable contributions from Lamb (1904) who developed the solution for the “dynamic Boussinesq” problem. Reissner (1936) provided the first engineering application of Lamb’s solution, and Hsieh (1962) showed that the solution for vertically loaded machine foundation can be represented by equivalent spring and dashpot with single-degree-of-freedom system.

Another notable breakthrough was achieved by Lysmer and Richart (1966). Their design methodology marked a new era of machine foundation design, in which they introduced the possibility of using frequency-independent parameters. The method is valid for certain range of a given frequency. Currently, the method is also known as the simplified method. This method is then expanded by Novak and Beredugo (1972) for embedded footing case. More recently, Gazetas (1991) has expanded the simplified method solutions for arbitrary foundation shape.

In the design of machine foundation, the following information are required:

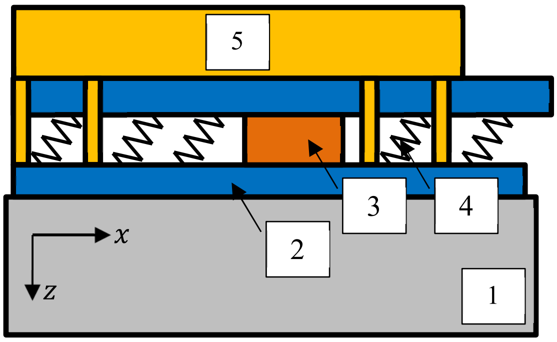
- Machine type: Rotating, reciprocating, or impact-type machinery.
- Foundation type: Block, table-top, pile foundation, base-isolated, etc.
- Static and dynamic load.
- Dynamic soil properties.

In the case study presented here, three machine foundations were built in an industrial facility, located in Cilegon, Banten, Indonesia. Each machine foundation supports a dynamic machinery weighing approximately 6 tonnes, which is powered by 9 kW motor (450 rpm). In addition, based on the manufacturer datasheet, the machine motor and driver produce lateral and vertical dynamic load of 5 tonnes and 3 tonnes, respectively. The lateral and dynamic loads are transmitted via spring system and the base frame into the foundation. Figure 1 shows the schematic of the machinery sitting on the block (shallow) foundation.

The vibrating motor discussed in this study is relatively small and, at the first glance, may not warrant a more detailed dynamic analysis. Indeed, American Petroleum Institute (API) (2009) specifically states that a dynamic analysis is only required for reciprocating compressor greater than 150 kW. As the machine was considered as a small machinery, the rule-of-thumb method by American Concrete Institute (2004) was previously used for the foundation design. The rule-of-thumb method specifies that the block foundation weight shall be set to at least three times the weight of a rotating machine and at least five times the weight of a reciprocating machine. Based on the design method, the size of block foundation was set to 7.0 x 1.7 x 1.7 m (2L x 2B x H), weighing almost 50 tonnes, achieving a foundation-to-equipment weight ratio of about 8.3. Therefore, the required weight ratio stipulated by the American Concrete Institute (2004) is satisfied.

Despite meeting the required design criteria, during the commissioning phase, one of the three foundations experienced excessive vibration. The measured vibration stroke on the vibrating machine was 28.78 mm, slightly above the stroke limit of 25 mm set by manufacturer. More importantly, when this machine was turned-on, the foundation visibly vibrates and produces an excessive ground-borne vibration. Although, the exact value of ground-borne vibration was not measured, the vibration could be clearly felt by people working in a nearby building.

In this paper, the potential root cause of the excessive vibration is explored. Then, the authors describe the soil improvement work that was applied to rectify the issue. The soil improvement technique chosen to reduce the vibration experienced by the vibrating machine is permeation grouting technique. This technique is suitable for cohesionless soil and can be used to improve the existing soil conditions.



1. Block foundation.
2. Base frame.
3. Motor and driver.
4. Spring system.
5. Hood.

Figure 1. Illustration of the machinery on the block foundation (elevation view).

2 SUBSURFACE SOIL CONDITION

The upper soil layer in the foundation area consists of soft cohesive soils with SPT N-value of 4-5; the thickness of this layer varies between 1 m to 4 m. The underlaying soils are stiff silty clay (SPT N-value of 14-24) and very dense sand (SPT N-value >50). Figure 2 shows the soil stratigraphy around the location of machine foundation. The groundwater level was found at depth of 1.0-5.5 m below the existing level.

Prior to the installation of the machine foundation, the existing soil was improved with rigid inclusion, which was installed in a grid pattern spaced 1.4 m apart. The inclusion diameter was 320 mm with transfer platform (sand fill) of 0.5 m thick. The design allowable shallow bearing capacity (SBC) is 100 kPa with settlement limit of 25 mm. In comparison, the required SBC based on load combinations for this machine foundation is only 50 kPa. It is only 50% of the allowable SBC, hence meeting the requirement given in API (2009) which states that the maximum soil pressure due to static and dynamic load combinations shall not exceed 75% of the allowable SBC.

After the excessive vibration issue was noticed, some additional field tests were performed. Five points around the machine foundation were selected for DCP (Dynamic Cone Penetrometer) tests for verifying the compactness of sand fill layer and several shallow samplings. At each point, seven DCP tests were performed down to depth of 2 m; the correlated CBR values were in the range of 16%-20%, indicating a loose-to-medium-dense sand fill layer. Samples from the upper soil layer (approximately 2 m thick) were also taken, which were then lab-tested. The corresponding sieve analysis results are shown in Figure 3. It is found that the soil type is predominantly sand.

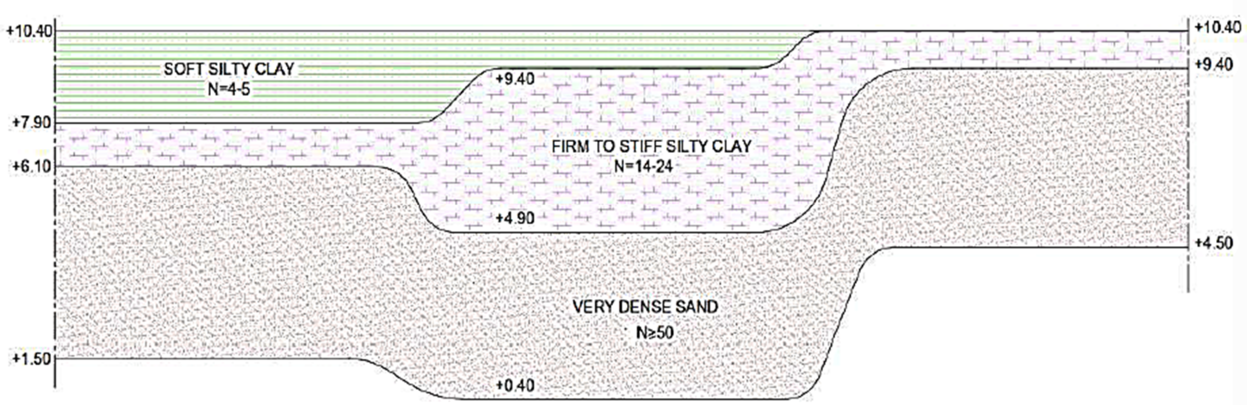


Figure 2. Soil stratigraphy in the machine foundation location.

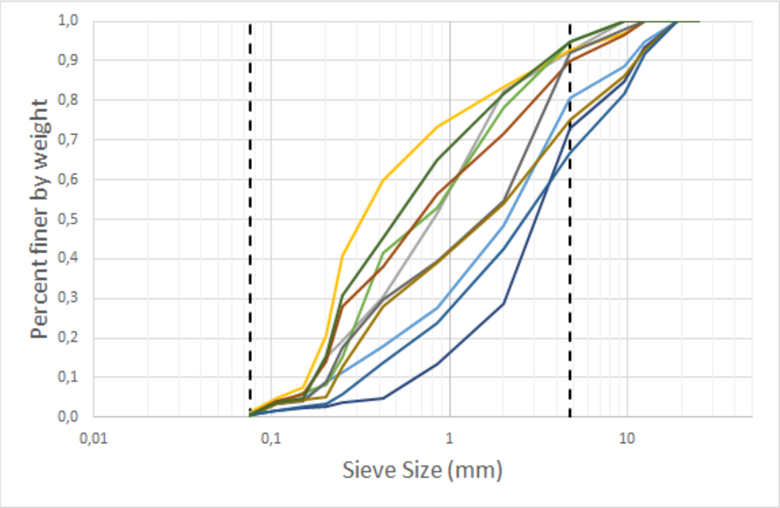


Figure 3. Sieve analysis data of sand fill layer.

3 DYNAMIC ANALYSIS USING SIMPLIFIED METHOD

3.1 Formulation of Simplified Method

After verifying the in-situ soil properties and ensuring that the machine still works within the prescribed limit given by manufacturer, the next culprit investigated is the interaction between the machine itself with the subsurface soil. Correspondingly, the authors decide to perform dynamic analysis for verifying the potential resonance issue caused by the dynamic machine-foundation-soil interaction.

In this paper, the generalized simplified method described by Gazetas (1991) is used. For conservativeness, the embedment effect is not considered. Considering soil embedment may increase the soil impedance, hence slightly increasing the system natural frequency. Using this approach, the dynamic impedances for each vibration mode (see Figure 4) are calculated. The analysis requires two parameters: Dynamic stiffness $\overline{K}$ for the real component parameter and damping coefficient C for the imaginary component. Note: Given that the load is perceivably not a torsion type, the impedance of torsion mode is not checked.

The dynamic stiffness $\overline{K}$ is calculated by multiplying the static stiffness K (Table 1) with the dynamic stiffness coefficient k (Table 2 and Figure 5) (Gazetas, 1991). Similarly, the radiation (geometric) damping coefficient C is calculated by multiplying the damping formula (Table 3) with the damping coefficient $\bar{c}$ (Figure 5). The material damping β is assumed equal to 5%. The combined damping can be calculated with $C_t = C + (2\overline{K}/\omega)\beta$, where ω is the machine angular frequency

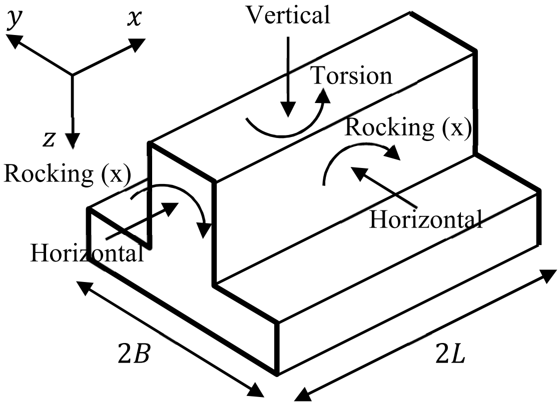


Figure 4. Vibration modes of machine foundation.

Only two soil parameters are required for this analysis: small-strain shear modulus G and Poisson's ratio v; these are elastic parameters. The corresponding shear wave parameter V_s can be calculated using $V_s = (G/\rho)^{0.5}$, with ρ is the soil mass density. The other parameters are described as follows:

- I_x and I_y are the second moment of area.
- a_0 is dimensionless frequency factor defined as $a_0 = \omega B/V_s$.
- V_{La} is the Lysmer's analog wave velocity, defined as $V_{La} = \frac{3.4}{\pi(1-v)} V_s$.

Once the dynamic impedance parameters have been calculated, calculating the system natural frequency ω_n is straightforward where $\omega_n = \sqrt{\overline{K}/m}$. Correspondingly, the frequency ratio $r = \omega/\omega_n$ can also be calculated; this ratio is required to verify the system resonant potential.

Table 1. Static stiffness formula for various vibration modes (Gazetas, 1991).

Vibration Mode	Static Stiffness
Vertical (z)	$K_z = \frac{2GL}{(1-v)}(0.73 + 1.54\kappa^{0.75})$ where: $\kappa = \frac{A_b}{4L^2}$
Horizontal (y)	$K_y = \frac{2GL}{(2-v)}(2 + 2.50\kappa^{0.85})$
Horizontal (x)	$K_x = K_y - \frac{0.2GL}{(0.75-v)}\left(1 - \left(\frac{B}{L}\right)\right)$
Rocking (ψ_x)	$K_{\psi x} = \frac{3G}{(1-v)} I_x^{0.75} \left(\frac{L}{B}\right)^{0.25} \left(2.4 + 0.5\left(\frac{B}{L}\right)\right)$
Rocking (ψ_y)	$K_{\psi y} = \frac{3G}{(1-v)} I_y^{0.75} \left(\frac{L}{B}\right)^{0.15}$

Table 2. Dynamic stiffness coefficient formula for various vibration modes (Gazetas, 1991).

Vibration Mode	Dynamic Stiffness Coefficient
Vertical (z)	See Figure 5a
Horizontal (y)	See Figure 5b
Horizontal (x)	$k_x \cong 1$
Rocking (ψ_x)	$k_{\psi x} \cong 1 - 0.20a_0$
Rocking (ψ_y)	$v < 0.40; k_{\psi y} \cong 1 - 0.26a_0$ $v \cong 0.50; k_{\psi y} \cong 1 - 0.26a_0\left(\frac{L}{B}\right)^{0.3}$

Table 3. Radiation damping coefficient formula for various vibration modes (Gazetas, 1991).

Vibration Mode	Radiation damping coefficient
Vertical (z)	$C_x = (\rho V_{La} A_b)\bar{c}_z$ See Figure 5c for $\bar{c}_z$
Horizontal (y)	$C_y = (\rho V_s A_b)\bar{c}_y$ See Figure 5d for $\bar{c}_y$
Horizontal (x)	$C_x = \rho V_s A_b$
Rocking (ψ_x)	$C_{\psi x} = (\rho V_{La} I_x)\bar{c}_{\psi y}$ See Figure 5e for $\bar{c}_{\psi y}$
Rocking (ψ_y)	$C_{\psi y} = (\rho V_{La} I_y)\bar{c}_{\psi y}$ See Figure 5f for $\bar{c}_{\psi y}$

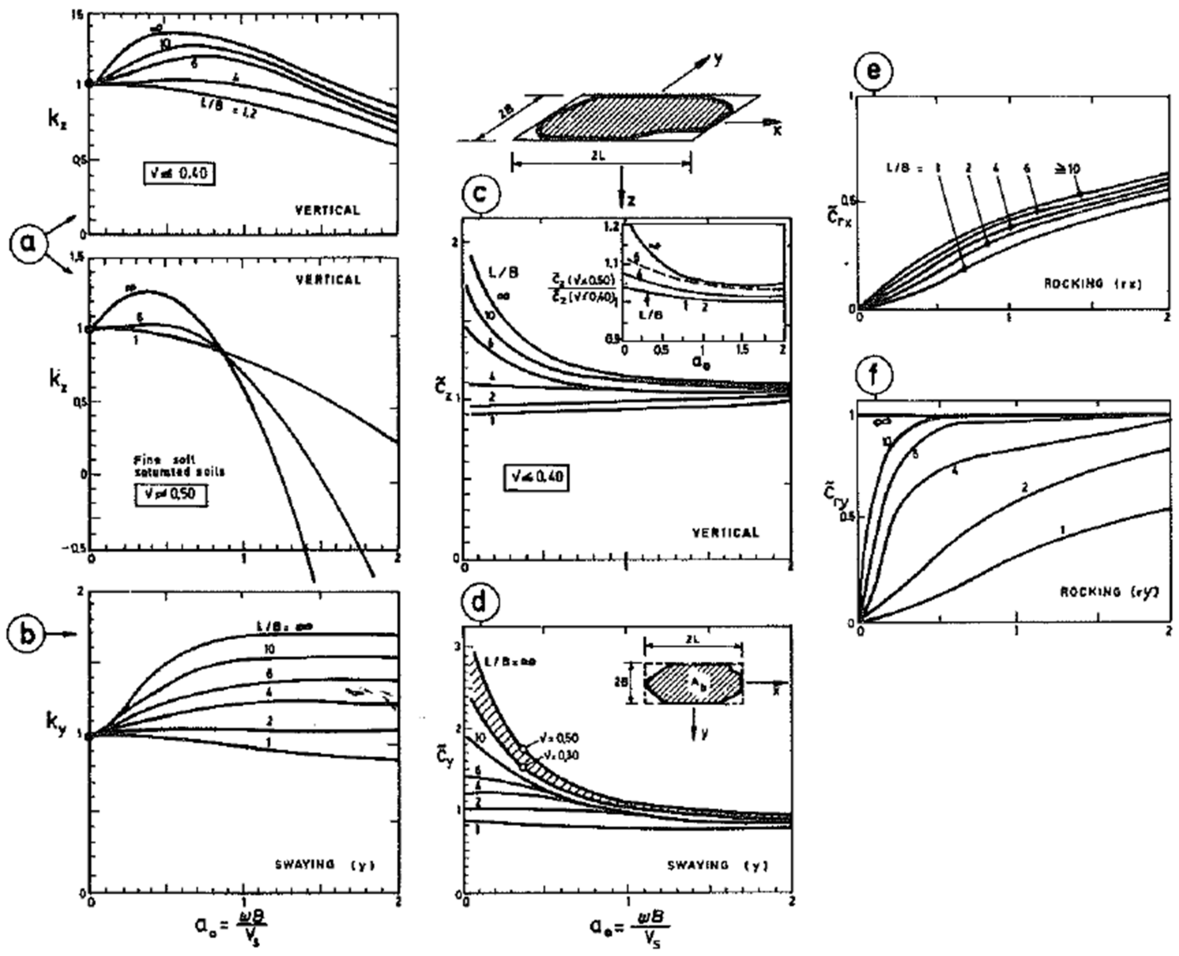


Figure 5. Graphs for determining the dynamic stiffness and damping coefficient (Gazetas, 1991).

3.2 Checking Resonant Potential

Inherently, there is some uncertainties in regard to soil properties. Therefore, we use the range of expected soil property values for the calculation of resonant potential.

Calculation results of various Poisson's ratios using constant shear modulus of $G = 25$ MPa, are shown in Table 4. It can be seen here that the frequency ratio r for rocking mode about the x-axis is very close to 1 (marked with bold), which indicates a resonant condition. When the resonant condition happens, the dynamic amplification factor will be high; the behavior at such condition would be controlled by the system damping ratio. Thus, the typical design criteria requires the fundamental frequency to be outside of the natural frequency by +/-20%. (Liu and American Society of Civil Engineers, 2018).

The influence of shear modulus on the frequency ratio (r) is shown in Table 5. It can be seen here that even with a relatively slight increase of shear modulus (say from 25 MPa to 40 MPa), the frequency ratio reduces for all vibration modes reduces to less than 0.8. This results also seem to correlate well with the given information of which that only one of the three identical foundations has the vibrating issue; possibly, there are some pockets of not-so-well compacted soils underneath this foundation.

The calculated damping ratios for Poisson's ratio $v = 0.3$ and $G = 25$ MPa are 59.8%, 41.1%, 47.8%, 7.2%, and 7.7%, respectively, for vertical, lateral, longitudinal, rocking about x-axis, and rocking about y-axis vibration modes. This is consistent with the chart provided by Richart et al. (1970), where for instance, the translational movement would have higher damping ratio than the rocking movement.

In summary, the excessive vibration experienced by this foundation is likely caused by the low soil shear modulus, especially at the ground surface. The soil improvement work to rectify this issue is discussed in the next section.

Table 4. Dynamic stiffness and frequency ratio for various vibration modes given variation of Poisson's ratio (using shear modulus $G = 25MPa$).

Poisson's Ratio	Vibration Mode	Dynamic Stiffness	Frequency Ratio
0.15	Vertical (z)	286.23 MN/m	0.69
	Horizontal (y)	238.12 MN/m	0.72
	Horizontal (x)	286.23 MN/m	0.66
	Rocking (ψ_x)	178.06 MN-m/rad	**1.01**
	Rocking (ψ_y)	1239.50 MN-m/rad	0.72
0.20	Idem	294.18 MN/m	0.67
		243.34 MN/m	0.71
		294.18 MN/m	0.65
		189.19 MN-m/rad	**0.98**
		1316.96 MN-m/rad	0.70
0.25	Idem	302.58 MN/m	0.65
		248.57 MN/m	0.70
		302.58 MN/m	0.64
		201.81 MN-m/rad	**0.95**
		1404.76 MN-m/rad	0.68

Table 5. Dynamic stiffness and frequency ratio for various vibration modes given variation of shear modulus (using $v = 0.30$).

Shear Modulus (MPa)	Vibration Mode	Dynamic Stiffness	Frequency Ratio
25	Vertical (z)	311.48 MN/m	0.62
	Horizontal (y)	253.72 MN/m	0.70
	Horizontal (x)	311.48 MN/m	0.63
	Rocking (ψ_x)	216.22 MN-m/rad	**0.92**
	Rocking (ψ_y)	15005.10 MN-m/rad	0.65
40	Idem	498.37 MN/m	0.49
		405.95 MN/m	0.55
		498.37 MN/m	0.50
		351.29 MN-m/rad	0.72
		2466.04 MN-m/rad	0.51
55	Idem	685.26 MN/m	0.42
		558.18 MN/m	0.47
		685.26 MN/m	0.42
		487.11 MN-m/rad	0.61
		3435.03 MN-m/rad	0.43

4 IMPROVEMENT WITH PERMEATION GROUTING

Once the potential cause of vibration issue has been understood, a rectification plan must be devised. The constraint of rectification work is the existence of already-built facilities surrounding this foundation, including concrete paving. Other factor that is considered is time, as this machine is already in operation. There is only a limited shutdown window (i.e., few days) to perform the improvement work.

The proposed applicable construction method is chemical grouting as permeation grouting. The selected method injects two liquid-based material into the soil to improve its characteristic (Putranto *et al.*, 2016). The details for improvement work were planned and executed by the ground improvement specialist.

The key challenge of this method is the selection of the suitable mixture that can fully permeate into the soil, filling existing voids and/or cavities with set-able solidification time. After preliminary trial mix, a cement milk solution consisting of micro-fine concrete is chosen. It was combined with a rapid hardening soil-stabilizing solution, with a hardener/cement ratio of approximately 1:4 by weight. These two solutions are placed in separate mixtures before being combined through Y-tube connector.

The grouting points are placed on the nearest side position from the vibrating machine with approximately 1 m spacing between injection points (see illustration in Figure 6). Commencement of work is started by drilling to the loose-to-medium-dense sand fill layer (approximately 1.2m deep). After the drilling has finished, pipe with packer is installed. In line with the pipe installation, pre-injection work is done. The grout composition is checked to ensure the solidification time of material. It is adjusted so that the designed permeation capacity of grouting material can be achieved on the targeted layer. The injection work is performed by injecting material with a certain designed volume, while also monitoring the injection pressure to ensure the permeation capacity of the improved layer. Injection volume is also monitored to confirm completion of work. The construction sequence of the injection works is shown in Figure 7.

In addition to solidification time, pressure control, and volume control, UCS (unconfined compressive strength) test was also conducted to verify the quality of grout. In this case, the target UCS is 500 kN/m^2 for 3 days curing time; this is in line with the planned idle time of vibrating machine.

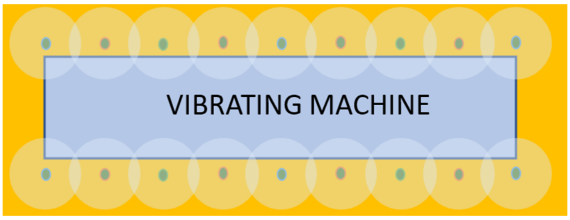


Figure 6. Schematic of grouting points around the vibrating machine.

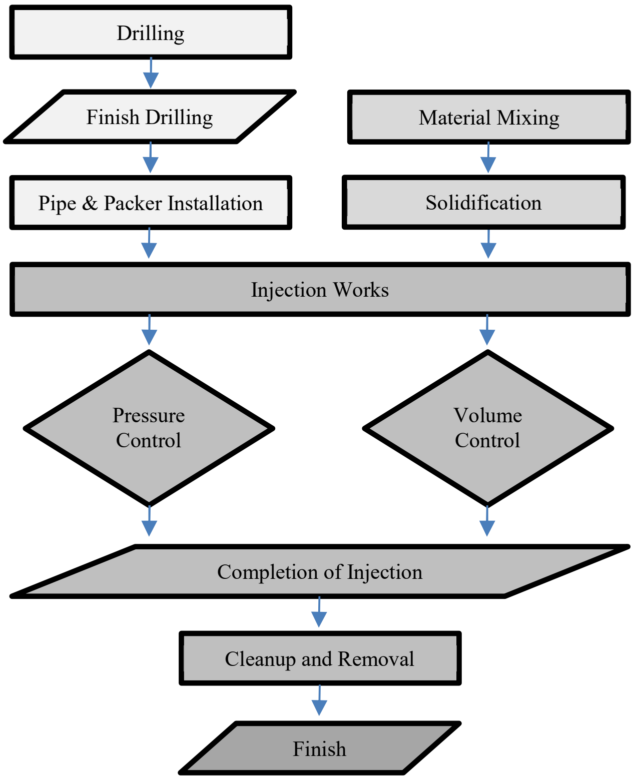


Figure 7. Construction sequence of the grouting work.

5 RESULT AND CONCLUSION

After the vibrating machine has been restarted, continuous observation of the machine shows that the vibration is now well below the prescribed vibration limits. The vibrating displacement measured at the base plate (just above the block foundation) reduces from 0.93-1.63mm to well below 0.01mm (not detectable by sensor). This indicates that the improvement work is successful.

In this study, we can highlight the following:

- The common rule-of-thumb method for vibrating foundation design (with foundation weight of 3-5 times the machine weight) is not applicable for all cases. Further check using the more sophisticated “simplified method” is deemed important.
- An analysis with the simplified method by Gazetas (1991) indicates that the rocking motion is the most critical mode which may happen when the soil small-strain shear modulus is in the range of 25 MPa (loose sand). This also hints why the vibration issue was only encountered in one of the three foundations.
- Considering the working space and downtime limitation of the machine, chemical grouting is used as permeation grouting. A cement milk solution consisting of micro-fine cement has been used.
- The injection steps have been carefully tailored to ensure the successful injection work; the grout solidification time, injection pressure, grout volume, and soil-grout mixture strength are all carefully checked.
- As the vibration issue has been solved after the grouting work, we can also conclude that the rocking vibrating mode as indicated from the simplified method is indeed the culprit of this issue. The simplified method is proven useful for predicting the machine-soil interaction behavior, especially in the low frequency machine such as this.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the authors.

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