Proceeding *20th SEAGC - 3rd AGSSEA Conference in conjunction with 22nd Annual Indonesian National Conference on Geotechnical Engineering.* Jakarta - INDONESIA, 6 -7 November 2018. ISBN No. 978-602-17221-6-9

Lessons Learned from Pressuremeter Tests on Stone Columns

Richard Ong[1]
[1]*Regional Technical Director, Menard Geosystems Sdn Bhd, Subang Jaya, Malaysia*
E-mail: richard@menard-asia.com

ABSTRACT: The Menard pressuremeter was developed by Louis Menard in the 1950s. Since its availability as a tool to the engineers for the last 60 years, pressuremeter has been used extensively for ground improvement projects. It is proven to be a valuable tool throughout the life cycle of a project, from the geotechnical investigation for design works to acceptance test conducted to verify the construction completed for a ground improvement project. This paper presents the application of Menard pressuremeter in the construction of an LNG tank in South-East Asia using stone columns as the foundation system. Some of the important lessons learned from the pressuremeter tests conducted for this project are presented and discussed in this paper.
Keywords: Menard pressuremeter, ground improvement, stone column, LNG tank.

1. INTRODUCTION

Stone columns are often used as reinforcing and stiffening elements in ground improvement works to increase the bearing capacity and reduce the settlement of the treated ground. Numerous methods (e.g., Priebe (1995), Goughnour and Bayuk (1979), Balaam and Booker (1981)) are available to calculate the settlement of ground improved by stone columns. These methods rely on the modulus of the stone column, E_c and that of the soil, E_s to determine the settlement reduction factor following ground treatment with stone columns. In recent years, numerical modelling such as finite element analysis has also been used in the design of stone column projects. These types of modelling also require reliable soil and stone column moduli to be utilised in the analysis. One of the in-situ tests that can provide a direct measurement of the soil modulus is the Menard pressuremeter test (PMT). This paper demonstrates the use of PMT in the construction of stone columns for the foundation of a large LNG tank in South-East Asia. The difficulties encountered to conduct the PMT inside stone columns for the project and the solution adopted are highlighted. Finally, some lessons learned from examining the results of the PMT by considering the nature and characteristics of the soils, the intensity of the stone column compaction and the measured Menard pressuremeter modulus, E_M at different depths are presented.

2. LNG TANK PROJECT

2.1 General Description of the Project

The purpose of the ground improvement works is to reinforce the soft compressible cohesive soil (i.e., Layer 2 in Figure 1) with stones and to improve the sand material on top of it (i.e., Layers 1b and 1c in Figure 1) to construct a Liquefied Natural Gas (LNG) storage tank of 77.9 m diameter on top of the treated ground.

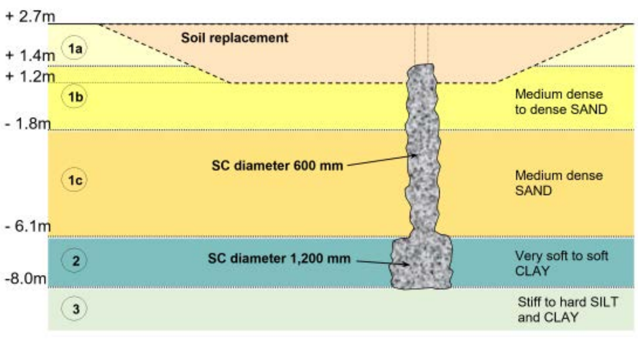

Figure 1 Cross section of ground improvement with stone column

The characteristics of the layers of soil to be treated are summarised in Table 1. The sand layers were quite homogeneous according to the standard penetration test (SPT) and cone penetration test (CPT) results. For the very soft to soft clay layer, two distinct zones were identified due to the existence of a former tank on the project site. This former tank applied some 150 kPa on the ground. Thus, the area in Layer 2 that was under the old tank footprint is over-consolidated, whereas it is normally consolidated everywhere else. Groundwater level is at about 1.0 m below the existing ground level.

Table 1 Soil characteristics

Layer	SPT N-value	CPT q_c (MPa)
1b: Medium dense to dense sand	23	14.5
1c: Medium dense sand	16	8.2
2: Very soft to soft clay	2	0.5-0.9

Note: The SPT N-value and q_c shown are average values.

2.2 Description of the Ground Improvement Works

The overall ground improvement works include the removal and replacement of Layer 1a (i.e., loose sand layer) with well compacted granular material and the wet top feed stone column method. Under the LNG tank footprint, Layer 1a will be excavated and replaced with well compacted granular fill (with minimum oedometric modulus, E_{oed} of 10 MPa) from +1.2 m EL to +2.2 m EL. From +2.2 m EL to the bottom of the tank slab (+2.9 m EL), the tank pad will be constructed with well compacted granular material with E_{oed} of 40 MPa. The scope of the stone column works includes penetration of the vibrofloat down to 10.7 m depth from working platform level (i.e., from +2.7 m EL to -8.0 m EL). This is followed with the installation of stone columns with average diameter of 1,200 mm within the clay layer and 600 mm in the sand layer as shown in Figure 1.

The tank dead load is shown in Figure 2.

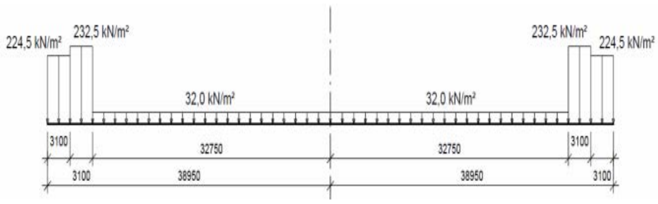

Figure 2 Tank geometry with dead load at the end of construction

Figure 3 shows the live load during hydrotest, which is the most critical stage of the live load applied to the tank. The ground improvement was therefore designed for it based on the live load during hydrotest.

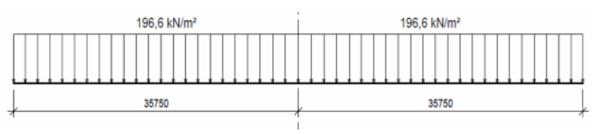

Figure 3 Live load during hydrotest

The ground improvement scheme for the LNG Tank foundation has been designed with the aim to minimise two differential settlements:

a. Settlement between centre and edge of slab must be lower than 1/300 (dishing criterion);
b. Settlement between two diametrically opposed edge points must be lower than 1/500 (tilting criterion).

The final design is for the stone columns to be installed with a 2 m square grid spacing pattern, giving the area replacement ratio, a_r of 7% within the sand layer and 28% within the clay layer.

2.3 Testing Programme

Apart from the digital recordings of the construction parameters (primarily depth and compaction effort versus time) for every stone column using a data logger during construction of stone columns, plate load test (PLT) and pressuremeter test (PMT) were specified as acceptance tests. The PLT was carried out on top of some stone columns using 600 mm diameter steel plate to check on the deformation modulus based on the settlement versus load graphs obtained. The PMT was carried out within some stone columns at 1 m interval to obtain the limit pressure, P_L and Menard pressuremeter modulus, E_M. The acceptance criteria for PMT were to achieve minimum P_L of 1.5 MPa and E_M of 15 MPa at each test location. These values were derived based on French recommendations NFP 11-212 (2005), which recommends the Young's modulus of the stone column (average value over the stone column), E_c to be 60 MPa.

3. PRESSUREMETER TEST RESULTS

3.1 Menard Pressuremeter Test (PMT)

The Menard pressuremeter was developed by Louis Menard for commercial application through his first Menard company known as "Centre d'Etudes Menard" in 1957. The original pressuremeter was developed in an attempt to solve the problem of sampling disturbance and to ensure that the macro-fabric of the soil can be adequately represented from an in-situ test. To date, the Menard pressuremeter has evolved as part of an international standard procedure to give design parameters directly. This procedure covers the type of probe, installation, testing and interpretation as provided in the publication "Interpretation and Application of Pressuremeter Test Results to Foundation Design" published in Sol-Soils (Menard, 1975). The pressuremeter test provides two main soil parameters, namely Menard pressuremeter modulus, E_M and limit pressure, P_L, which can be used directly for settlement and bearing capacity calculation, respectively.

3.2 Initial PMT Result

Figure 4 shows the plot of P_L and E_M versus depth from the initial pressuremeter test (PMT) conducted from the working platform level at +2.7 m EL. The result suggests that the upper 5 m of the stone column was well constructed. However, below that level it appears as though the stone column was not properly compacted within the medium dense sand layer (i.e., Layer 1c) and the test result within the clay layer is even worse where the P_L and E_M obtained are not any better than the P_L and E_M of the natural soil.

This kind of PMT test result was not expected in the project as the site recordings during construction showed that stone consumption was much higher than the theoretical volume required and very high compaction energy (i.e., not less than 180 A) was applied during the construction of the stone column. Hence, it is suspected that the pressuremeter probe might have walked out of the stone column as it went deeper from the working platform level. This is not an uncommon phenomenon when conducting tests inside a stone column.

A few other attempts had been made to ensure verticality of the pressuremeter probe during penetration but were not fruitful to ensure the probe is within the stone column at the soft clay layer. Thus, the idea of constructing "test" stone column within the clay layer was adopted. The "test" stone column was constructed by installing stone column only within the clay layer with stone consumption and compaction energy similar to those applied for the construction of normal stone columns. The difference was that beyond the clay layer, the hole created for the construction of the "test" stone column was backfilled using sand with little compaction. This ensured the pressuremeter probe can penetrate to the "test" stone column within the clay layer and meaningful test can be conducted.

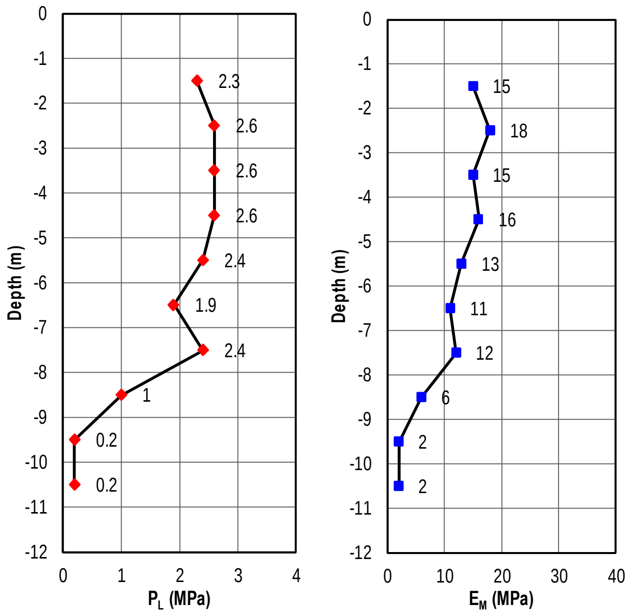

Figure 4 Initial pressuremeter test result

3.3 PMT Result for Stone Column within Clay Layer

Figure 5 shows the typical PMT result obtained from a "test" stone column formed within the clay layer. It is shown that the P_L is about 1.1 MPa and the E_M is around 8.5 MPa. This indicates that the P_L and E_M are below the specified values despite being much higher than the natural soil's P_L and E_M. The E_M of 8.5 MPa translates to Young's modulus within stone column, E_c of 34 MPa (i.e., $E_c = E_M/\alpha$; where $\alpha = 0.25$ for gravel). This is about 11 times higher than the Young's modulus of the natural clay (i.e., E_s of about 3 MPa) and it is well above the typical modular ratio (i.e., E_c/E_s) for the application of stone columns in soft soil. In fact, for the design approaches using elastic methods that consider vertical deformation only, Barksdale and Bachus (1983) have suggested that E_c/E_s in practice to be ranging from 3 to 10, depending on the area replacement ratio, a_r adopted. The reasons why such a high stiffness ratio was obtained for this project are likely to be due to the fact that high area replacement ratio, a_r was adopted with column diameter of 1.2 m and high compaction energy was applied during construction.

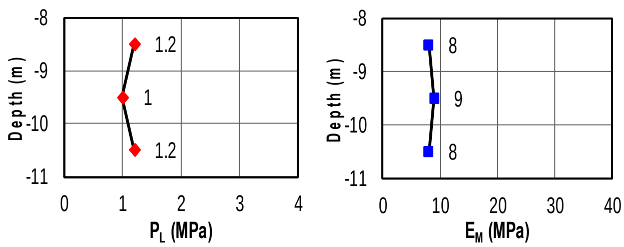

Figure 5 PMT result of stone column within clay layer

3.3 PMT Result for Stone Column within Sand Layer

Figure 6 shows the typical PMT result for the test conducted on a stone column within the sand layer when the pressuremeter probe did not walk out from the centre of the column. The P_L is about 2.8 MPa and the E_M is around 22 MPa, which are higher than the required values in the specification. The Young's modulus of the stone column, E_c is calculated to be 88 MPa, which is 3 to 4.5 times higher than the Young's modulus of the original sand layer (i.e., E_s of 20 MPa to 30 MPa).

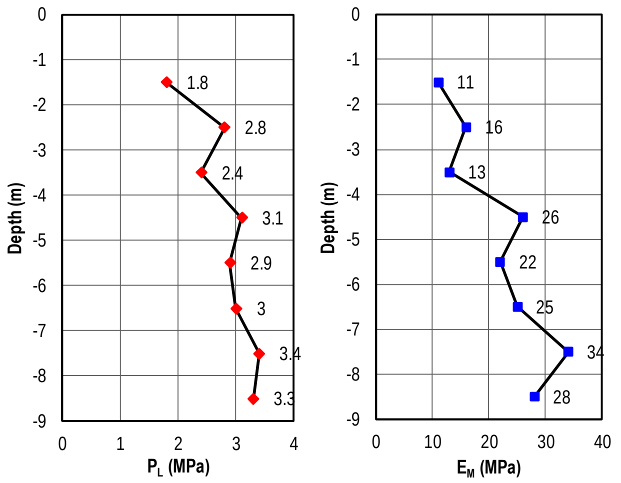

Figure 6 PMT result of stone column within sand layer

4. DISCUSSION ON THE PMT RESULTS

4.1 Stone Column Modulus

In this project, the modulus of the stone columns, E_c had been specified to be 60 MPa throughout the length of the column. The PMT results show that the E_c in the clay layer and sand layer is 34 MPa and 88 MPa, respectively. Clearly, the value of E_c is not constant throughout the length of a stone column. From various literature, the value of E_c is shown to range from 25 MPa to 100 MPa and it is a function of the confining pressure (Castro, 2017). In fact, the value of E_c is likely to be interdependent on factors such as the stiffness of the natural soil, the compaction energy provided, the area replacement ratio (i.e., spacing and diameter of stone columns), etc. Therefore, it may not be suitable to specify or design a stone column project using a constant E_c throughout the treatment depth, especially when the subsoil is heterogeneous.

4.2 Modular Ratio

Table 2 shows the modular ratio between stone column and natural soil (i.e., E_c/E_s) obtained from the pressuremeter test conducted in this project.

Table 2 Modular ratio

Stone column in	Natural soil		Stone column		Modular ratio
	E_M (MPa)	E_s (MPa)	E_M (MPa)	E_s (MPa)	**(E_c/E_s)**
Sand	7 to 10	20 to 30	22	88	3 to 4.5
Clay	2	3	8.5	34	11

The modular ratio is not constant and ranges from 3 in dense sand to 11 in soft clay. This suggests that the modular ratio is likely to be higher in soils with low Young's modulus than those with high Young's modulus. Having said so, there should be a limit on the maximum modular ratio to be adopted in the design. Take for instant the targeted E_c for this project, which is 60 MPa. If this targeted E_c is indeed achievable in the soft clay layer, the modular ratio will be 20 (i.e., E_c/E_s = 60/3). However, as noted from the PMT results, the modular ratio achieved is only about 11. Clearly, a constant E_c should not be specified and a limit on the modular ratio should be imposed in the design of stone columns. The following limits can be considered:

- In sand, despite the fact that relatively high E_c is achievable, the modular ratio is likely to be around 3 to 5 due to the relatively high E_s for sand.
- In clay, although relatively low E_c is the norm, the modular ratio is likely to be around 5 to 12 due to the relatively low E_s for soft clay.

The above limits are similar to the findings by Barksdale and Bachus (1983), which suggested E_c/E_s in practice is ranging from 3 to 10 and Han (2012) which noted that the modular ratio is from 1 to 5 for flexible columns and 5 to 10 for semi-rigid columns.

4.3 Settlement Calculation

Based on the experience in this project, it appears that it is better to consider the minimum modular ratio between stone column and soil (i.e., E_c/E_s) in the design of stone column than specifying a constant stone column modulus, E_s to be achieved. In fact, designing and specifying stone column projects using the modular ratio should come quite naturally as most of the analytical methods to calculate settlement of the soil treated with stone columns are using this ratio to determine the settlement reduction factor for the settlement calculation. Settlement reduction factor, n is the ratio of the settlement of the untreated ground to the settlement of the ground improved with stone column.

Zooming into the Priebe's (1995) method, which is one of the most popular methods used for calculating the settlement of ground treated with stone columns, the maximum allowable settlement reduction factor is given by the equation below:

$$n_{max} = 1 + a_r\left(\frac{E_c}{E_s} - 1\right) \quad (1)$$

where:

n_{max} = maximum allowable settlement reduction factor
a_r = area replacement ratio = A_c/A
A_c = cross section area of the stone column
A = tributary soil area of the stone column (or unit cell area)
E_c/E_s = modular ratio between stone column and soil

It should be noted that the above equation (1) is not normally the settlement reduction factor to be adopted in the calculation of settlement after stone columns installation using Priebe's (1995) method, but it is the cap of the settlement reduction factor that can be adopted in the analysis. To illustrate quickly the effect of natural soil and stone column moduli in settlement calculation, the above equation is adopted to calculate the maximum settlement reduction factor for this project as tabulated in Table 3.

Table 3 suggests that by using a constant E_c of 60 MPa to calculate the settlement of the soft clay treated with stone columns, the settlement calculated might be about 38% lower than the reality (i.e., the settlement calculated based on the actual E_c of 34 MPa). Indeed, this is quite an alarming discrepancy. For the stone columns installed in the sand layer, the issue of using the constant E_c of 60 MPa might not be that severe with the calculated settlement to be about 6% higher than the reality. This implies that the E_c to be adopted in the design, especially for soils with low E_s (e.g., the soft clay layer in this project) needs to be selected carefully.

To help the selection of the E_c to be adopted in the settlement analysis, it might be useful to rely on the proposed limits of modular ratio. It can be seen from Table 3 that the n_{max} for the clay treated with stone column is within the n_{max} calculated using the proposed range of modular ratio for soft clay (i.e., $5 \le E_c/E_s \le 12$). For the sand layer treated with stone column, the n_{max} measured at site is also within the proposed modular ratio for sand (i.e., $3 \le E_c/E_s \le 5$). Indeed, the proposed modular ratio seems to be a good tool to estimate the range of settlement reduction factor following the installation of stone columns to treat the soils in a project.

Table 3 Calculation of settlement reduction factor

Natural soil	a_r	E_c (MPa)	E_s (MPa)	E_c/E_s	n_{max}	Note
Clay	28%	34	3	11.3	3.92	(a)
		60	3	20	6.37	(b)
		-	-	5	2.13	(c)
		-	-	12	4.11	(d)
Dense Sand	7%	88	30	2.9	1.14	(a)
		60	30	2	1.07	(b)
		-	-	3	1.14	(e)
		-	-	5	1.28	(f)

Note:
(a) Actual data from project
(b) The E_c is specified to be 60 MPa
(c) Using lower bound of modular ratio (i.e., $E_c/E_s = 5$)
(d) Using upper bound of modular ratio (i.e., $E_c/E_s = 12$)
(e) Using lower bound of modular ratio (i.e., $E_c/E_s = 3$)
(f) Using upper bound of modular ratio (i.e., $E_c/E_s = 5$)

4.4 Recommendations

The above section shows that the important parameters for the calculation of settlement of a ground treated with stone columns are the area replacement ratio, a_r and the modular ratio, E_c/E_s. The area replacement ratio, a_r is related to the diameter and spacing of stone columns which can be designed or determined with relatively high precision. The difficult part in the design or settlement calculation of ground treated with stone columns is determination of the modulus of stone column, E_c to be adopted. It has been shown that the approach of using a constant E_c in the settlement calculation of ground treated with stone columns might not be a good idea, especially for heterogeneous soils (with mixture of sand and clay or silt). As such, the modulus of stone column, E_c should not be specified with a constant value, especially with a high value that might not be achievable for stone columns constructed in soft soils due to the low confining pressure from the soft soils. Thus, it is recommended for the modular ratio, E_c/E_s with the limits proposed on the above to be used in the settlement analysis to get the idea of the likely improvement factor of installing stone columns for a project. Following this, a verification at site can be done by conducting in-situ test such as the pressuremeter test. Finally, if necessary, improvements or changes in the design can be conducted before full production works is carried out.

5. CONCLUSION

This paper has presented the application of Menard pressuremeter test as part of the quality control measures for the application of stone columns as the foundation system for a large diameter LNG tank. The challenges associated with conducting pressuremeter test inside the stone column is presented and the solution to overcome these challenges is provided. The pressuremeter test results from this project are presented showing the limit pressure, P_L and pressuremeter modulus, E_M obtained inside stone columns within the sand and clay layers. It is shown that the P_L and E_M inside stone columns are interdependent of the nature and characteristics of the natural soils treated with stone columns, the area replacement ratio (i.e., spacing and diameter of the stone columns) and the compaction energy adopted during construction of the stone columns. The pressuremeter test results also suggest that specifying or designing using a constant E_c throughout a stone column might not be appropriate, especially for heterogeneous soil. It is best to utilise the modular ratio between stone column and soil (i.e., E_c/E_s) for the settlement analysis of soil treated with stone columns.

6. REFERENCES

Balaam, N. P., and Booker, J. R. (1981). "Analysis of rigid rafts supported by granular piles". International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 5, Issue 4, pp379-403.

Barksdale R.D. and Bachus R.C. (1983). "Design and Construction of Stone Columns Volume I". Federal Highway Administration Report FHWA/RD-83/026, National Technical Information Service, Springfield, Virginia.

Castro, J. (2017). "Modeling Stone Columns". Materials, Vol. 10 (7), Article 782 (https://doi.org/10.3390/ma10070782).

Goughnour, R. R., and Bayuk, A. A. (1979). "Analysis of Stone Column – Soil Matrix Interaction Under Vertical Load", Proceedings of International Conference on Soil Reinforcement, Vol. 1, Paris, pp279-285.

Han, J. (2012). "Recent Advances in Column Technologies to Improve Soft Foundations", Proceedings of International Conference on Ground Improvement and Ground Control, Wollongong, Australia, pp99-113.

Menard, L. (1975). "The Menard Pressuremeter: Interpretation and Application of Pressuremeter Test Results to Foundation Design". General Memorandum D.60.AN. Sols Soils, N° 26, pp5-43.

Normes Françaises NFP 11–212. (2005). "Recommandations sur la conception, le calcul, l'exécution et le contrôle des colonnes ballastées sous bâtiments et ouvrages sensibles au tassement". Revue Française de Géotechnique, N° 111, pp3-16.

Priebe, H. J. (1995). "The design of vibro replacement". Ground Engineering, December, pp31-37.