Research on Integrated Liquefaction Assessment for Stone Column Applied in Coral Sand Area within High Earthquake Magnitude Zone

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Abstract. For deep and thick coral reef sand with high fine contents in high magnitude zone where the traditional vibro-compaction is not sufficient to compact, the stone column shall be applied as liquefaction mitigation measure. Based on the analysis of the three major antiliquefaction criterion of stone column, an integrated evaluation method combined densification, shear stress distribution and drainage criterion for liquefaction mitigation was proposed, further a field test with 10.1\% replacement ratio was launched. According to the analysis of the test result, the loose reclamation coral sand could be improved to an average 4.3 times SPT N value comparing. While for the medium dense coral sand, the densification among columns is limited, SPT N value is only increased by 1.3 times, and the densification decreases with fines content increasing. Further, the safety factor of liquefaction is only 0.70 and 1.01 when only considering densification criterion, or combined with shear stress redistribution criterion. However, if assessed by integrated assessment method which is mainly based on drainage criterion together with densification criterion and shear stress redistribution criterion, the calculated pore pressure ratio is still far less than the design value of 0.6 and that indicated the risk of liquefaction is still low. Moreover, when the bottom feed vibro-replacement process is adopted, the permeability coefficient of stone gravel is expected to reduce by half after stone column construction completion.

1. Introduction
In general, the compaction method is adopted for liquefaction mitigation of sand foundation, such as vibro-flotation, dynamic compaction, mainly by improving the densification of the sand to resist the liquefaction caused by the earthquake motion. Normally the dynamic compaction treated depth is limited to a maximum depth of 12m for conventional equipment [1], and vibro-compaction method should be adopted for deep loose layer, however the vibro-compaction method is generally only suitable for sand with fines content (particle size less than 0.075mm) less than 15\% [2]. Therefore, for
the deep loose sand foundation with high fines content in high earthquake magnitude zone, the stone column method based on drainage criterion [3] should be considered.

Many researchers have studied the three major liquefaction criterions of stone column, i.e. drainage criterion, densification criterion and shear stress redistribution criterion. Seed & Booker [4], Onoue [5-6], Zhiying Xu [7-8], Sigen Wang [9] have proposed the assessment method for drainage criterion. Priebe [10] has presented a method to assess the shear stress redistribution during earthquake. Baez[11] has studied the densification effect among stone columns and proposed an integrated assessment method which combined three major anti-liquefaction criterion.

Furthermore, Jianfeng Zhang [12], Jianguo Zheng [13], Guangne He [14] have also proposed quantitative evaluation methods, using the corresponding coefficients to consider the three major anti-liquefaction effects, but the corresponding coefficients are difficult to determine, which hinders the application of the project to a certain extent, so it is necessary to further compare and analyze different comprehensive assessment methods of liquefaction mitigation of stone column, and propose a suitable integrated evaluation method for engineering application. In addition, there are few studies on stone column applied to mitigate the coral reef sand liquefaction potential, which could provide a reference for similar strata in engineering application.

2. Method
It can be seen from the above analysis Baez [11] have provided guideline for liquefaction criterion based on different type of soil. For densification criterion, most of researches has concluded that it only plays a role in silica sand with fines content less than 15% [12]. While for shear stress redistribution and drainage criterion, it should be considered in clean or silty sand. In addition, for non-plastic silts, only need to consider shear stress redistribution criterion.

Regarding the assessment method of drainage criterion, many researchers [13-16] have proposed assessment method for stone column, the widely used is Seed and Booker [4]’s method. This method selected the pore pressure ratio index as assessment of drainage against liquefaction and the analysis process is established by the finite element analysis method. Several calculation charts are provided for application which is showed in Figure 1, however, the calculation chart is not continuous which is only based on several $\frac{N_{eq}}{N_l}$ value. It is difficult to choose the design value if $\frac{N_{eq}}{N_l}$ is not in line with design chart.

![Figure 1. Design charts of stone column for liquefaction remediation](image)

In addition, Seed & Booker [4] believes that when the ratio of the permeability coefficient of stone column to sand is greater than 200, the influence of the well resistance on the calculation of the pore pressure ratio can be ignored. However, Onoue [6] found that based on the vibration field test, even if the permeability coefficient ratio is greater than 200, the measured pore pressure ratio is only one-tenth of the value predicted by Seed & Booker [4]. Therefore, it is recommended that in the actual drainage against liquefaction analysis, the Onoue [6] method considering well resistance should be adopted, and the radial average pore pressure ratio $\overline{r_g}$ is calculated as follows:
\[ \tilde{r}_g = \frac{\bar{u}(z,t_d)}{\sigma_{vo}} = \frac{1}{a(z) \cdot t_d} \frac{N_{eq}}{N_i} (1 - e^{-a(z) t_d}) \quad (8) \]
\[ \alpha(z) = \frac{BC_h}{u_r D_e^2} \quad (9) \]
\[ C_h = k_h / (\gamma_w m_p) \quad (10) \]
\[ u_r = F(n) + \frac{\pi^2 L_w}{8} (1 - \frac{1}{n^2}) (2 - \frac{H}{\eta})(2 - \frac{H}{\eta}) \quad (11) \]
\[ L_w = \frac{32}{\pi^2} \frac{k_h}{k_w} \left( \frac{H}{D_w} \right)^2 \quad (12) \]
\[ F(n) = \frac{n^2}{n^2 - 1} \ln(n) - \frac{3n^2 - 1}{4n^2} \quad (13) \]
\[ n = D_e/D_w \quad (14) \]

Where \( L_w \) is the coefficient of well resistance, \( H \) is drainage length, \( k_w \) is the horizontal permeability coefficient of column material, \( k_h \) is the horizontal permeability coefficient of soil; \( n \) is the well diameter ratio, \( C_h \) is the horizontal consolidation coefficient of soil, \( m_p \) is the soil compression coefficient, \( \gamma_w \) is the unit weight of water, \( N_i \) is number of cycles required for liquefaction, \( N_{eq} \) is the equivalent number of cycles at design magnitude, \( F(n) \) is the dimensionless parameter, \( n \) is known as Barron’s index, \( D_e \) equivalent diameter of stone column, \( D_w \) is the diameter of stone column.

Based on the above analysis, it is proposed that the design pore pressure ratio shall be referred to the value of 0.6 recommended by Seed & Booker [4], Onoue [5-6], and Iwasaki [17]. The proposed integrated evaluation of liquefaction mitigation process is showed in Figure 2.

As showed in below figure, the Onoue method [6] is adopted for drainage criterion. Regarding shear stress redistribution criterion, the assessment method of reduction coefficient for shear stress redistribution criterion should select the larger value of the two methods, Priebe’s method [10] and Baez’s method [11] for conservative considerations. Further, the densification criterion for liquefaction mitigation is included in the parameters of the compression coefficient \( m_v \) and the number of cycles \( N_l \) which shall be obtained after stone column installation rather than pre installation.

![Figure 2. Design flow chart of integrated liquefaction assessment method based on drainage](image-url)
3. Results

3.1 Geological conditions of coral reef sand

The Tibar Port project in East Timor is located on the Pacific Rim Seismic Belt within high earthquake magnitude zone. The design seismic acceleration in reclamation area is as high as 0.53g. The original geological conditions are a mixed layer of marine deposited and diluvial deposited coral reef sand or gravel, with uneven distribution of fines content. The treatment depth of liquefaction is 15m, of which the top is covered with about 5m of filling coral reef sand, and the lower part is about 10m of loose to medium dense coral reef subsoil. The filling coral reef sand is controlled by 20% fines content. The N value of SPT prior to ground stone column is around 15~40 with an average value of 20. The coral reef subsoil within the ground improvement depth are mainly unit 3-1a and 3-1b strata as showed in Table 2. This stratum is mainly a loose to medium dense silty Sand with gravel or Gravel with sand. The PSD (particle size distribution) for unit 3-1a and 3-1b are shown in Figure 3 below. The main mechanical properties are shown in Table 1 below.

![Figure 3. PSD for unit 3-1a and 3-1b coral sand](image)

| Unit No. | Strata name                                      | SPT N value | Carbonate content (%) | Coefficient of permeability cm/s | Constrained modulus (MPa) |
|----------|--------------------------------------------------|-------------|-----------------------|----------------------------------|--------------------------|
| 3-1a     | Very loose to loose, locally medium dense Marin deposit/ sily Sand or Gravel with silt. | 0-18        | 90.18                 | 6.40E-02                        | 20                       |
| 3-1b     | Medium dense, locally dense silty Sand or Gravel with silt. | 7-35        | 66.06                 | 2.00E-02                        | 25                       |

The vibro-compactionability has been conducted for sand layer 3-1a and 3-1b based on PSD test result by the assessment method proposed by Brown [2] which is showed in Figure 4. It can be seen that the PSD range of the treated layer 3-1a and 3-1b coral reef sand is wide, and most of them are distributed in the transition area which means the compactability for vibro-flotation is lower as the fines content is high ranging from 0 and 50%. With reference to the Brown [2] study, the conventional vibro-compaction method is only suitable for sands with a fines content less than 15%. Therefore, under the design earthquake magnitude of 0.53g, the required densification would be high, however considering the high fine content, the vibro-compaction method is not suitable to compact properly, thus the vibro-placement method, i.e. stone column method mainly based on drainage criterion against liquefaction is adopted for ground improvement design and minimum replacement ratio of 10.1% is proposed.
3.2 Analysis of densification criterion

For the analysis of densification among stone column, both FHWA Barksdale and Bachus [18] and Baez [11] have proposed an empirical relationship chart for sand with fines content less than 15%. However, this relationship chart is built based on siliceous sand, and is not suitable for coral reef sand, thus it is necessary to further evaluate the method specially for coral reef based on field tests.

Based on the analysis of the detailed geotechnical investigation report, the typical coral reef sand layer was selected on site, and a total of three field test areas with replacement ratio of 10.1% were carried out. The layout of the field test area for stone column is shown in Figure 5 below, and the relevant information of the test area is shown in Table 2 below. The vibrator used in the test area is BJZC-BFS-400-180 with power 180kW which is from Beijing vibrator company ltd.

In order to analyze the densification among stone columns, 5 sets of SPT tests were conducted. Since the compaction effect is reduced with the distance increasing from the compaction probe, the three different location of SPT among compaction probe triangle for each group should be selected for densification assessment. The schematic diagram of points is shown in Figure 4. All sets of SPT has been conducted at three location, i.e. centroid position, 1/2 position and 1/3 position except for fifth set and average is calculated as the representative value.

Table 2 Test details of field trail area

| S.N.     | Diameter / space (mm) | No. of structured stone columns | Length of column (m) | No. of Set | SPT sets       |
|----------|------------------------|---------------------------------|----------------------|------------|---------------|
| Field test A | 800/2400               | 49                              | 20                   | 3 sets     | Post-BL09-1~Post-BL09-9 |
| Field test B | 800/2400               | 7                               | 20                   | 1 set      | Post-BL09-10~Post-BL09-12 |
| Field test C | 800/2400               | 19                              | 15                   | 1 set      | Post-TA9-1    |

Table 3 Statistical Analysis result of densification among stone columns for trail areas

| Strata layer   | Average N value ratio of Post to Pre SPT | Pre SPT relative density (%) | Post SPT relative density (%) | FC% range            |
|----------------|------------------------------------------|-------------------------------|-------------------------------|----------------------|
| Reclamation layer | 1.5                                      | 76                            | 20                            | Range 10–20 with average of 17 |
| 3-1a layer      | 4.3                                      | 36                            | 80                            | Range 19–32 with average of 25 |
In order to compare the density improvement of different soil layers, the curve for correlation between SPT N value pre and post construction with depth is present in Figure 5(a). For comparison, the curve of fines content with depth is showed in Figure 5(b). It can be seen from Figure 5(a) that the densification improvement of the reclamation layer after vibration is not significant after stone column construction and would decrease in some surface layer. This is mainly due to the lack of constraint stress on surface layer during vibration process. Thus, when assess the improvement of densification of reclamation coral sand layer, the top two sets of SPT values near surface layer are excluded.

The statistical analysis result for densification is showed in Table 3. The SPT N value of reclamation coral sand layer with fines content of 10%~20% could be increased from 18 to 34 with an average improvement 1.5 times, and corresponding average relative density is 82%. While for loose coral sand 3-1a layer with fines content of 19% to 32%, the SPT N value could be increased from 5 to 30 with an average 4.3 times and relative density is increasing from 36% to 80%. For medium dense coral sand with fines content of 28% to 40%, the SPT N value could be increased from 12 to 15 with average 1.3 time and corresponding relative density is increasing from 53% to 60%.

It can be concluded that for reclamation coral reef sand layer and loose coral reef sand layer, the improvement in densification after vibration is more significant, while for the medium dense coral reef sand layer with high fines content, the improvement in densification is limited. It is mainly due to the high fines content which would cause high excess pore pressure during vibration and lead to equal volume deformation among sand particles.

3.3 Analysis of shear stress redistribution criterion

Regarding the analysis of shear stress redistribution, the reduction coefficient $K_C$ of Baez [11]’s method and the reduction coefficient $\alpha$ of Priebe [10] can be calculated separately based on the proposed calculation flowchart of Figure 3 above, and the minimum value of two method would be adopted. The design internal friction angle of gravel material of stone column is 42° based on required gravel grading. Since the shear modulus of the soil and stone column are generally difficult to obtain, the shear modulus ratio of column to soil $G_c$ can be approximated by the constrained modulus ratio of stone columns to soil. The calculation is as below.

$$G_c = \frac{E_{sc}}{E_s}$$  \hspace{1cm} (13)
Here, $E_{sc}$ is the constrained modulus of stone column, $E_s$ is the constrained modulus of sand. Further the 150MPa is selected for constrained modulus of the stone column according to experience, and the constrained modulus of sand can be estimated by SPT N value based on below correlation:

$$E_s = 1200 (N + 6)$$

Equation (14)

The represented SPT N value after stone column construction in above Table 4 is substituted into equations (13) and (14) to obtain the shear modulus ratio $G_r$. Therefore, the reduction coefficients for different coral reef sand layers after stone column completion can be calculated according to equations (1) to (5), as shown in Table 4 below.

**Table 4 Selection of reduction coefficient for shear stress concentration criterion**

| Strata type   | Baez’s method (1995) | Priebe’s method (1995) | Adopted value |
|---------------|----------------------|-------------------------|---------------|
| Reclamation layer                          | 0.81                  | 0.68                    | 0.81          |
| 3-1a layer            | 0.78                  | 0.68                    | 0.78          |
| 3-1b layer            | 0.72                  | 0.68                    | 0.72          |

From the calculation result summarized in above table, it could obtain the reduction coefficient for shear stress concentration. The adopted value for reclamation, 3-1a and 3-1b layer is 0.81, 0.78 and 0.72 separately.

3.4 Analysis of drainage criterion

According to the Onoue [6] method of evaluating the drainage criterion against liquefaction, the key soil parameters affecting the drainage liquefaction are mainly the stone column permeability coefficient $k_w$, sand horizontal permeability coefficient $k_h$ and the soil compression coefficient $m_v$. The compression coefficient of the soil should adopt the value after stone column construction, which is the reciprocal of constrained modulus, i.e. equal to $1/31.2=0.032$MPa$^{-1}$. The horizontal permeability coefficient of sand shall refer to the geotechnical investigation report and $6.40E-02$cm/s is suggested. While the horizontal permeability coefficient $k_w$ of stone column can be calculated based on the design of the column gravel PSD based on the empirical formula from Engineering Geology Manual which is showed in Table 6.

The permeability coefficient of gravel can be obtained based on d50 value. According to the design grading, the design permeability coefficient shall be 20cm/s according to Table 7. In fact, during the stone column construction, the gravel would mix parts of the original coral reef sand, and resulting in the reduction of the permeability coefficient. Therefore, the design permeability coefficient should consider a certain reduction. Thus the permeability of 10cm/s for stone column is adopted.

3.5 Assessment of proposed integrated assessment of Liquefaction Mitigation

Based on the analysis of the densification for stone column, the increasing densification for 3-1b coral reef sand layer with a fines content of 28%-40% is minimum, and the average SPT N value after vibration is only 15. Therefore, this layer should be considered as the most unfavorable strata to liquefy after stone column treatment and should be selected for design of liquefaction mitigation. According to Euro code 1998-5 [19], the normal maximum liquefied depth is 15m, thus the maximum design length of stone column is set to 15m and the corresponding elevation of most unfavorable strata layer is -6~-9.5mCD.

Based on the above design conditions, the assessment of liquefaction is calculated separately for different combination cases as follow.

Case 1: only densification criterion
Case 2: densification criterion + shear stress distribution criterion
Case 3: Proposed integrated assessment which include three criterions

The assessment method for densification criterion is based on the safety factor (FS) calculated by SPT procedure recommended by NCEER [20]. The SPT N value of pre and post stone column construction shall be referred to Table 4. The calculation for case 1 and case 2 is showed in below Table 5.

### Table 5 Safety factor of anti-liquefaction without considering drainage

| Ele. mCD | prior to treatment | Case 1 FS-Pre | Case 2 FS1-Post |
|----------|--------------------|---------------|-----------------|
| -6       | 0.59               | 0.84          | 1.19            |
| -7       | 0.57               | 0.79          | 1.12            |
| -8       | 0.55               | 0.74          | 1.07            |
| -9       | 0.53               | 0.71          | 1.03            |
| -9.5     | 0.53               | 0.70          | 1.01            |

The assessment of drainage is calculated by equations (8) to (14). Further, the equivalent number of cycles $N_{eq}$ of 10 and duration time $t_d$ of 30s is obtained according to the corresponding relationship proposed by Steven [21] based on design magnitude $M=6.8$. The number of cycles $N_l$ required for liquefaction normally should be determined by dynamics triaxial test based on undisturbed sample. Whereas since it is difficult to collect the undisturbed sand ample from site, the empirical correlation based on Baez’s method [22] is applied in engineering project which is showed in below Figure 8. The correct (N1) 60 value is calculated by design N value of 15 based on NCEER [19]’s recommended correction method. The $CSR_l$ is calculated by the adopted reduction coefficient in Table 5. Thus, the number of cycles $N_l$ of 5 is selected for assessment based on the empirical chart Figure 6.

Lastly, for comparative analysis, according to the flow chart Figure 3 of the proposed integrated assessment method mentioned above, considering three major criterions, the pore pressure ratio $\bar{r}_g$ is calculated with and without gravel permeability coefficient reduction consideration. The results are showed in Table 6 below.

### Figure 6. Empirical liquefaction curves for $CSR_l$ and $N_l$

### Table 6 Calculation result of proposed integrated assessment method

| S.N | Calculation condition | permeability coefficient (cm/s) | $\bar{r}_g$ |
|-----|-----------------------|--------------------------------|------------|
| 1   | Permeability coefficient without reduction consideration | 20                  | 0.152      |
4. Discussion

It can be seen from the results in Table 6 that when only densification criterion is considered, the minimum FS of anti-liquefaction for most unfavorable layer is 0.70. If the shear stress distribution is included, i.e. case 2, the minimum FS of anti-liquefaction is 1.01. Therefore if the drainage criterion against liquefaction is not considered, the corresponding minimum anti-liquefaction safety factors are 0.70 and 1.01 for case 1 and 2 separately, which is not met the required design 1.1. However, while applying the drainage criterion together with consideration of densification and shear stress criterion, the calculated pore pressure ratio is much less than critical value of 0.6, which means the sand has been improved much for liquefaction mitigation and has a very low liquefaction potential. Thus, if the assessment of stone column without consideration of drainage criterion would cause the underassessment of liquefaction mitigation.

In addition, it can be seen from the comparison of PSD curves for gravel material prior and post imported to column, the permeability coefficient of the gravel will be reduced to a certain extent. When the reduction of permeability coefficient caused by bottom feed vibration is considered, the pore pressure ratio is increased from 0.152 to 0.286 inclined to unsafe side, thus in actual calculation, the reduction of the permeability coefficient of stone column should be considered.

5. Conclusions

Based on Tibar Port Project in East Timor, the analysis of densification criterion, shear stress criterion and drainage criterion for stone column against liquefaction is conducted based on field test. Further an integrated assessment method was proposed for stone column ground treatment, and the following conclusions could be drawn:

1. The proposed integrated assessment should be applied for liquefaction mitigation of stone column. Here, the reduction coefficient for shear stress criterion is recommended to adopt the minimum value calculated by Priebe’s method [10] and Baez’s method [11]. The drainage criterion assessment is suggested to apply Onoue’s method [6] which considering the well resistance. The densification criterion is included by selection of the compression coefficient $m_v$ and $N_l$ number of cycles after stone column construction.

2. For the 10.1% replacement ratio of stone column applying in coral sand, the densification would be increased to 4.3 times high for loose coral sand after stone column treatment, while for the medium dense coral sand, the densification could only be improved to 1.3 times after construction. And the higher fines content, the less improvement would be achieved.

3. When the bottom feed vibration construction process is adopted, the permeability coefficient of column material would be reduced to half due to mixture of sand particle.

4. Based on the analysis of the field test area, when the 10.1% replacement rate is applied for coral sand, the corresponding minimum safety factors are 0.70 and 1.01 if only considering densification criterion or densification combined with shear stress criterion against liquefaction. However, while applying the drainage criterion together with consideration of densification and shear stress criterion, the calculated pore pressure ratio is much less than critical value of 0.6 even considering the deduction of the permeability coefficient due to mixture of sand particle during construction, which means the liquefaction mitigation ability of stone column is underassessment without considering drainage criterion.
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