The Efficiency Evaluation of the Joint Application of Stone Column and Soil Mixing Method for Liquefaction Prevention of a Caisson Wall

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Abstract. Waterfront caisson wall is commonly seen port structure that could be heavily damaged by liquefaction. Although the mitigation measures were mostly proved efficient in theory, yet insufficient, particularly in providing an easily implemented remedial plan with design parameters for routine practices of liquefaction risk reduction. In this study, using the damaged caisson wall structure recorded from case history as the unimproved benchmark, the remediation effectiveness of a joint method - the stone column and deep mixing method for liquefaction risk reduction is examined based on the deformation comparison between the damaged and hypothetically improved seismic performance of the wall-soil system. Highlights on the establishment of liquefaction risk reduction process for caisson walls are generated as recommendations for practices.

1. Introduction
Waterfront caisson wall is a widely used port structure that have been heavily damaged by soil liquefaction during or after seismic events in histories. Overall, three major failure modes including horizontal (seaward) displacement, vertical settlement and ocean ward tilting of the wall could occur to the wall structure under the influence of soil liquefaction [1]. Various remedial mechanisms for caisson wall structures have been used including compaction, installment of the deformation panel behind the wall, etc. Most of the studies rarely provided the executable remedial plan with implementation details for routine practice. Therefore, the purpose of this paper is to establish an optimized remediation measure of using a joint method combining stone column (SC) and deep mixing method (DMM) depending on the calculated improved performance of a well-calibrated caisson wall reported in previous case in history [2,3].

2. Numerical Modeling Verification
To evaluate the remediation effectiveness of the applied remediation methods, it is important to ensure the reasonableness of the numerical modeling, which include two aspects: first, the numerical modeling for capturing the liquefaction failure mechanism; second, the damaged performance of the caisson wall in case history. Therefore, in this study, before the hypothetical application of remedial measures, the numerical modeling verification process was conducted to verify the liquefaction failure mechanism and the case history. The details of this verification process can be referred to previous references [4,5], and in this paper, only the detailed process of the remediation process and optimization was introduced in this paper.
3. Liquefaction mitigation simulation setting

For caisson wall structure, stone columns are commonly used to reduce the risk of liquefaction of the foundation soil and decrease the potential deformation of the soil under the wall structure; DMM walls are normally applied in the backfill soil to reduce the lateral deformation and dynamic active pressure applied on the wall structure.

In this study, three Ar% values (5%, 10% and 23%) are assumed, where $Ar\% = \frac{Ac}{Ae} \times 100\%$, where Ac is the circular area of stone column, Ae is the tributary, and $De = \text{equivalent diameter of the tributary area} = 1.05 \times \text{center-to-center spacing between the stone columns installed in a rectangular pattern}$. The parameter Ar% represents for the density of installed stone columns. The three examined Ar% values corresponding to center-to-center distance of 4, 3 and 2 diameters of the installed stone column, respectively. The permeability of native soil is assumed to be 1.0E-6 m/s for loose granular soils. Hence, the corresponded post-equipment SPT blow count values can be determined to be 14, 18 and 23 for Ar% values of 5% (Ar_5), 10% (Ar_10) and 23% (Ar_23), respectively.

In this paper, the thickness and depth of the DMM wall is 1 and 15 meters, respectively. The DMM walls are assumed “connected and fixed” at the bottom layer because of the fixed-end wall was believed to be more effective and reliable than the other types of walls such as the floating type wall. The dynamic and physical properties and stress-strain relationship of soil mixing mixed materials are mainly based on previous literature. The important parameters for DMM materials are used as below: 56-day $qu = 2.1$ (MPa); Elastic modulus (E50) = 300*qu = 620 (MPa); mixed soil density (kg/m3) = same as the density of soil without mixing by assuming that adding mixing to the soil will not increase the density significantly; the value of Poisson ratio = 0.3; Cohesion=$= 1500$ (kPa) [34]; Tensile strength = 15% of qu = 0.31 (MPa); Friction angle (degree) = 30; Permeability (cm/sec) = 1.0E-7; Since the construction quality of DMM project can be highly variable, a Quality Assurance and Quality Control program must be conducted to ensure the mixed material satisfies the specifications as mentioned in regulation. Three types of DMM wall layouts are studied and their remediation effectiveness was evaluated and compared, respectively. The DMM walls are installed at the distances of 30 meter, 15 meter and 10 meter from the wall in the remedial cases of wall-1, wall-3 and wall-5, respectively: wall-1: install one DMM wall at a distance of 30 m away from the quay wall; wall-3: install three walls at the distance of about 13 m, 28 m and 45 m, respectively, away from the quay wall; wall-5: install five DMM walls at the distance of 10 m, 20 m, 30 m, 40 m and 50 m, respectively, away from the caisson wall.

4. Results and Discussions

4.1. Remedial deformations of the caisson wall

A summary of residual deformations measured at the top seaward corner of the quay wall is provided. According to the performance-based design of the caisson wall structure, the overall deformation of the caisson wall structure is 0.5 meter, 1.1 meter and 2.1 meter for degree I, II and III, respectively.
The three black dashed lines in Figure 2 indicate the different specified performance grades. Three levels of damages defined in performance-based design can be represented by the performances from the structural and operational aspects. According to the calculation results, the majority of the evaluated designs would improve the performance of the case history from totally damaged to unlikely acceptable, either “Repairable or Serviceable”. Meanwhile, if the caisson wall were improved by following the the remedial case 6, 7, 10, 11, 12 and 13, the results could satisfy the specifications of “Repairable” by reducing deformation to be less than 10% of wall height of 18 meters (approximately 1.8 m) but still larger than 0.9 meter which is 5% of the wall height. The best improved deformation is about 0.7 m, which is 85% less than the unimproved zone by remedial cases 14 and 15, and this results indicate that at least three DMM walls should be installed in backfill soil with equal distance behind the quay wall in addition to the improvement of foundation soil by stone columns with Ar% of 23%. Therefore, the examined remedial cases can be classified into three categories based on their different improved performance: (1) improved performance is serviceable; (2) improved performance is repairable; (3) improved performance is acceptable. The unacceptable level includes case 1, 2, 3, 4, 5 and 8; repairable level includes: case 6, 7, 9, 10, 11, 12 and 13; serviceable level includes: case 14 and 15;

Another important observation is that the reduction of the horizontal displacement of the quay wall is critically influenced by the reduction of vertical displacement of the foundation soil behind the soil. In other words, a better improved foundation soil performance can increase the effectiveness of improving backfill for the analyzed quay wall. Without improving the foundation soil to satisfactory level, the effectiveness of improving backfill soil could stay low or with significant increase. Based on above observations, the two values of the effectiveness are positively correlated with each other. For example, comparing the results among cases 1, 5, 9 and 13 or 2, 6, 10, 14, the results indicate that increasing the value of Ar% from 5% to 23% of the installed stone columns in foundation soil, the reduction of lateral displacement of quay wall could also increase greatly even though the number of installed DMM walls in backfill soil remains constant. Therefore, above results indicate the interactive influences of improving the backfill soil and foundation on the deformation of quay wall. The interactive influence should be considered in the liquefaction mitigation design of caisson quay wall by ground improvement. At the same time, since the above observations are generated based on limited number of trail calculation, therefore, it is recommended to verify the observations by conducting more trials calculation.

4.2. Improved deformations on backfill soil surface
The seismic deformation on the backfill soil surface is also important for evaluating the seismic stability and damaged foundations or structures located in backfill soil such as heavy cranes and many buried utilities. Therefore, deformations are measured at the selected locations on the backfill soil
surface starting from the inward edge of the quay wall with equal interval distance of 5 m toward inland direction. The furthest location where only very small deformations occur is about 80 m away from the quay wall. The curves plotted in the following figures could represent the surface of the backfill. As can be seen, the deformation for all three curves or cases decrease along with the distance from the wall, which indicate the influence of liquefaction gradually decreases at the further locations from the wall structure.

(a) Without improvement in foundation soil

(b) Stone column method (Ar = 5%)
5. Conclusions
This paper studied the effectiveness of the stone column and DMM wall used for waterfront quay wall. Combining the stone column and DMM wall method, the improved seismic performance of caisson quay wall and generations of EPWP in liquefiable soils are evaluated in this study. The improved displacement at the top seaward corner of the quay wall and the deformations on the surface of backfill land are the two primary evaluation parameters. The following conclusions of this study can be drawn:

- The remedial program of combining both two methods is effective in reducing the seismic deformation of the quay wall in the case study.
- The proposed optimum remedial program/cases to achieve the different specified performance grades based on PIANC are: Unacceptable level for cases 1, 2, 3, 4, 5, 8; repairable level: cases 6, 7, 9, 10, 11, 12, 13; serviceable level for cases 14 and 15;
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References
[1] Moghada A.M., Ghalandarzadeh A., Towhata T., “Studying the effects of deformable panels on seismic displacement of gravity quay walls”, Ocean Engineering, 2009; 36 (15–16), 1129-1148.
[2] Arablouei A., Ghalandarzadeh A., Mostafagharabaghi A.R., Abedi K., “A numerical study of liquefaction induced deformation on caisson-type quay wall using a partially coupled solution”, Journal of Offshore Mechanics & Arctic Engineering, 2008; 133 (2), 1352-1355.
[3] Yang Z., Adalier K., Elgamal A., Sharp M.K., “Earth dam on liquefiable foundation and remediation: numerical simulation of centrifuge experiments”, Journal of Engineering Mechanics, 2004; 130 (10), 1168-1176.
[4] Tong B, Schaefer V. 2016. Optimization of Vibrocompaction design for liquefaction mitigation of gravity Caisson Quay Walls. Int J Geomech. 16(4):04016005.
[5] Bin Tong, Vern Schaefer, Yingjun Liu & Bing Han (2019) Optimization of deep mixing design for seismic liquefaction mitigation of Caisson walls, Geomatics, Natural Hazards and Risk, 10:1, 287-313.
[6] Bahadori H., Farzalizadeh R, Barghi A., Hasheminezhad A., “A comparative study between gravel and rubber drainage columns for mitigation of liquefaction hazards,” Journal of Rock Mechanics and Geotechnical Engineering, 10 (2018) 924-934.