Assessment on the improvement of liquefiable ground by stone-column, micro-pile and densification measure

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Submission date: 18-Jan-2024 01:10PM (UTC+0700)
Submission ID: 2273052574
File name: 59._Assessment_on_the_improvement_of_liquefiable.pdf (822.59K)
Word count: 1519
Character count: 8348

Smart Geotechnics for Smart Societies – Zhussupbekov, Sarsembayeva & Kaliakin (Eds)

Assessment on the improvement of liquefiable ground by stone-column, micro-pile and densification measures

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ABSTRACT: Soil liquefaction is an important issue in geotechnical engineering that would cause damages as a result of bearing loss, lateral spreading, or even flowsliding in a mildly sloping ground. Mitigation of excess pore pressure generation and lateral deformation thus become major concerns for liquefiable deposits. This paper examines three commonly adopted mitigation measures (stone-column/SC, micro-pile/MP, and densification/DS) on their effectiveness in reducing the influences of soil liquefaction. A numerical tool is employed and a real soil deposit of liquefaction concern is assumed for the assessment. In this study, we investigate the improvements for each of the mitigation measures, with their usual ranges of design specifications, on liquefaction phenomena of the original deposit. The study indicates both SC and DS options could effectively reduce the generation of excess pore pressure in soil. However, in reducing the lateral deformation of sloping ground, MP option would be superior than the other two options.

1 INTRODUCTION

Soil liquefaction is a key problem in geotechnical engineering, in particular for lateral spreading or liquefaction-induced flow sliding, which could sometimes be devastating and damaging; such as the case of Petobo flow failure causing significant movements in a mildly sloping ground due to 2018 Palu-Donggala Indonesia earthquake (Kusumawardani et al. 2021). Accordingly, mitigation or prevention of liquefaction disasters would be a primary concern in engineering practice. This paper addresses the numerical assessment of several liquefaction mitigation measures, including stone-column (SC), micro-pile (MP) and densification (DS), with an aim to provide a clearer understanding on the effectiveness of these methods.

2 ANALYSIS METHOD

The assessment adopts a numerical tool, OpenSees, through a graphical user interface for conducting 3D ground-structure finite element analysis (http://opensees.berkeley.edu). A 20-8-node brick element is assumed, where 20 nodes are for solid translational degrees of freedom and 8 corner nodes for fluid pressure. Multi-yield conical surfaces with considering phase transformation are applied for soils. The coupled solid-fluid option of the software enables the performance of liquefaction studies. Details of theoretical background are referenced to the manual (Lu et al. 2011).

DOI: 10.1201/9781003299127-70

Figure 1 indicates a typical soil column of the improved ground with a depth of 30 m, where a periodic boundary condition is assumed for the vertical faces and a fix end at the base of column. Due to symmetry, only one half of the soil column is assumed in the numerical analysis. As indicated, the seismic shaking is assigned at the base of the soil column and acting in X-direction.

A liquefaction-prone area at Chuoshui river alluvial fan-delta of Taiwan (CRAFD; Chang et al. 2012) is selected as the target site, where the log of Borehole W5-3, as shown in Figure 2, is adopted as the soil deposit with improvements by several mitigation measures in current study. It is noticed that nearly top 25m of the deposit comprises of sandy soils which are prone to liquefaction due to seismic shaking. Table 1 indicates the assumed material parameters of soil deposit and mitigation measures in the numerical simulations.

The input motion of this study adopts the recorded motion at CHY002 station during 1999 Chi-Chi earthquake (M_w = 7.6) of Taiwan. The recorded motion, however, should be scaled to the design earthquake of the site (M_w =7.1 & PGA=0.308g) based on local building code (MOI 2011), and then deconvoluted from ground surface to a depth of 30m of the site for OpenSees analysis. Figure 3 shows the deconvoluted input motion for this study (a_{max} = 0.250g).

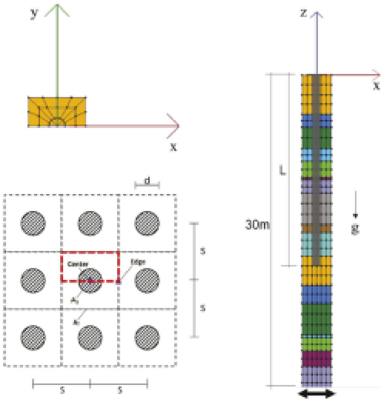


Figure 1. Finite element meshes of representative soil column for numerical simulations.

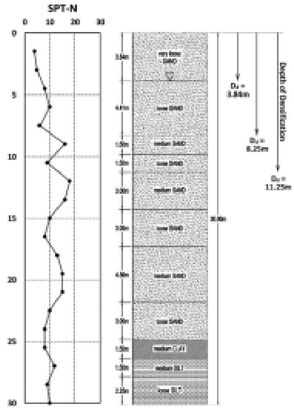


Figure 2. Typical soil/SPT-N profile, based on Borehole W5-3 in CRAFD, for current analysis.

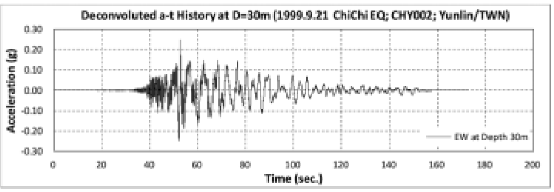


Figure 3. Deconvoluted input motion originally recorded at Station CHY002 (ground surface), in the proximity of Borehole W5-3 with a distance <2 km, during the 1999 Chi-Chi earthquake of Taiwan.

3 ASSESSMENT RESULTS

Three mitigation options are considered, including stone-column (SC), micro-pile (MP) and densification (DS), and the results are compared with the original deposit (i.e., original ground, OG; without improvement). Typical ranges of design specifications for each of the options are selected, as indicated in the relevant figures, with varied spacing (s) for SC option, embedment depths (L) for MP option, and depths of densification (D_d) for DS option.

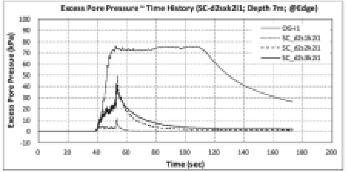
Table 1. Adopted material parameters for original soil deposit (original ground; OG) and for liquefaction mitigation options of stone-column (SC) and micro-pile (MP).

	Original Ground (OG)						Stone Column (SC)	Micro Pile (MP)
Parameters	Very Loose SAND	Loose SAND	Medium SAND	Loose SILT	Medium SILT	Medium CLAY		
γ (kN/m^3)	16.7	16.7	18.6	16.7	18.6	14.7	18.5	24.5
ϕ (deg.)	29	29	33	29	33	0	33	-
c (kPa)	-	-	-	-	-	37	-	-
ϕ_{PT} (deg.)	29	29	27	29	27	-	27	-
G_r (kPa)	5.5E4	5.5E4	7.5E4	5.5E4	7.5E4	6.0E4	7.5E4	1.4E7
B_r (kPa)	1.5E5	1.5E5	2.0E5	1.5E5	2.0E5	3.0E5	2.0E5	-
K_{soil} (m/s)	6.6E-5	6.6E-5	6.6E-5	1.0E-7	1.0E-7	1.0E-9	-	-
K_{SC} (m/s)	-	-	-	-	-	-	1E-4, 1E-2, 1E0	-
E_r (kPa)	-	-	-	-	-	-	-	3.5E7
ν	-	-	-	-	-	-	-	0.2
σ_{py} (kPa)	-	-	-	-	-	-	-	5.2E4

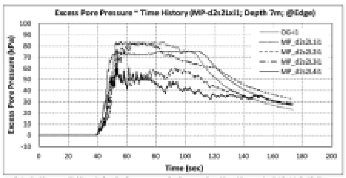
Note: γ = unit weight; ϕ = friction angle; c = cohesion; ϕ_{PT} = phase transformation friction angle; G_r = shear modulus at a reference effective confining pressure of 80kPa; B_r = bulk modulus at a reference effective confining pressure of 80kPa; K_{soil} = hydraulic conductivity of soil; K_{SC} = hydraulic conductivity of stone-column; E_r = Young's modulus at a reference effective confining pressure of 80kPa; ν = Poisson's ratio; σ_{py} = yield stress.

3.1 *Excess pore pressure time history*

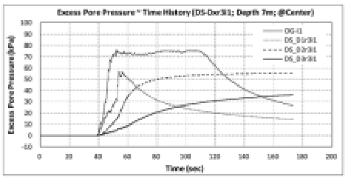
For level ground, the computed excess pore pressures at a depth of 7m of deposit are shown in Figure 4. As seen, the SC option would appear most effective in preventing excess pore pressure generation, hence reducing liquefaction potential. The DS option would also be effective in delaying the pore pressure generation if the depth of densification becomes deeper.



(a) Stone-Column (d=0.8m, $s_1/s_2/s_3$=1.4/2.8/4.2m, K_{SC}=1E-2 m/s, L=20m, i=0deg.; SC-d2-sx-k2-i1)

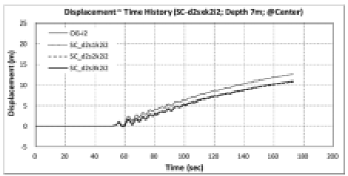


(b) Micro-Pile (d=0.3m, s=0.9m, $L_1/L_2/L_3$=4.5/9/18/27m, i=0deg.; MP-d2-s2-Lx-i1)

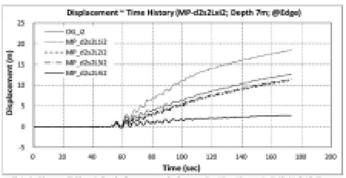


(c) Densification ($D_{d1}/D_{d2}/D_{d3}$=3.84/8.25/11.25m, D_r=75%, i=0dg.; DS-Dx-r3-i1)

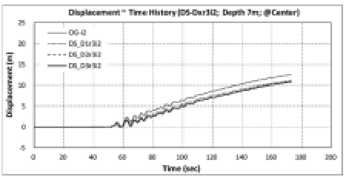
Figure 4. Computed excess pore pressure time histories at a depth of 7m (loose SAND) of the level ground ($i = i_1$ = 0deg.) for various liquefaction mitigation options. (Note: OG – original ground; SC – stone-column; MP – micro-pile; DS – densification).



(a) Stone-Column (d=0.8m, $s_1/s_2/s_3$=1.4/2.8/4.2m, K_{SC}=1E-2 m/s, L=20m, i=3deg.; SC-d2-sx-k2-i2)



(b) Micro-Pile (d=0.3m, s=0.9m, $L_1/L_2/L_3$=4.5/9/18/27m, i=3deg.; MP-d2-s2-Lx-i2)



(c) Densification ($D_{d1}/D_{d2}/D_{d3}$=3.84/8.25/11.25m, D_r=75%, i=3deg.; DS-Dx-r3-i2)

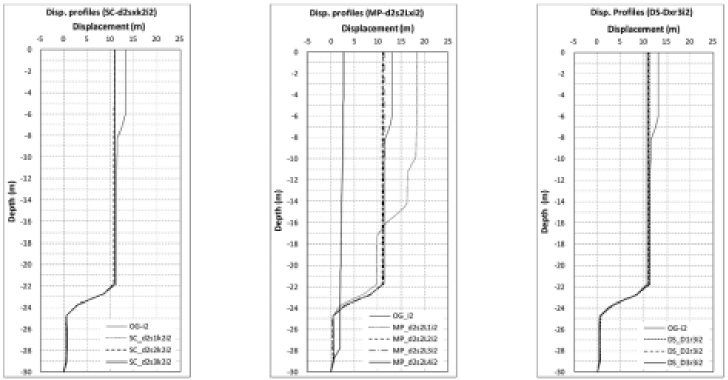
Figure 5. Computed lateral deformation time histories at a depth of 7m (loose SAND) of the inclined ground ($i = i_2$ =3deg.) for various liquefaction mitigation options. (Note: OG – original ground; SC – stone-column; MP – micro-pile; DS – densification).

3.2 *Lateral deformation time history*

Figure 5 shows lateral deformation time histories computed at a depth of 7m of a mildly sloping ground (*i*=3deg.). As seen, Both SC and DS options would appear not effective in holding lateral deformation of the ground. For MP option, however, if the embedment depth of micro-pile is long enough, penetrating through the liquefiable zone of deposit, then the lateral deformation of the ground would be significantly reduced.

3.3 *Lateral deformation profile*

Figure 6 illustrates the lateral deformation profiles of soil deposit with a slightly inclined ground (i = 3deg.). Similarly, Both SC and DS options would appear ineffective, while MP option with an embedment depth greater than the liquefiable zone would substantially hold the deformation.



(a) Stone-Column (d=0.8m, $s_1/s_2/s_3$=1.4/2.8/4.2m, K_{SC}=1E-2 m/s, L=20m, i=3deg.; SC-d2-sx-k2-i2)

(b) Micro-Pile (d=0.3m, s=0.9m, $L_1/L_2/L_3$=4.5/9/18/27m, i=3deg.; MP-d2-s2-Lx-i2)

(c) Densification ($D_{d1}/D_{d2}/D_{d3}$=3.84/8.25/11.25m, D_r=75%, i=3deg.; DS-Dx-r3-i2)

Figure 6. Computed lateral deformation profiles of an inclined ground (i = i_2 = 3deg.) for various liquefaction mitigation options. (Note: OG – original ground; SC – stone-column; MP – micro-pile; DS – densification).

4 CONCLUDING REMARKS

The numerical assessment of various liquefaction mitigation options indicates the stone-column (SC) and densification (DS) options would be effective in reducing or delaying the excess pore pressure generation, hence the risk of soil liquefaction. The micro-pile (MP) option could substantially reduce lateral deformation if the embedment depth is deeper than the liquefiable zone.

ACKNOWLEDGEMENTS

Financial support by MOST, Taiwan (Grant: MOST110-2221-E-224-054) is acknowledged.

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