Engineering of Ground for Liquefaction Mitigation Using Granular Columnar Inclusions: Recent Developments

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Abstract: Problem statement: Liquefaction was the most hazardous damage during an earthquake. Ground improvement techniques were employed to mitigate liquefaction hazards. Most common methods to improve engineering properties of soils are densification, reinforcement, grouting/mixing and drainage. Among various remedial measures available, installation of columnar granular inclusions is the most widely adopted method for liquefaction mitigation. Approach: Columnar granular inclusions function as drains and permit rapid dissipation of earthquake induced pore pressures by virtue of their high permeability. Results: One of the chief benefits of ground treatment with granular piles is the densification of in situ ground by which the in-situ properties of the ground get modified to mitigate liquefaction potential. Further, the very high deformation modulus and stiffness of the granular pile material provide reinforcement for the in situ soil and offer another mechanism to mitigate liquefaction. The study described briefly the phenomenon of liquefaction and the associated features. A short discussion on various ground improvement methods available for liquefaction mitigation was presented highlighting the importance of columnar inclusions. Construction methods of different granular columnar inclusions like sand compaction piles/granular piles were discussed briefly. Recent developments in the research of columnar granular inclusions as liquefaction counter measures were presented in relation to physical, numerical and analytical model studies. Conclusion/Recommendations: Columnar granular inclusions were demonstrated to be very effective for liquefaction mitigation in different case studies and research investigations.

Key words: Liquefaction, mitigation, columnar inclusions, granular piles, stone columns, analytical/numerical studies

INTRODUCTION

Liquefaction and its associated ground displacements resulting from earthquake shaking are the major cause of damage in loose saturated granular soils. Many liquefaction induced failures or near-failures of foundations, buildings and infrastructure facilities like highway/railway embankments, port facilities and earth dams have been reported across the globe during various earthquakes. The 1995-Kobe earthquake emphasized the importance of foundation liquefaction as a potential source of damage. Liquefaction can be manifested either by the formation of boils and mud-spouts at the ground surface, by seepage of water through ground cracks or in some cases by the development of quicksand conditions over substantial areas[1].

Ground improvement techniques like densification, reinforcement, grouting/mixing and drainage are commonly employed to mitigate liquefaction hazards. Provision of columnar granular inclusions like gravel drains/granular piles/stone columns is the most commonly adopted ground treatment methodology for liquefaction mitigation which has proved its effectiveness in many instances[2]. Granular piles are the most widely preferred alternative all over the world, due to technical feasibility, low energy utilization and cost effectiveness. They improve the ground by reinforcement and densification of the surrounding soil apart from providing drainage. Different mechanisms operate in the function of gravel drains/granular piles in liquefaction mitigation. These mechanisms can be stated as drainage, storage, dilation, densification and reinforcement.

Ground improvement by means of granular piles/stone columns/geopiers, which is associated with partial substitution of the in situ soil, originated in the sixties. Stone columns generally use gravel or crushed...
stone as backfill. Effect of method of installation, cased and uncased holes, number of lifts and magnitude of compactive energy per lift given to granular piles and pile spacing were discussed by Madhav and Thiruselvam[3]. Consideration of granular piles/drains installation as a possible method of stabilizing a soil deposit, susceptible to liquefaction, started with the work by Seed and Booker[4]. They state that pore-water pressures generated by cyclic loading get dissipated almost as fast as they are generated through the system of gravel or rock drains. Since then, different types of columnar inclusions are used as liquefaction remedial measure, which basically provide the drainage facility to dissipate the excess porewater pressures during cyclic loading almost as fast as they generated.

This study presents some of the recent developments in this very vital area of liquefaction and its counter-measures highlighting the importance of columnar granular inclusions.

**Liquefaction and counter measures:** Liquefaction is the state when saturated sandy soil loses its shear strength due to increased pore pressure and consequent reduction in effective stresses. Terzaghi[5] originally introduced the term liquefaction into the engineering community in the classical book Erdbaumechanik[6] and Casagrande[7], in 1936, used the term to explain the massive soil failures at Fort Peck Dam. The concept of liquefaction gathered worldwide attention in the 1960’s, when in 1964 large magnitude earthquakes located near Anchorage, Alaska and Niigata, Japan caused massive structural damage through ground failure. Significant amount of work on this topic has been performed in the last few decades since these earthquakes, resulting in several state-of-the-art papers relating to the study, evaluation and remediation of liquefaction[8-19].

As a consequence of the applied cyclic stresses, the structure of the cohesionless soil tends to become more compact but with a resulting transfer of stresses to the porewater and a reduction in the effective stresses on the soil grains. As a result, the soil grain structure rebounds to the extent required to keep the volume constant and this interplay of volume reduction and soil structure rebound determines the magnitude of the increase in porewater pressure in the soil[10]. The basic phenomenon is illustrated (Fig. 1) schematically by Seed[11]. The mechanism can be quantified so that the pore pressure increases due to any given sequence of stress applications can be computed from knowledge of the stress-strain and the volume change characteristics of the sand under cyclic strain conditions and the rebound characteristics of the sand due to stress reduction. Relationships between cyclic stress ratio and pore pressure ratio, number of cycles required to cause liquefaction and critical stress ratio with relative density were presented by Seed et al.[20] based on the study on porewater pressure changes during soil liquefaction. The effect of seismic history on liquefaction characteristics of saturated sands was studied by[21] with a concluding remark that the deposits of sand subjected to low magnitude earthquakes, which were not sufficiently strong to cause liquefaction, will develop an increased resistance to liquefaction in subsequent earthquakes even though, there may not be a significant change in density. Seed[11] developed a method to estimate liquefaction potential for sand under level ground conditions using standard penetration test data. This method was based on field performance data from sites, which either had or had not experienced liquefaction due to earthquake loading. Similar such research works on the liquefaction and its evaluation are extensively reviewed and presented[14,15]. The recent review on this very interesting topic is the work by Sawicki and Mierczynski[18], wherein the authors reviewed historical developments of mechanics of saturated granular soils in relation to the liquefaction phenomenon, development of theoretical approaches to liquefaction-related problems and modeling. In the recent years studies on the micro mechanical behavior of granular assemblies, in relation to liquefaction and associated mechanisms, are carried by several researchers[16, 18, 22, and 23].

![Fig. 1: Schematic illustration of mechanism of pore pressure generation during cyclic loading](image)
Table 1: Various ground improvement methods and their locations considered by Mitchell and Wentz[2]

| Sr. No. | Name                          | Location          | Soil conditions         | Method                      | Year of treatment |
|---------|-------------------------------|-------------------|-------------------------|-----------------------------|-------------------|
| 1       | Medical/dental clinic         | Treasure Island   | Hydraulic sand fill     | Stone columns               | 1989              |
| 2       | Office building No. 450       | Treasure Island   | Hydraulic sand fill     | Sand compaction piles       | 1967              |
| 3       | Facilities 487-489            | Treasure Island   | Hydraulic sand fill     | Vibrocompaction             | 1972              |
| 4       | Approach area, pier 1         | Treasure Island   | Hydraulic sand fill     | Stone columns               | 1984              |
| 5       | Building 453                  | Treasure Island   | Hydraulic sand fill     | Non-structural timber piles | 1969              |
| 6       | Esplanade extension           | Richmond          | Silty, sandy             | Stone columns               | 1986              |
| 7       | East shore, marina bay        |                  |                         | and gravelly fill           |                   |
| 8       | East bay park condominiums    | Emeryville        | Silty sand fill          | Vibrocompaction             | 1981              |
| 9       | Harbor bay business park      | Alameda           | Hydraulic sand fill      | Deep dynamic compactin      | 1985              |
| 10      | Hanover properties            | Union city        | Silty sand fill          | Deep dynamic compactin      | 1988              |
| 11      | Facilities 487-489            | South San Francisco| Hydraulic sand fill     | Compaction grout            | 1978              |
| 12      | Approach area, pier 1         | Treasure Island   | Hydraulic sand fill     | Stone columns               | 1985              |
| 13      | Riverside avenue bridge       | Santa Cruz        | Sands and gravelly      | Deep dynamic compactin      | 1978              |
| 14      | Adult detention facility      | Santa Cruz        | Silty, sandy fill        | Deep dynamic compactin      | 1978              |

Various ground improvement methods that can be used as liquefaction counter measures can be classified into two broad categories[32]: (i) Prevention of liquefaction and (ii) Reduce the damage to structures due to liquefaction. The former one can be achieved by increasing the undrained cyclic strength as well as by improving the resistance to deformation or by dissipation of pore water pressure. The second one, reducing the damage, could be attained by strengthening the foundation of the structures and the ground supporting the structures to avoid reduction in bearing capacity or making the structures more flexible so that it can deform in accordance with the ground movement in case of buried structures[24]. Resistance to liquefaction can be improved by increasing the density, modifying the grain size distribution, stabilizing the soil fabric, reducing the degree of saturation, dissipation of the excess pore pressures generated and intercepting the propagation of excess pore pressures. PHRI[25] summarize (Fig. 2) the basic strategies for liquefaction remediation.

Fig. 2 Strategy for liquefaction remediation[25]

The 1989 Loma Prieta earthquake experience provided the first opportunity to evaluate the behavior of treated ground that has been actually subjected to significant seismic shaking[26]. Twelve sites treated with different improvement methods prior to the earthquake were evaluated comprehensively by Mitchell and Wentz[2] (Table 1). They conclude that the procedures used for prediction of liquefaction were reliable and the ground improvement was very effective in mitigating liquefaction. Provision of gravel drains/granular piles/stone columns was the most commonly adopted ground treatment methodology for liquefaction mitigation which has proved its effectiveness in many instances.

Yasuda et al.[26] investigated the liquefied and non-liquefied subsoil conditions of two reclaimed islands in Kobe City after the 1995 Hyogoken-Nambu earthquake. Based on the study it was found that the non-liquefied zones had been improved by several methods, including sand compaction piles, rod (vibro) compaction, sand drains and preloading, before buildings had been constructed on them. Figure 3 depicts performance of different ground improvement methods in reducing the ground subsidence in the earthquake affected sites.

Fig. 3: Comparison of ground subsidence in zones treated with different methods[26]
Fig. 4: Liquefaction-induced settlement of a bridge pier built with different in-situ densification widths\cite{27}

It can be observed that the subsoil treated with columnar inclusions like sand compaction piles did not liquefy and nor subside even though the earthquake shaking was very strong. Madabhushi\cite{27} discussed and showed the effectiveness of three different ground improvement methods, viz., in-situ densification, gravel drains and grouting, through dynamic centrifugal model tests. Figure 4 evidences the effectiveness of in situ densification and its extent.

Among the different ground improvement methods available, provision of columnar granular inclusions in the in-situ soil is considered to be the most effective method for liquefaction mitigation due to its ability to provide drainage facility in lowering the excess porewater pressures and strengthen the ground.

MATERIALS AND METHODS

**Columnar granular inclusions as liquefaction counter-measure:** Columnar inclusions are of different types viz. sand drains, sand compaction piles; pre-fabricated vertical drains, granular piles or stone columns and lime or cement columns which are stiffer and stronger that the ambient soil, that can be installed in different arrays as shown in the Fig. 5. Installation of sand compaction piles in dynamic vibratory and static methods was discussed by Tsukamoto et al.\cite{28} (Fig. 6). Theoretical background, analysis, design aspects and installation techniques for stone columns/granular piles were being developed since 1970s by various researchers and practitioners\cite{29-34}. Granular piles are installed by vibro-compaction, vibro-replacement, cased borehole (rammed stone columns/rammed granular piles) or by simple auger methods\cite{31,35}.

Fig. 5: Various arrangements of columnar inclusions and zones of influence; (a): Triangular; (b): Square; (c): Hexagonal

Fig. 6: Installation of sand compaction piles\cite{28}

In cased borehole method\cite{36}, granular piles are installed into the ground by full displacement methods and by ramming in stages, using a heavy falling weight, within a ‘pre-bored casing’ or ‘driven closed end casing’ and retracting the casing pipe stepwise (Fig. 7). In recent
years, use of encased columns as a ground improvement method is increasing. Granular inclusions are encapsulated in geosynthetic materials to increase the resistance to bulging

The pioneering work on gravel drains as a possible method to stabilize liquefaction susceptible soil deposit is reported by Seed and Booker[4]. Numerous publications[43-47] describe the use of stone columns for ground reinforcement and their potential to mitigate liquefaction.

Granular columnar inclusions (Granular piles) help in mitigating earthquake induced liquefaction effects through one or more of these functions or effects:

- Granular piles function as drains and permit rapid dissipation of earthquake induced pore pressures by virtue of their high permeability with the additional advantage that they tend to dilate as they get sheared during an earthquake event
- Pore water pressures generated by cyclic loading get dissipated almost as fast as they are generated due to significant reduction in the drainage path
- Granular piles density and reinforce the in-situ soil; improve the deformation properties of the ambient soil
- Granular piles, installed in to a very dense state, are not prone to liquefaction and replace a significant quantity of in-situ liquefiable soil
- Granular piles modify the nature of earthquake experienced by the in situ soil

RESULTS

Adalier and Elgamal[48] reviewed the current state of stone column technologies as a liquefaction countermeasure. Sasaki and Tinaguchi[49] conducted large scale shaking table test on gravel drain system as a liquefaction counter-measure. Figure 8 shows different model configurations considered and typical distribution of the pore water pressures[49]. Adalier et al.[50] performed a series of highly instrumented dynamic centrifuge model tests (Fig. 9) to evaluate effectiveness of stone columns in mitigating the liquefaction potential of non-plastic silty deposits. Al-Homoud and Degen[47] present an introduction to earthquake-resistant design of marine stone columns. Similar studies on different types of granular columnar inclusions include[51,28,52] on sand compaction piles[53] on prefabricated vertical drains[57,54,55] on gravel drains.

Analytical studies on columnar inclusions as liquefaction remedial measure: Seed and Booker[4] were the first to propose an analytical model for the generation and dissipation of pore pressure in a soil deposit with vertical drains. Under the assumptions of purely radial drainage, constant coefficient of compressibility and infinite permeability of drains,
design charts (Fig. 10) were developed to evaluate the effects of drain diameter and spacing for the expected earthquake loading on excess pore pressure ratio. For flow into a gravel drain, assuming pure radial flow and constant coefficients of permeability ($k_0$) and volume compressibility ($m_v$), the governing equation can be written as\[^{[4]}\]:

\[
\frac{k_h}{\gamma_w m_v} \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) = \frac{\partial u}{\partial t} - \frac{\partial u_g}{\partial t} - \frac{\partial N}{\partial t} \frac{\partial N}{\partial t} \tag{1}
\]

Where:
- $u$ = The excess pore pressure at a radial distance, $r$, from the centre
- $t$ = Time, $\gamma_w$ - the unit weight of water
- $u_g$ = Peak excess hydrostatic porewater pressure generated by the earthquake

The rate of generation of pore pressure during an earthquake event is defined by:

\[
\frac{\partial u_g}{\partial t} = \frac{\sigma'}{\sigma_o} \frac{1}{\alpha \pi N_l} \left( \frac{\pi}{2} \frac{r}{t} \right) \cos \left( \frac{\pi}{2} \frac{r}{t} \right) \tag{2}
\]

Where:
- $r_i = u / \sigma_o'$ = The pore pressure ratio
- $\sigma_o'$ = The initial mean bulk effective stress for axi-symmetric conditions or the initial vertical effective stress for simple shear conditions
- $N_l$ = The number of cycles required to cause liquefaction
- $\alpha$ = An empirical constant which is a function of the soil properties with a typical average value of 0.7

The irregular cyclic loading induced by an earthquake is converted\[^{[56]}\] to an equivalent number, $N_{eq}$, of uniform cycles at an amplitude of 65% of the peak cyclic shear stress, i.e., $\tau_{cyc} = 0.65 \tau_{max}$, occurring over a duration of time, $t_d$ and:

\[
\frac{\partial N}{\partial t} = \frac{N}{t_d} \tag{3}
\]

Tokimatsu and Yoshimi\[^{[57]}\], Sasaki and Taniguchi\[^{[49]}\] and Onoue\[^{[58]}\], report results similar to those of Seed and Booker\[^{[4]}\] taking into consideration additional factors such as well resistance (finite permeability of gravel drain) and drain slenderness ratio (slenderness ratio: $L/r$, where $L$ is the length and $r$ the radius of the gravel drain). Pestana et al.\[^{[59,60]}\] analyzed the provision of a reservoir to minimize the drain resistance to flow in to the drain. Poorooshash et al.\[^{[61]}\] propose an equivalent coefficient permeability, $k_{eq} = k_{unt} / t_{50}$ (for untreated ground)/$t_{50}$ (for treated ground), for the treated soil, in terms of the permeability, $k_{unt}$, of untreated ground and $t_{50}$ values for the untreated and granular pile treated ground are the times for 50% degree of consolidation based on one dimensional and radial consolidation theories respectively. Dilation effect on the drainage function of granular piles was studied by Madhav and Arlekar\[^{[62]}\]. The densification effect of granular piles in improving deformation properties of the ambient soil was studied by Murali Krishna and Madhav\[^{[63]}\] and Murali Krishna et al.\[^{[64,65]}\]. Murali Krishna et al.\[^{[64]}\] incorporated the densification effect of granular piles, with respect to variation of flow parameters from the centre of the granular pile, in the analysis of pore pressure generation and dissipation that was originally developed by\[^{[4]}\].
The modified form of the governing Eq. 1 with the inclusion effects of densification is:

$$\frac{k_h(r)}{k_v(m(r))} \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) + \frac{1}{\xi_r m_r(r)} \frac{\partial k_h(r)}{\partial r} \frac{k_h(r)}{k_v} \frac{\partial u}{\partial r} - \frac{\partial u}{\partial t} - \frac{\partial u}{\partial N} \frac{\partial N}{\partial t}$$  \hspace{1cm} (4)

In this case coefficients of permeability, $k_h(r)$ and volume change, $m_r(r)$, are functions of radial distance, r, from the point of densification and degree of densification. Murali Krishna et al.\[64\] studied the densification effect with respect to the coefficients of permeability and volume change at the near and at the farthest ends of the granular pile, individually and together, on maximum pore pressure variations during an earthquake event. Figure 11 and 12 show the densification effect on maximum pore pressure ratio with respect coefficient of volume change at the near and farthest ends respectively. $R_{ma}$ and $R_{mb}$ are normalized coefficients of volume change due to densification at the near and farthest ends respectively.

**DISCUSSION**

Densification effect on the coefficient of volume change is positive in that the maximum induced pore water pressure ratios get reduced and sensitive to the type of variation considered as pore pressure ratios are lesser for the exponential variation compare to linear variation. Densification effect, on the coefficient of permeability alone or in addition to effect on coefficient of volume change, increases the maximum pore water pressure ratios giving a negative effect. The pore pressures ratios are not sensitive to the type of variation of permeability with distance. Densification effect on both coefficients of permeability and volume change result in a either slightly negative or positive effect depending on the degree of densification.

Further research is essential in the area of columnar granular inclusions as liquefaction countermeasure especially regarding encased granular columns.
CONCLUSION

Liquefaction is the most disastrous feature during an earthquake that causes huge loss and damage to various structures founded on or in the ground. Ground improvements are extensively used to reinforce the in situ ground and also as liquefaction countermeasures. Columnar granular inclusions are the most widely used remedial measures against the liquefaction. Columnar granular inclusions provide drainage to mitigate the liquefaction potential of the ground. Various mechanisms such as reinforcement, densification, dilation along with the drainage mitigate the damages due to liquefaction. The study presents an overview of the recent findings on the topic.

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