



Deep Mixing Columns

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Abstract - The deep mixing columns (DMCs) is a stabilisation technique that uses cement and lime as stabilisation agents to improve the ultimate bearing capacity of soils. This method has numerous applications, such as foundation engineering, providing supporting wall for excavation, liquefaction mitigation, hydraulic cut-off wall, and environmental remediation. This current paper presents a brief history and a review of this promising technique for the purpose of ground improvement. Moreover, several previous works related to the ultimate bearing capacity of DMCs ground are reviewed which includes analytical analyses, laboratory works (small scale), and full scaled field tests. Finally the paper suggests further study and development topics and proposes steps forward to enhance the potential of alternatives for cement and lime replacement in this promising technique.

Keywords: Deep mixing columns, soil stabilisation, ultimate bearing capacity.

Introduction

A variety of soil stabilization techniques have been applied to improve the bearing capacity of soft ground, such as granular and prefabricated vertical drains, vacuum consolidation, granular column reinforcement (sand compaction piles, vibrated stone columns), and stabilising techniques (deep mixing, pre-mixing and lightweight treated soil) (Kirsch & Bell, 2012; Sabih, Shafique, & Hussain, 2011). Of the soil stabilising techniques, deep mixing columns (DMCs) is becoming well established in an increasing number of countries because it is a cost-effective approach with numerous technical and environmental advantages including speedy implementation, elimination of off-site disposal, high ground strength, and impeding of biodegradation (Fang, Chung, Yu, & Chen, 2001; Saitoh, Suzuki, & Shirai, 1985).

In a broad perspective, deep stabilisation of soils is an in situ soil modification technique using a stabilizing agent not only to improve bearing capacity but also to reduce settlement, preventing shear deformation of soils, and treating contaminated soils (Porbaha, 1998; Topolnicki, 2004). According to the literature, this method has several advantages (Kitazume, 2002; Kitazume & Terashi, 2013): (1) speed of construction, (2) strength calibration, (3) reliability, (4) variety of applications, and (5) effective use of resources.

This method has numerous applications, such as foundation engineering, providing supporting wall for excavation, liquefaction mitigation, hydraulic cut-off wall, and environmental remediation (Hashizume, Okochi, Dong, Horii, Toyosawa, & Tamate, 1998; Okumura, 1996; Terashi, 2005).

For instance, this method was successfully used to develop soft soil areas such as the Rawang-Ipoh Rail Double Tracking Project in Malaysia (Raju, Abdullah, & Arulrajah, 2003), and the Carriageway Trasa Zielona in Poland (Topolnicki, 2004). Several road and rail embankment stabilization projects have been completed in China, France, United Kingdom and Italy using this method (Massarsch & Topolnicki, 2005; Liu, Yi, & Zhu, 2008). Besides, the method has widely been used in the United Kingdom to treat the contaminate soil and encapsulation of contaminated soils, including cut-off walls

and reactive barriers (Al Tabbaa & Evans, 2003). In addition, Japan extensively uses this promising method for different applications, one of which was the construction of about 15 km long Trans-Tokyo Bay Highway; whereby the soft clayey foundation soil was improved using a cement mixture to safeguard the tunnel (Kitazume, 2002). Elsewhere, this method was used for stabilizing failed levees and flood walls along Orleans Avenue Canal in New Orleans, USA (McGuire, Templeton, & Filz, 2012).

In DMCs, the chemical agents, which are either slurry (wet mixing) or powder (dry mixing), are mixed into the soft ground to form columns of soil binders. For this purpose, a rotary mixing auger is drilled to the treatment depth. The drill's rotation direction is then reversed and retrieved whilst binders are pumped through the auger drill bit and the soil and binders are mixed (Bruce, 2001).

Due to their robustness, easy adoptability, and economic value, cement and lime are employed as stabilizing agents in DMCs to produce stronger and firmer ground, namely soil–cement/lime columns (Kawasaki, Suzuki, & Suzuki, 1981; Prusinski & Bhattacharja, 1999; Saitoh, 1988). Although these traditional cementitious binders can improve many engineering properties of soils, they have several shortcomings, especially when viewed from an environmental perspective.

This current paper presents a brief history and a review of this promising technique for the purpose of ground improvement. Moreover, several previous works related to the bearing capacity of DMCs ground are reviewed which includes analytical analyses, laboratory works (small scale), and full scaled field tests. Finally the paper suggests further study and development topics and proposes steps forward to enhance the potential of alternatives for cement and lime replacement in this promising technique.

Deep mixing installation pattern

Specially designed machines are used to construct in situ columns of soil-binder in various patterns. Several configurations of this method have been applied in the field, including: group, grid, wall, and block (Kitazume, 2002; Kitazume & Terashi, 2013).

In the group column type improvement, treated soil columns or elements are installed in rows with either rectangular or triangular arrangements in a ground. The execution needs a relatively short curing period, and the volume of improvement is quite small (Figure 1 (a)). The group column type has been constructed to support small structures especially on land (Kitazume & Terashi, 2013).

In the wall type improvement, as shown in (Figure 1 (b)), the long walls of treated soil with or without short walls oriented perpendicular to the centreline of superstructures are produced by overlapping adjacent columns (Kitazume & Terashi, 2013). The expected function of long wall is to bear the weight of superstructure and other external loads, and transfer them to the deeper stiff layer.

The grid type improvement is an intermediate type between the block type improvement and the wall type improvement. The stabilized soils columns are installed by overlapping execution so that grid shaped improved masses are produced in the ground (Figure 1 (c)). This pattern is highly stable next to the block type improvement and its cost ranges between the block type and wall type improvements (Bruce, 2001; Kitazume & Terashi, 2013).

In the block type improvement, a huge improved soil mass is formed in a field by overlapping all the stabilized soil columns (Figure 1 (d)). This type of improvement is normally applied to heavy and permanent structures such as breakwater and sea revetment in port, and harbour structures (Kitazume & Terashi, 2013).

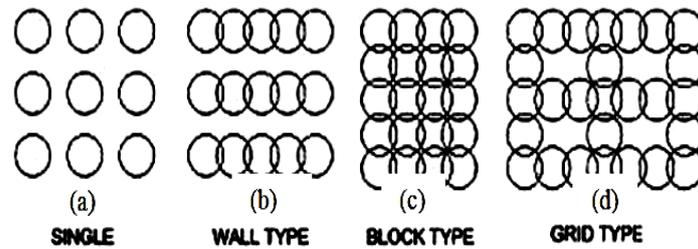


Figure 1: Several configurations of deep mixing have been applied in the field including (a) Group column type improvement, (b) Wall type improvement, (c) Grid type improvement, and (d) Block type improvement

From economical and construction considerations, the group columns type is desirable due to the small amount of improvement area and ease of installation as the treated columns are constructed without any overlapping (Kitazume & Terashi, 2013; Terashi, 1981).

The deep mixing columns (DMCs) technique has some features in common with other ground improvement techniques such as the stone column technique. Both methods are employed to improve bearing resistance and control settlement in soft ground condition (Terashi, 2005). In addition, the design used in both cases depends on the area replacement area ratio. However, important differences are the material and installation technique used. The stone columns require granular material of suitable grading to be available and the vibrations generated during installation can cause problems.

Deep mixing design

The DMCs are designed to precisely address the needs of any particular situation, either by adjusting one or a combination of the following variables: columns diameter, replacement area ratio, mixing definitions, binder quantity, and binder type (Porbaha, Shibuya, & Kishida, 2000).

In DMCs, the diameter of the columns ranges from 0.5 to 1.75 m, the spacing is generally 1.0 to 1.5 m centre to centre and the length usually varies from 10 to 30 m in normal practice for land applications. In some circumstances especially for harbour structures, 60 m long cement columns have been used (Bruce, 2001).

The replacement area ratio, α , is the ratio between the total sectional area of the columns to the area of the ground occupied by the columns. According to Bruce (2001), in the common treatments applied in the Scandinavia and the United States, α , varies between 10 to 30%. In some situations, for preventing a sliding failure and lateral deformation due to seismic conditions, an α value of 30 to 50% has been applied (Bergado, Anderson, Miura, & Balasubramaniam, 1996). Those authors suggested that the total width of improved ground should be more than half of the thickness of the soft ground if a low α value is used.

In DMCs, the stabiliser agent is injected at a pressure of up to 280 Bar into the hole by using a pumping system and a nozzle to mix the soil with the stabiliser agents either in the form of slurry (wet) or powder (dry) (Druss, 2002; Porbaha, 1998). After mixing process, there is a chemical reaction between the stabilising agent and soil that produces a composite material.

This composite material is often compacted to a relatively high density so that its properties become similar to soft rock. The shear strength and modulus of elasticity of this material could be typically 10 to 20% of plain concrete (Jo, Hafez, & Norbaya, 2011) and hence they can be considered as an engineered low strength concrete columns. In such a condition, a substantial improvement in the soil bearing capacity is achieved which in turn reduces the overall foundation cost by allowing the structures to be built on shallow footing rather than pile foundation. It has been documented that the degree of this substantial improvement in the soil bearing capacity can be related to quantity of binder,

binder type, and curing time (Chew, Kamruzzaman, & Lee, 2004; Kawasaki et al., 1981; Kitazume & Terashi, 2013; Terashi, 1981).

A number of studies have investigated the maximum effective percentage of binders to be mixed with particular types of soils to gain a considerable increase in the compressive strength and to achieve a desired improvement ratio (Kitazume & Terashi, 2013). Ahnberg, Ljungkrantz, and Holmqvist (1995) reported that between 5 to 40% of binder content with respect to the dry weight is usually required to stabilise soil columns. Meanwhile, 20 to 30% of binder content is typically used in Japan (Okumura, 1996; Yoshizawa, Tanaka, & Shekdar, 2004) and 10 to 50% of binder content is used in the United States (Bruce, 2001; Porbaha et al., 2000). From the literature, the difference in binder amount is due to the binder type and different reaction pathways in order to attain structural integrity (Kawasaki et al., 1981).

Binder type

Traditional cementitious binders

Traditionally, the common binders in soil stabilization are lime, cement, or lime/cement (i.e., a mixture of lime and cement) (Kawasaki, Saitoh, Suzuki, & Babasaki, 1984; Kawasaki et al., 1981). Incorporation of these cementitious binders has gained popularity due to their robustness, easy adaptability, and cost effectiveness (Akpokodje, 1985; Miura, Horpibulsuk, & Nagaraj, 2001; Prusinski & Bhattacharja, 1999).

In cemented soil, when the pore water of the soil makes contact with cement, hydration of the cement occurs rapidly and the major hydration (primary cementitious compounds) produces calcium silicate hydrate (C-S-H), calcium silicate hydrate (C-A-H), and hydrated lime Ca(OH)_2 (Janz & Johansson, 2002). In lime-stabilized soil, soil particles become closer and the soil is treated through flocculation and pozzolanic reactions (Bell, 1996; Kamon & Nontananandh, 1991). Although the type of reaction in cemented soil is completely different in comparison with lime-stabilized soil, the final products, based on Si and Ca compounds, are very much alike. In terms of mechanical strength, cement-based binders usually deliver substantially better results than lime-based binders (Janz & Johansson, 2002). It should be noticed that the use of cementitious binders (i.e., cement and lime) in soil stabilization and specifically in DMCs is under discussion, not only for their negative environmental effects during manufacture but also for their cost.

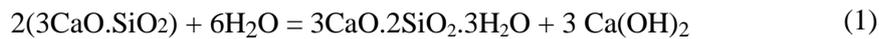
In the case of cement, this traditional binder generates around 7% of artificial CO_2 emissions, because of carbonate decomposition (Gartner, 2004; Matthews, Gillett, Stott, & Zickfeld, 2009). It is estimated that every ton of cement produces around one ton of CO_2 , a major greenhouse gas implicated in global warming (Kim & Worrell, 2002; Lothenbach, Scrivener, & Hooton, 2011; Taylor, Tam, & Gielen, 2006). In addition to the emission of CO_2 , another by-product of cement production is NO_x . Most of these nitrogen oxides are produced in cement kilns, which can contribute to the greenhouse effect and acid rain (Hendriks, Worrell, De Jager, Blok, & Riemer, 1998).

Beyond these problems, the use of cementitious binders in DMCs shows poor tensile and flexural strength and a brittle behaviour (Correia, Oliveira, & Custódio, 2015; Sukontasukkul & Jamsawang, 2012). For instance, when the cemented soil column is subjected to seismic loads, either lateral earth pressures (as for deep-mixed soil walls) or horizontal displacements (as in the case of columns installed under the sides of embankments and in slopes), the stabilized soil tends to fail under tension, due to its brittleness (Correia et al., 2015; Sukontasukkul & Jamsawang, 2012). Another issue concerning about cement is associated with the intrinsic characteristics of the material that allow water and other aggressive elements to enter cemented soil columns, resulting in corrosion and carbonation problems (Fang et al., 2001). In the case of lime, it is essential to note that this soil binder reacts with water rapidly and increases the difficulty during deep mixing projects (Bell, 1996; Cong, Longzhu, & Bing, 2014).

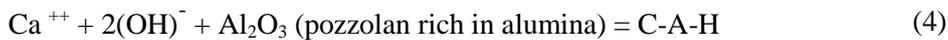
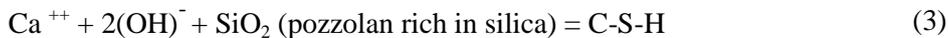
Pozzolanic materials

Several studies have focused on finding supplementary materials as partial replacements for traditional cementitious binders. In this respect, the use of pozzolanic materials deserves special attention. These materials are rich in silica (SiO₂), alumina (Al₂O₃), and iron oxide (Fe₂O₃) with little or no cementitious value. It is a well-documented fact that pozzolanic binders cannot react completely by themselves during stabilization (Basha, Hashim, Mahmud, & Muntohar, 2005; Chen & Lin, 2009). However, when certain pozzolanic materials containing silica and alumina are added during the hydration of cementitious binders, the reaction produces an additional amount of C-S-H and C-A-H gels, the main cementing components (Dwivedi & Jain, 2014).

A pozzolanic reaction takes place when high amounts of reactive SiO₂, Al₂O₃, and Fe₂O₃ are mixed in the presence of water. Usually CaO is added to the mixture as lime or cement in Equation 1, while SiO₂, Al₂O₃, and Fe₂O₃ can be presented in the pozzolan to develop further cementation gels including C-S-H and C-A-H. In this process, as shown in Equation 2, the hydration of the CaO liberates OH⁻ ions, which causes the pH value to increase up to approximately 12. Under such circumstances, as shown in Equations 3 and 4, pozzolanic reactions occur: the Si, Al, and Fe combine with the available Ca, resulting in further cementation gels. Depending on the pozzolanic activity, the contribution of this reaction is usually developed at later curing stages (Dermatas & Meng, 2003; Pourakbar, Asadi, Huat, & Fasihnikoutalab, 2015; Seco et al., 2012). Therefore, pozzolanic materials require Ca(OH)₂ in order to form strengthening products, while cementitious materials themselves contain quantities of CaO and can exhibit a self-cementitious (hydraulic) activity (Papadakis & Tsimas, 2002).



Pozzolanic reactions:



The use of pozzolanic materials in DMCs is still at the early stage of development and, hence, need comprehensive research works in order to become technically and economically viable.

Researches on deep mixing

Analytical analyses

Theoretically, a stress concentration on the treated soil columns occurs when the treated columns are much stiffer than the surrounding soil (Broms, 2003). In such condition, the foundation components will carry external loads and deform together. Thus, the internal stability of the columns may become a significant aspect of the design. Consequently the majority of the existing analytical methods for the determination of ultimate bearing capacity (q_{ult}) value of treated soil columns were mainly dependent on the strength performance of the columns.

In light of the abovementioned explanation, the q_{ult} value of the model ground has been determined in several laboratory and full scale experiments based on two analyses including Broms (2000) and weighted method as shown in Equations 5 and 6, respectively.

Broms' method $q_{ult} = 0.7 q_{uc} \cdot \alpha + \lambda (1 - \alpha) \cdot C_{us} \quad (5)$

Weighted method $q_{ult} = C_{uc} \cdot \alpha + (1 - \alpha) \cdot C_{us} \quad (6)$

where C_{us} and q_{uc} are undrained shear strength of the soft ground and the unconfined compressive strength (UCS) value of the treated columns, respectively, where λ is a dimensionless coefficient, proposed by Bergado et al. (1996) to equal 5.5. Furthermore, as mentioned earlier, α is the replacement area ratio.

Lower bound (q_{min}) and upper bound (q_{max}) of the q_{ult} of treated soil by means of group columns were established by Boussida and Porbaha (2004), and Bouassida, Jellali, and Porbaha (2009). Those researchers established lower and upper bounds based on the yield design theory. They assumed that the treated soil columns and untreated surrounding columns, which are deemed to have the same unit weight, are purely cohesive materials and that their resistance obeys Tresca's criterion.

According to the above-mentioned studies, the lower and upper bonds of q_{ult} can be computed using Equations 7 and 8. In addition, K_c indicates the cohesion ration band on Equation 9.

$$q_{min} = C_{us} \cdot [4 + 2\alpha (k_c - 1)] \quad (7)$$

$$q_{max} = C_{us} \cdot (2 \sqrt{2} \cdot \sqrt{[1 + \alpha(kc - 1)][2 + \alpha(kc - 1)]}) \quad (8)$$

$$K_c = C_{uc} / C_{us} \quad (9)$$

in which C_{us} and C_{uc} are undrained shear strength of native soil and treated soil column, respectively, and α is replacement area ratio.

Laboratory research studies

A study conducted by Terashi (1981), who performed ten physical modelling tests in a laboratory with a range of improvement of the area ratio from 13 to 32% and the strength ratio that ranged from 11 to 173. That author used cement as a soil binder and the prefabricated soil cement columns were inserted into consolidated model ground for the column installation process. A rigid plate was used to load the model ground and the loading was displacement controlled. They reported a clear peak was observed when a strong column was used ($q_{uc} = 1040$ kPa) which indicates a brittle failure. According to their test results, progressive failures in the columns occurred so that individual column displacements at the overall peak load did not coincide.

Other studies were conducted by Kitazume (1996), and Kitazume, Okano, and Miyajima (2000), who carried out physical modelling tests with an improvement area ratio of 79%, subjected to various combinations of vertical loads. The strength of the columns, q_{uc} , ranged from 213 to 27200 kPa. Sand was used as a drainage layer at the bottom of the specimen box and the box was then filled with kaolin slurry. Acrylic pipes with 20 mm inside diameter and 250 mm length were used to fabricate the cemented columns and extracted after seven days of curing. Further weeks of curing were conducted under water at room temperature. All the model tests were carried out in an undrained condition. They reported that the magnitude of the stress increased rapidly with the increase in displacement and the peak stress occurred at about 0.05 to 0.10 of normalised vertical displacement. Moreover, they found that the failure mode depends on the column strength (due to presence of cement) and vertical load component.

Boussida and Porbaha (2004) carried out the research on the q_{ult} of ground improved by means of the group column type. The study focused on an improvement area ratio of 18.8% with varying column strength. Clay was used to construct the soft ground and sand was used for a drainage layer at the bottom of the box. Soil cement columns of diameter 20 mm were constructed and cured outside of the

soil. The column installation technique was similar to that of Terashi (1981). The model was left in fully saturated conditions for two days before loading was carried out. According to their test results, peak load values were observed for all tests at less than 10% of normalised displacement and the failures were classified as brittle failures.

A study was performed by Yin and Fang (2010), who conducted a physical modelling test on DMCs with an improvement area ratio, α , of 12.6%. A rigid box with dimensions 900 mm width by 300 mm length was used to study the q_{ult} value of the cemented soil column under a 300 mm wide footing. The column preparation and installation technique were similar to that of Terashi (1981). According to this study, a brittle failure was observed from the stress-normalised displacement curve.

Full scale-field tests

Bergado, Ruenkairergsa, Taesiri, and Balasubramaniam (1999) conducted a case study on the Bagna-Bangkaong Highway in Thailand improved by the DMCs. The purpose of the study was to investigate the q_{ult} and settlement of the DMCs. The column diameter was 0.6 m and the length was either 14 m or 16 m. The spacing centre to centre between the columns was 1.5 m. A wet mixing method with 150 kg/m³ of cement was used in order to achieve 600 kPa column strength in the field. The floating column group was constructed on soft clay having an average shear strength of 12.5 kPa. Those authors found that the q_{ult} was larger than the embankment loading and measurements from plate bearing tests.

Lin and Wong (1999) conducted a static load test on floating soil cement columns at the Fu-Xia Expressway, Fujian Province, China. Two columns were loaded, after being mixed in situ and cured for 28 days, by jacking against steel beams loaded with sand bags. The diameter of the columns was 0.5 m and the length was 9.6 m for column three and 8.6 m for column four. By considering that the failure occurred when the settlement reached 25 mm, the q_{ult} of columns was 150 kN and 183 kN and the maximum compression strength was 667 kPa and 832 kPa, respectively. Lin and Wong (1999) concluded that the failure of columns three and four could be due to either soil or column material failure. Those authors found that the ultimate unit skin friction was 50% for column three and 70% for column four of the average shear strength of the soft clay, 15 kPa. Disturbance of the surrounding clay during column installation could have reduced the skin friction initially. For the column material failure, they suspected that could have been caused by the heterogeneity of the cement mixing with the soil in the field. As a result, the strength of the column in the field was lower than the strength obtained from a laboratory trial mix.

Chai, Liu, and Du (2002) observed the performance of the DMCs at the Lian-Yun-Gang section of the Xu-Lian Expressway in eastern China. The field vane shear strength ranged from 5 kPa to 25 kPa over a 10 m depth. A group of cement columns with a diameter of 0.5 m and 10 m long were installed using the dry mixing method. The columns were arranged in a triangular pattern with 1.1 m to 1.6 m spacing. In most cases, the amount of cement used was 59 kg/m³ to achieve the strength of 0.8 MPa. Field loading tests were conducted on a single column and on a composite foundation which covered either two or three columns. For the single cement column, a square loading plate with an area of 0.25 m² was used. Chai and his co-workers found that the average compression strength of the column was 0.96 MPa which was close to the value of the laboratory unconfined compression strength (0.8 MPa). As a result, they concluded that the q_{ult} of a single fully penetrated cement column was due to the failure of the column itself. For the composite foundation, a study was made with different column spacing (1.1 m, 1.2 m, 1.4 m and 1.6 m) with different areas of loading plate for the three columns group (3.14 m², 3.84 m², 5.25 m² and 6.65 m²). As a result, different improvement area ratios underneath the loading plate were tested (8.9%, 11.2%, 15.3% and 18.8%). They concluded that the q_{ult} increased with increasing improvement area ratio, although the conditions in each test were not exactly the same and a precise comparison is not possible to achieve under field conditions.

Summary and conclusions

From the review of the literature available to date, it can be seen that the DMCs provides an alternative to more traditional methods of soil stabilization. Several configurations of this method have been applied in the field, including: group, grid, wall, and block. From economical and construction considerations, the group columns type is desirable due to the small amount of improvement area and ease of installation as the treated columns are constructed without any overlapping.

The majority of the existing analytical methods for the determination of ultimate bearing capacity value of DMCs were mainly dependent on the strength performance of the columns. In this respect, the ultimate bearing capacity value of the model ground has been determined in several laboratory and full scale experiments based on two analyses including Broms and weighted methods.

According to the laboratory results, the failure mode depends on the column strength (due to the presence of cement and other cementitious binders) and vertical load component. Moreover, according to full scale tests, the strength of the column in the field was lower than the strength obtained from a laboratory trial mix.

Traditionally, the common binders in DMCs are lime, cement, or lime/cement (i.e., a mixture of lime and cement). Although the type of reaction in cemented soil is completely different in comparison with lime-stabilized soil, the final products, based on Si and Ca compounds, are very much alike. The use of cementitious binders (i.e., cement and lime) in DMCs is under discussion, not only for their negative environmental effects during manufacture but also for their cost. Since the pozzolanic materials are rich in silica, alumina, and iron oxide with little or no cementitious value, the use of these materials in DMCs deserve special attentions.

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