Applications of deep mixing technology for mitigating earthquake disaster in Urban Area

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Abstract. Many earthquakes take place every year in Japan, in which the 1995 Hyogoken-Nambu earthquake and the 2011 Tōhoku earthquake induced both a humanitarian crisis and massive economic impacts. As liquefaction, which occurs in a loose and saturated sand layer, induces quite large damages of infrastructures, the importance of liquefaction mitigation has been emphasized to minimize earthquake disasters for many years. Many kinds of ground improvement techniques based on various improvement principles have been developed for earthquake disaster mitigation. Among them, the deep mixing technology has been often applied to liquefaction mitigation. In the techniques, in-situ soil is mixed with binder by several types of methods: mechanical mixing, high pressure injection mixing and combined mixing. The high applicability of the method was confirmed in several earthquakes, including the 1995 Hyogoken-Nambu earthquake and the 2011 Tōhoku earthquake. In this paper, the outline of the deep mixing method and some applications of the deep mixing method to earthquake disaster mitigation are briefly introduced.

1. Introduction

Many earthquakes take place every year in Japan, in which the 1995 Hyogoken-Nambu earthquake and the 2011 Tōhoku earthquake induced both a humanitarian crisis and massive economic impacts. Table 1 shows an example of the amount of damage of port facilities due to earthquake [1]. According to the table, the amount of damage when liquefaction takes place is about 20 to 50 times larger than that without liquefaction, which highlights the importance of liquefaction mitigation to minimize earthquake disasters. Many ground improvement techniques based on various improvement principles have been developed for earthquake disaster mitigation. Among them, the deep mixing method (DMM), an in-situ cement stabilization techniques, was developed in 1970s in Japan and has been

| Earthquake          | Magnitude | Port   | Soil type | Max. ac.cel. (gal) | Liquefaction | Damage (mil. yen) |
|---------------------|-----------|--------|-----------|--------------------|--------------|-------------------|
| Niigata, 1964       | 7.5       | Niigata| Sand      | 159                | Yes          | 49,980*           |
| Tokachi Oki, 1968   | 7.9       | Hachinohe| Sand    | 233                | No           | 1,980*            |
| Miyagiken Oki, 1978 | 7.4       | Shiogama| Clay      | 273                | No           | 160*              |
| Uarakawa Oki, 1982  | 7.3       | Ishinomaki| Sand    | 195-210           | Yes          | 3,008*            |
| Nihonkai Chubu, 1983| 7.7       | Akita  | Sand      | 205                | Yes          | 6,400             |

* converted into 1978 prices.
frequently applied to improvements of clayey and sandy soils [2]. The grid type DMM has been often applied to prevent liquefaction, where the grid of stabilized column walls function to restrict generation of excess pore pressure in the soil in between the grid. The improvement effect of the method was first evaluated in the Hyogoken-Nambu earthquake in 1995 and was also evaluated in the Tōhoku earthquake in 2011. In this paper, the outline of the deep mixing method and some successful applications of the method to earthquake disaster mitigation in urban area are briefly introduced.

2. Deep mixing method

2.1 Outline of the method

In the deep mixing method (DMM), soft soil is stabilized in situ with chemical binder. The deep mixing method originally developed in Japan and Nordic countries has now gained wide popularity in the worldwide market. During the past five decades, a variety of deep mixing processes has been developed by contractors as their proprietary techniques. The deep mixing method has been usually applied to improvement of soft clays and organic soils for various purposes such as stability increase, settlement reduction, excavation support and seepage control [2]. The mixing processes are classified by the introduction of binder, wet or dry method, and type of mixing tool, mechanical mixing, high pressure injection mixing and combined mixing. For liquefaction mitigation, the block and grid types of DMM have been applied irrespective of the type of mixing tool.

The mechanical deep mixing method was put into practice in Japan in the middle of 1970s to improve soft marine deposits, and then was spread into China, South East Asia, and recently to the other part of the world. Five decades of practice have made equipment improved, binders changed, and applications diversified. Figures 1(a) shows the deep mixing machines of the mechanical deep mixing method. In the method, the special machines used to stabilize soft soil are basically composed of several mixing shafts and blades, and a binder supplying system. In one operation, a column of stabilized soil is constructed in a ground. Through a series of construction procedures, any arbitrary shape of improved soil mass (such as block, wall and grid types) can be formed in the ground.

In the high pressure injection method, the binder slurry is injected at a high pressure of 10 to 60 MN/m² through the nozzle into a ground. The binder slurry disturbs the original ground and is mixed with the soil, while the injection pipe is slowly rotated and withdrawn to the ground surface. The injection tool is designed to withstand high injection pressures using proper materials as well as the specialized seals between the rod joints (Figure 1(b)). Basically, there are three types of the techniques: single fluid technique, double fluid technique and triple fluid technique.

![Deep mixing machines](image1.png)

(a) Mechanical mixing method  (b) High pressure injection mixing method

**Figure 1.** Deep mixing machines.
2.2 Grid type improvement for liquefaction mitigation

The grid type DMM has been often applied to prevent liquefaction, where the grid of stabilized column walls function to restrict generation of excess pore pressure in the soil in between the grid. In the grid type improvement, the spacing of the grid wall is one of the essential factors for the liquefaction design, which the thickness and strength of the grid wall are the other essential factors for the external and internal stabilities. The development of the grid type improved ground for liquefaction mitigation was initiated by the Ministry of Construction in the late 1980s by a collaborative study with several Japanese construction firms, in which many centrifuge model tests, large scale shaking table tests and numerical analyses were carried out to investigate these factors on the liquefaction [3]-[8]. According to these reteach, the Ministry of Construction proposed the draft of the design procedure and guideline of the grid type deep mixing improvement in 1999 [9].

Figure 2(a) shows the design flow of the grid type improvement. In the assumption of dimension of improved ground, the ratio of the grid space and thickness of liquefiable layer is determined by Figure 2(b), in which the maximum excess pore pressure ratio, $\Delta u/\sigma_v'$ at the mid depth of potentially liquefiable layer is plotted. The Ministry recommended that the grid ratio, $B_{cl}/H_i$ should be smaller than about 0.8 to assure the effect of liquefaction prevention. In the external stability analysis of the improved ground, three failure modes are examined: sliding, overturning and bearing capacity failures. In the internal stability analysis, the induced stresses due to the weight of structure and seismic inertia load in the improved ground are calculated based on the elastic theory. The width of improved ground and the thickness of grid wall are determined so that the induced stresses become lower than the allowable strengths of the stabilized soil. In the slip circle analysis, the overall stability of the improved ground, superstructure and soft ground is evaluated.

![Design flow](image1)

![Relationship between grid ratio and max. pore water pressure ratio](image2)

**Figure 2.** Design flow of grid type improvement for liquefaction prevention [9].

In order to brush up the design guideline, series of centrifuge model tests were carried out to investigate the effect of grid spacing on generation of pore pressure and seismic response in a sand layer and proposed a new design guideline in 2006 [10]-[14]. In 2008, a new design procedure was also proposed for building application based on the numerical analyses and case histories [15]. The new design procedure has been adopted to many building construction projects and to evaluate the effect of the grid space more precisely.
3. Applications and performances of mechanical deep mixing method

3.1 Application and Performance to Building in the 1995 Hyogoken-Nambu Earthquake

The grid type DM improved ground was applied to a building foundation at Kobe port to prevent liquefaction during earthquake. Figure 3(a) shows the soil profile at the site, which consisted of 10 to 12 m of soft reclaimed sand and gravel, layers over the seabed [16], [17]. The seabed layer consisted of alternating layers of clay, sand and gravel. Due to the small SPT N-value lower than 10, the top layer had been anticipated to liquefy due to earthquake excitation. The building was supported by cast-in-place reinforced concrete piles with a diameter of 2.5 m extending to dense diluvial sand and gravel at a depth of 33 m for bearing capacity. Its section and plan diagrams are shown in Figure 3(b) [17]. A grid type improvement was applied to prevent liquefaction in the upper loose fill. More than 1,000 stabilized soil columns with a diameter of 1.0 m were constructed by the mechanical mixing method, where 200 kg/m³ of blast furnace slag cement type B was mixed to obtain the design strength of 2,400 kN/m² for the sand layer and 3,600 kN/m² for the clay layer. The improvement area ratio was approximately 0.2. The unconfined compressive strength of the stabilized soil after about six weeks curing was 4,000 to 6,000 kN/m² [17], which assures the design strength.

At the 1995 Hyogoken-Nambu earthquake, the ground improvement and piles’ installation were already completed but the building was under construction. As the reclaimed ground around the building was not improved, liquefaction took place, which caused serious damages of the quay wall near the building as shown in Figure 4(a). The concrete caisson type quay walls were subjected to the large excess pore water pressure due to the liquefaction. And they on the west, south and east sides displaced horizontally toward the sea by 1 m, 2 m and 0.6 m respectively and the ground behind the quay walls settled by 0.5 m, 0.6 m and 0.3 m. Sand boils and ground cracks were observed at the ground surface there. At the building area, however, there was no damage at the surface of the improved ground as shown in Figure 4(b). The head of the cast-in-place piles supporting the building was found to be intact. Moreover, negligible differential settlement was observed on the first floor of the building.
Figure 3. Application of grid type deep mixing to building at Kobe port.

Figure 4. Ground deformation after the 1995 Hyogoken-Nambu earthquake.

3.2 Application and Performance to Building foundation in the 2011 Tōhoku Earthquake

Figure 5(a) shows a four-story parking building with 213 m in length and 71 m in width in Urayasu city, which was supported by the pre-stressed high-strength concrete piles with diameter from 500 mm to 1000 mm and length from 33 m to 60 m [18] - [20]. Figure 5(b) shows the ground condition, in which a landfill and sand layer were stratified from the surface to the depth of GL -14 to 16 m,
and a soft clay layer was distributed over the lower part. The SPT $N$-values of the landfill and sand layers were around 10 from the surface to around GL-14 m. Figure 5(c) shows the estimated liquefaction potential of the site according to the Architectural Institute of Japan recommendations for foundations [21]. The liquefaction potential, $F_L$, became smaller than 1.0 in the case of the surface acceleration of 200 gal, and liquefaction might take place in the soil from GL-1.8 m to GL-12 m. The typical 15.6 m by 16.5 m grid type improvement were applied there for liquefaction prevention by the mechanical mixing method, which was designed based on the AIJ recommendations for ground improvement [21] and the simplified method [15]. The design unconfined compressive strength of the stabilized soil was 1,800 kN/m$^2$. After the completion of the ground improvement and building construction, the building was subjected to the 2011 Tōhoku earthquake attack. Extensive soil liquefaction was observed in the reclaimed land in Urayasu city. However, neither the ground damage nor building damage was observed after the earthquake, as shown in Figure 5(a).

### 4. Applications of high pressure injection deep mixing

Since the 2011 Tōhoku earthquake, the necessity and importance of earthquake reinforcement and liquefaction mitigation have been highlighted on new infrastructures and existing residential houses. The high pressure injection mixing method is preferable for the ground improvement of existing building because the mixing machine is smaller than that of the mechanical mixing. And in general, the high pressure injection mixing method causes less ground movement and ground heaving during the construction rather than the mechanical mixing method.

#### 4.1 Application of high pressure injection DM method to building foundation

The Osaka Prefectural Nakanoshima Library is designated as National Important Cultural Property, where the Neo-baroque style is enhanced with four massive columns standing at the building's front entrance and the copper roof dome (Figure 6(a)). The building was built in 1904 as a donation by Kichiemon Sumitomo and was followed by the construction of exterior appearance in 1922. The ground condition is shown in Figure 6(b), where several soil layers are deposited at the site: the fill layer at the top, underlain by the Alluvial sand layer, As1, and the Alluvial sand and gravel layer, Asg1, the Alluvial clay layer, Ac1, the Alluvial sand layer, As2, and the Alluvial sand and gravel layers, Asg2 and Asg3. Figure 4(b) also shows the SPT $N$-value distributions along the depth [22]. As the SPT $N$-values of the As1 and Ac1 layers are relatively small, liquefaction is likely to take place in the layers, which may cause serious damage to the building.

The stabilized soil columns were constructed beneath the building piles and slabs to increase the bearing capacity of the building, as shown in Figure 7. Additional stabilized soil columns were constructed between the building piles to form the grid type improved ground to prevent the liquefaction and reinforce the ground. In the figure, the length of columns is distinguished by different colours. The grid spacing was designed as $L/d = 1.4$, where $L$ and $d$ are the grid spacing and the thickness of liquefiable
layer, respectively. As the ground improvement should be carried out beneath the existing building, the high pressure injection method was applied instead of the mechanical deep mixing techniques. The double fluid techniques was applied, where the diameter and design strength of the high pressure injection column were 3 m and 16 MN/m², respectively.

(a) Library building.

(b) Ground condition, ground stratum and SPT $N$-values.

**Figure 6.** Osaka Prefectural Nakanoshima Library [22].
4.2 Application of high pressure injection DM method to house foundation

The Iwasaki garden is the former estate of the Iwasaki clan in Tokyo who were the founders of Mitsubishi Corporation. The premises have three buildings: a western-style house designed by British architect Josiah Conder, a Japanese-style house and a billiard house, and cover an area of about 17,000 m². The western-style residence is a two-story building constructed of wood that also has a cellar. The design is based on the Jacobean style of England in the 17th century, which incorporates Islamic motifs of the Renaissance. The Japanese-style house was integrated with the western-style residence. At the time the building was completed, the total floor space amounted to 1,815 m², making it nearly comparable in size to the western-style building. The billiards house was designed to be reminiscent of a Swiss mountain chalet, a style very rarely seen in Japan. This building is made completely of wood, it features log walls with carved pillars and a roof with protruding eaves, a design that shows signs of Gothic style. The European-style building and billiard are designated as an important cultural property in 1961.

The ground condition at the Japanese-style house is shown in Figure 8(b), where typically four soil layers are deposited at the site: the loam layers, Lm1 and Lm2, at the top with the SPT N-value of about 3 to 5, underlain by the fine sand layers, Hos and Tos [22]. Figure 8(b) also shows the SPT N-value distributions along the depth. As the SPT N-values of the Lm1 and Lm2 layers are relatively small, ground settlement have taken place due to less bearing capacity and underground water flow. The house were reinforced by the high pressure injection techniques in order to prevent further ground settlement and liquefaction.

The stabilized soil columns were constructed beneath the building piles and slabs by the high pressure injection mixing method to increase the bearing capacity of the house. As the ground improvement should be carried out beneath the existing house, the high pressure injection method was applied instead of the mechanical deep mixing method. The small size high pressure injection machine was applied in this project, where size and weight of machine are 50 cm (length), 50 cm (width) and 120 cm (height), and 120 kg. The high pressure injection column of 2.4 m in diameter and its design strength was 1.2 MPa. The construction of the high pressure injection method is shown in Figure 9.

After the ground improvement, boring core sample were taken from the ground for the unconfined compression test. The average unconfined compressive strength strength of the core sample is 4,959
kN/m², which satisfied the design strength of 3,266 kN/m², and its coefficient of variation is 32%, which assures the design criteria. Negligible ground deformation was observed in the ground and the house during the construction, which is due to smooth flow out the spoils to the ground surface.

(a) Small size high pressure injection machine. (b) Ground improvement work.

Figure 9. Ground improvement by high pressure injection deep mixing method.

5. Concluding remarks
This manuscript introduces the outline of the deep mixing method and its several successful applications to the new and existing building, which emphasizes the high applicability of the method to liquefaction mitigation and ground reinforcement. The deep mixing method has been often applied to many types of infrastructures and many building foundations, and its high applicability and improvement effect have been evaluated in many earthquakes. Its design, execution and quality control and assurance have been improved based on the accumulated laboratory and field experiments, numerical analyses, field experiences and know-how. Since the 2011 Tōhoku earthquake, the necessity and importance of earthquake reinforcement and liquefaction mitigation have been highlighted on new and existing buildings and houses. The deep mixing method is expected to be applied to many types of structures for reinforcement and liquefaction prevention in future.

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