Sustainable land reclamation in coastal area

Masaki Kitazume*

Tokyo Institute of Technology, Tokyo, Japan

Abstract – Many land reclamation projects have been carried out worldwide for many years to create new land from oceans, seas, riverbeds or lakebeds for several purposes. Historically, agriculture was the first drive for land reclamation, followed by urbanization and industrialization. Recent worldwide globalization has enhanced international trading and promoted many land reclamation projects in coastal areas. Land reclamation requires a large amount of relatively high-quality fill soil, which is used to obtain from mountains, rivers and seabeds. For this purpose, many land reclamation projects have been carried out together with other projects, such as dredging projects at rivers and coastal areas and/or the development of mountainous areas. Recently, it has become difficult to obtain such soil at reasonable cost because of restricted environmental protection, which requires the use of lower-quality soil as a reclamation material. Reclaimed land and sea walls are highly susceptible to ground instability, ground settlement and soil liquefaction, which can amplify the amount of damage to buildings and infrastructure there. Various ground improvement techniques have been developed to assure the stability of the sea wall and reduce and accelerate the ground settlement of reclaimed land. As environmental issues have become very critical in recent years, it is necessary to develop sustainable land reclamation techniques to promote the beneficial use of dredged soil and waste, minimize the environmental impact and create a rich natural environment. In this manuscript, the history of land reclamation in the Tokyo Bay area is briefly introduced, and current technologies regarding ground improvement and preservation of environmental conditions are presented to determine the future trends of sustainable land reclamation technologies.

Keywords: land reclamation / ground improvement / natural reproduction

Résumé – Prise en compte des contraintes environnementales dans les projets d’extension en mer. De nombreux projets de création de terrains gagnés sur les océans, les mers, les bords de rivières ou bien les lacs ont été réalisés depuis de nombreuses années de par le monde. Historiquement, ces projets d’extensions ont été tout d’abord menés avec l’objectif d’augmenter la superficie des terres agricoles, puis pour des raisons d’urbanisation et d’industrialisation. Le récent phénomène de mondialisation a conduit à une augmentation du commerce international et au développement de nombreux projets d’extension en mer. Ces projets nécessitent un grand volume de matériaux de remblaiement de relativement bonne qualité qui sont habituellement obtenus dans les montagnes, rivières ou fond marins. Pour cette raison, beaucoup de projet d’extension ont été menés concomitamment à des opérations de dragage de rivières ou de zones côtières et/ou de développement en montagne. Récemment, il est devenu difficile d’obtenir de tels matériaux à un coût raisonnable en raison des restrictions liées aux contraintes environnementales, qui impose d’utiliser des matériaux de qualité moindre pour les projets d’extension. Les terrains gagnés sur l’eau ainsi que les digues sont très sensibles à la stabilité des sols, aux tassements ainsi qu’au phénomène de liquéfaction, ce qui peut amplifier les dégâts aux bâtiments et infrastructures qui se trouvent là. Différentes techniques d’amélioration et de renforcement des sols ont été développées pour assurer la stabilité des digues, réduire et accélérer le tassement des terrains gagnés sur l’eau. Du fait des contraintes environnementales qui sont devenues un des problèmes les plus importants ces dernières années, il est nécessaire de développer des techniques respectueuses de l’environnement afin de promouvoir la valorisation de sol dragué ou de déchets, minimiser l’impact environnemental et créer un environnement naturel riche. Ce manuscrit présente tout d’abord les étapes historiques de la construction des extensions en mer réalisées dans la baie de Tokyo. Il décrit ensuite les techniques actuelles d’amélioration et de traitement de sol, puis celles environnementales liées à la création de nouveaux habitats naturels. Enfin, il discute des évolutions futures de techniques respectueuses de l’environnement pour les projets d’extension en mer.

Mots clés : projets d’extension en mer / amélioration du sol / reproduction naturelle

* Corresponding author: kitazume.m.aa@m.titech.ac.jp
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1 Introduction

Many land reclamation projects have been conducted worldwide for many years to create new land from oceans, seas, riverbeds or lakebeds for several purposes (e.g., Maeda, 1991; Nagao, 1991; Kitazume, 2007; Bo and Arulrajah, 2013; Wang et al., 2014; Watabe and Sassa, 2015). Historically, agriculture was the driver for land reclamation before urbanization and industrialization. Farmers reclaimed paddy fields by enclosing an area with a stonewall on the seashore near the river mouth or river delta. Urbanization enhanced the population inflow to the city areas, which caused a shortage of residential areas, which in turn promoted land reclamation projects for city facilities and residential houses. These were carried out with soil cut from hills and mountains and/or dredged soil from coasts, moats and canals. As the population grew in the city areas, waste and garbage disposal became a critical issue. Waste and garbage were often dumped at the roadside and on vacant land in an unsanitary manner, where flies, mosquitoes and mice bred and transmitted diseases that caused epidemics. It was necessary to develop reclaimed land for dumping waste and garbage. As industrialization intensified during the 19th and 20th centuries, it became important to develop reclaimed land for urban use, office buildings, industrial uses and transportation. Recent worldwide globalization has enhanced international trading and promoted many land reclamation projects in coastal areas for port and airport facilities, electric power plants, manufacturing plants, residential areas and so on (Kinoshita, 1996; Wang et al., 2014). Figure 1 shows two examples of international airports constructed on reclaimed land.

In a land reclamation project, a retaining wall is constructed along the periphery of reclaimed land, which is followed by filling in the enclosed area. It is essential to obtain a large amount of reclamation material. For this purpose, many land reclamation projects were carried out together with other projects, such as dredging at rivers and coastal areas or the development of mountainous areas. In the former case, coastal areas were dredged to ensure the depth of the water route, and dredged soil was used as reclamation material (e.g., van Beemen, 2010; Ikeda et al., 2015; Indraratna et al., 2015; Alzaylaie and Abdelaziz, 2015). In the latter case, hills and mountains were cut to develop residential areas, and cut soil was used as reclamation material (Glaser et al., 1991; Miyanaga and Takeyama, 1991). The combinations have been thought to be economical and desirable to serve a double purpose, that is, killing two birds with one stone.

Reclaimed land and sea walls are highly susceptible to ground instability, ground settlement and soil liquefaction, which can cause a large amount of damage to buildings and infrastructure located there (Wakamatsu, 1991; Cubrinovski et al., 2000; Furudoi, 2010). Various ground improvement techniques have been developed for these problems (Kitazume, 2007; Chu et al., 2009; Kirsch and Bell, 2013; Ikeda et al., 2015, Indraratna et al., 2015; Lam et al., 2015). The replacement method, one of the ground improvement techniques, is often used in land reclamation projects, in which the soft soil under the sea wall is excavated and filled with sandy material to improve the stability and decrease the ground settlement. In response to increasing environmental awareness, it became practically difficult to obtain a large amount of appropriate sandy soil for the method. In addition, due to emerging major concerns about the demand for rapid construction and the seawater pollution caused by dredging, non-dredged sea wall construction in association with ground improvement techniques has been preferred.

Most of the reclaimed lands constructed in coastal areas change the shape of the shoreline and the loose shoal and tideland, which affects the life of the creature inhabiting these areas. It is desirable to carry out natural reproduction and beach nourishment areas after land reclamation to minimize the adverse impact on the surrounding environment and create a rich natural environment (Choi, 2014).

As environmental issues have become very critical in recent years, it is necessary to develop sustainable land reclamation techniques to minimize the environmental impact and create rich natural environments (Tanaka, 2002; Matsuto and Tanaka, 2005; Inoue and Inane, 2005). In this manuscript, the history of land reclamation is briefly introduced by reviewing the land reclamation projects in the Tokyo Bay area, Japan, and the current technologies regarding ground improvement and preservation of environmental condition to discuss the future trend of sustainable land reclamation technologies.

2 History of land reclamations in the Tokyo Bay area, Japan

Tokyo Bay is a bay located in the southern Kanto region of Japan and spans the coasts of Tokyo, Kanagawa Prefecture and Chiba Prefecture. The Tokyo Bay region is both the most populous and largest industrialized area in Japan. Many land reclamations have been carried out along the coast of Tokyo Bay over many years. The current topography of the shoreline of Tokyo Bay differs greatly from that of the premodern period due to past and ongoing land reclamation projects. Tokyo Bay included approximately 249 km² of reclaimed land area in 2012 (Koarai and Nakano, 2013).

The Tokyo Bay area is divided into three port areas: Tokyo Port, Yokohama Port and Chiba Port. Land reclamation projects carried out over many years differ for each area because of the historical context and natural conditions. Table 1 and Figure 2 briefly show the land reclamation projects in the three areas. As shown in Table 1, land reclamation was initiated in the Tokyo Port area by the Edo government in the 1600s, followed by the Yokohama Port area as the country opened in 1858. Many land reclamations were performed then for the port facility. After World War II, many land reclamations were done very rapidly in the three areas, especially in the Chiba Port area, for industry, residential, and port and airport facilities. Table 1 also shows the fill material used for land reclamation. Mountainous soil was used in the 1600s to 1800s, and then waste and garbage from the city were used. With the development of port facilities in the Meiji and Taisho eras, dredged soil, mainly sandy soil, excavated from coastal areas was used as reclaimed material. After World War II, mountainous soil from the Boso Peninsula, Chiba Prefecture, was used to obtain a large amount of reclaimed

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Fig. 1. International airport constructed on reclaimed land.

Fig. 1. Aéroport international construit sur le terrain gagné sur mer.

Table 1. Chronological table of the land reclamation projects in the Tokyo Bay area.

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material (Endoh, 2004; Koarai and Nakano, 2013). As the city area grew, large disposal sites developed in coastal areas, such as the Yumenoshima, Kasai, Wakasu and Central Breakwater sites at Tokyo Bay and Minami Honmoku at Yokohama Port. In Chiba, on the other hand, waste and garbage are filled mostly in the mountainous areas except for the reclaimed land at Soga. The development of land reclamation in these areas is briefly introduced in the following sections.

2.1 The Tokyo Port area

Figure 3 shows the progress of land reclamation in the Tokyo Port area. In the middle period of the 15th century, wasteland spread to the west side of the current railway. When the Tokugawa Shogunate opened the government in Edo (current Tokyo) in 1603, it was a local village with a large wetland. The Tokugawa Shogunate cut the hill at Kanda to reclaim Hibiya Inlet for developing its capital city, which was followed by land reclamation in the Fukagawa and Konagi areas with dredged soil excavated in the development of waterways in the Edo area (Ozawa, 1971; Hamasuna et al., 1991). As Edo was a major consumer area, annual rice, specialty products and daily goods were transported from all over Japan to Edo and delivered to consumers using canals, where the reclaimed lands and dikes were constructed along the Sumida River, Nihonbashi River and Sanmabori River to handle local products.

The population in Edo was approximately 0.15 million in the 1600s but grew rapidly to more than 1 million in the 1800s. As Edo grew, waste and garbage disposal became critical issues. The Tokugawa Shogunate issued a decree in 1655 that fixed the Eitai area for the disposal site, after which the Eitai and Sunamura areas was used as a disposal site for 75 years to create reclaimed land of approximately 20 ha. After filling them, the Fukagawa-Echujima area was designated as a disposal site in 1730.

Just before the civil revolution, the Tokugawa Shogunate terminated the more than 200 years’ national seclusion and opened Yokohama Port to foreign countries in 1858. The new governments, the Meiji and Taisho governments, promoted dredging projects at the Sumida River for transportation and carried out land reclamation in the Kiyosumi, Kameido and Sunamachi areas using local dredged soil and garbage from the city areas for transportation and industry. However, as it was difficult to maintain the deep-sea depth due to the large amount of sediment flowing from the Sumida River, Tokyo Port was developed for domestic maritime transportation instead of international trading until 1941, when the Showa government opened Tokyo Port for international maritime transportation. After World War II, large land reclamation projects were conducted at Hinode, Aomi, Shinagawa and Oi mainly to...
construct container terminals for international transportation, where the sea floor was excavated at the Tokyo Port area and the mountains cut at the Boso Peninsula, Chiba Prefecture, to obtain fill material.

Waste and garbage disposal became one of the big problems as the Tokyo area grew. The government prepared a disposal site at Yumenoshima of approximately 43 ha. The location was originally conceived in the 1930s as a site for a new Tokyo Municipal Airport to replace Haneda Airport, but the airport plan was officially abandoned following the war, as the allied occupation authorities favored expanding Haneda rather than building a new airport. After filling up the site in 1967, much of the aggregate household waste production was turned into ash and disposed of at new disposal sites, the Kasai, Wakasu, Central Breakwater Landfill Site and Haneda areas. Tokyo/Haneda Airport was constructed on reclaimed land in 1931 and expanded several times to reclaimed lands that used construction waste soil and dredged soil.

As described above, land reclamation projects have been done in the Tokyo Port coastal area with garbage, dredged soil and mountainous soil for approximately 200 years, creating large areas of reclaimed lands of approximately 20 km² to expand port functions and to build container terminals, a cleaning plant, a water reclamation center, a steam driven generating plant, a Shinkansen maintenance base, housing developments, parks and markets and so on (Fig. 4) (Endoh, 2004). Recently, the Tokyo Metropolitan government designed a development plan for the Tokyo Port area, where 442 ha of reclaimed land will be converted into 7 subcenters to achieve a balance of business and residential space.

2.2 The Yokohama and Kawasaki Ports area

Figure 5 shows the progress of land reclamation in the Yokohama Port area. Several rice fields were developed at Yoshida by land reclamation in coastal areas in the Edo era (Nagao, 1991). After the Edo Shogunate opened Yokohama Port to foreign countries in 1858, Yokohama Port was developed for international trading, where raw silk, silkworm eggs and Japanese tea were exported and cotton fabrics were imported (Tanaka, 1991). The first Japanese railroad was constructed at the coastal line between Shimbashi and Yokohama in 1872, where 10 km of the total 29 km was constructed on the reclaimed dikes.

Inspired by the excellent technologies and port facilities in European countries and America, Mr. Soichiro Asano, one of the great businessmen and entrepreneurs, promoted many land reclamation projects in the Tsurumi area and Kawasaki area to support industrial growth from 1913 to 1927 (Toa Corporation, 1989). The coastal areas were excavated to obtain reclamation material and developed to attract factories and firms. Sand pump dredgers with cutter heads were used for rapid dredging (Fig. 6) (Nagao, 1991). Many industrial firms and infrastructures were constructed on reclaimed lands, which became one of the industrial belt areas in Japan.
A large earthquake, the Kanto earthquake, resulted in huge damage including more than 100,000 deaths and more than 370,000 damaged buildings in the Tokyo and Yokohama areas in 1923. A large amount of the debris from the earthquake was dumped at Yokohama Port to create Yamashita Park in 1930. Waste and garbage were disposed of at the inland disposal site from 1973 to 2011 and at the Minami Honmoku disposal site (approximately 16.4 ha) from 2007.

Almost all port and harbor facilities and industries were destroyed during World War II, after which the Yokohama Municipal government promoted many land reclamations at Yokohama Port to construct the Takashima, Honmoku, Daikoku wharfs and Ogi Island for trading and industry, which made Yokohama city the industry and the international harbor city (Fig. 7). Recently, the Yokohama Municipal government promoted the redevelopment projects of the coastal area “Minato Mirai (future of port)”, where many industrial firms in the city center were transferred and relocated to the surrounding reclaimed land areas to obtain residential area in the city center.

2.3 The Chiba Port area

Unlike the Tokyo Port and the Yokohama Port areas, the Chiba Port area was a quiet local village by the 1900s, as shown in Table 1, where fishermen caught fish, shellfish and harvested laver in tidal flat areas (Yonezawa, 2016). Two land reclamations were carried out before World War II: approximately 11 ha of land was constructed with dredged soil at Dezu for port facilities in 1910, and approximately 200 ha of land was constructed at Imai for industrial areas in 1940. After World War II, the local Chiba government promoted industrialization, in which many land reclamations were constructed at the Urayasu, Kemigawa, Inage, Makuhari and Chiba areas for industry together with residential areas to cope with the rapid population growth of the Tokyo metropolitan area after the late 1950s (Fig. 8a). A total of more than 12,000 ha of land area were reclaimed along the coastal area with dredged soil and mountainous soil obtained on the Boso Peninsula (Fig. 8b) (Sudo and Fujihashi, 2005). Recently, the Chiba local government promoted the reorganization of port facilities at Chiba Port to develop and improve the logistics function, where a reclaimed land of approximately 28 ha is constructed for container terminals and yards.

3 Geotechnical technology for land reclamation

3.1 Background for sustainable technology

Reclaimed land and sea walls constructed along the periphery of reclaimed land are highly susceptible to ground instability, ground settlement and soil liquefaction, which can cause a large amount of damage to buildings and infrastructure. The replacement method is one of the ground improvement techniques for the stability of sea walls. In this method the soft soil under the sea wall is excavated and filled with sandy material to improve the stability and decrease the ground settlement. However, it became practically difficult to obtain a large amount of appropriate sandy soil for this method, which is usually obtained by cutting mountains. In addition, the demand for rapid construction and the seawater pollution caused by dredging became major concerns. In response to increasing environmental awareness, non-dredged seawall construction in association with ground improvement techniques has been preferred. These circumstances have promoted the development of sustainable land reclamation methods. The replacement method has gradually been replaced by the
non-dredged techniques such as the vertical drain method, stone column method, sand compaction pile method and deep cement mixing method.

A large amount of dredged soil is produced annually to ensure the depth of the sea route and sea berth. In addition, a large quantity of industrial byproducts and construction waste and subsoil are discharged from factories, thermal power stations and construction sites. Some of these soils and wastes are used as reclamation material (Indraratna et al., 2015), but others are discarded in the disposal ground. As environmental issues have become one of the critical issues in recent years, these circumstances promote the reduction of the amount of mountainous soil cut and the beneficial use of dredged soft soil, waste materials and construction subsoils as reclamation materials to minimize the environmental impact. In the following section, several ground improvement techniques are briefly introduced to highlight their techniques and approaches for sustainable development.
3.2 Vertical drain method (with preload)

(1) Outline of technique

In the vertical drain method, artificial drainage layers are installed in clay layers to accelerate the consolidation phenomenon (Fig. 9). The material for the drainage layer is usually sand or plastic board, which are called the "sand drain method" and "prefabricated drain method", respectively. The sand drain has a circular cross-section of approximately 300 to 500 mm and is built up of granular material with high permeability. The fabric-packed sand drain method, in which sand piles are wrapped by geotextiles, has often been used for soft soil in land construction works (Ichikawa, 1978; Kitazume et al., 1993). In the Kansai International Airport construction project, approximately 120 million sand piles 400 mm in diameter were installed with a 2.5 m by 2.5 m square grid pattern into the Holocene clay layer to a depth of −45 m (Furudoi, 2010). Eight sand drain barges capable of driving 12 sand piles at a time were operated.

(2) Approach to sustainable development

In the sand drain method, a large amount of sand is necessary for the pile and sand mat materials, which may cause environmental impacts to the mountainous areas. To minimize the environmental impact by reducing the amount of soil, the prefabricated vertical drain method (PVD) is preferable (Fig. 10) (Chu et al., 2009; Lam et al., 2015; Indraratna et al., 2015; Ikeda et al., 2015). The prefabricated vertical drain is composed of a plastic core encased by a geotextile and has a channeled or studded plastic core wrapped with a geotextile. The plastic core functions as support for the filter fabric and provides longitudinal flow paths along the drain length. It also provides resistance to longitudinal stretching as well as buckling of the drain. The drain jacket acts as a filter to limit the passage of fine-grained soil into the core area. It also functions to prevent closure of the internal water flow paths under lateral soil pressure. There are many types of PVDs on the market, the width and thickness of which are generally 100 mm and 5 mm, respectively.
For both the sand drain method and the PVD method, a sand mat of 0.5 to 1.0 m in thickness is first placed over the expected preloading area. A large amount of clean sand with a high discharge capacity is required for the sand mat. A prefabricated horizontal drain was developed to reduce the amount of sand mat, the width and thickness of which were 200 or 300 mm and 8 mm, respectively (Fig. 11). Since the drain’s discharge capacity is significantly higher than that of sand, the required thickness of the sand mat can be reduced to ensure the design discharge capacity if it is installed on the sand mat. This enables a reduction in the environmental impact to mountainous areas (Yamasaki et al., 2001).

The plastic materials of PVD and the horizontal drain are remaining in the ground for a long period even after their function is no longer terminated. As they may cause an environmental impact and mechanical inconvenience in future construction projects at the site, it is desirable for them to disappear after the completion of their function. A new biodegradable nonwoven PVD drain was developed (Mochizuki, 1993), which is made of biodegradable plastic and capable of being decomposed by bacteria or other living organisms, as shown in Figure 12 (https://www.aomi.co.jp/tech/lactboard.html).

### 3.3 Sand compaction pile method

- (1) Outline of method

The sand compaction pile (SCP) method has been developed and frequently adopted for many construction projects in Japan, in which sand is fed into the ground through
a casing pipe and is compacted by vibration, dynamic impact or static excitation to construct a compacted sand pile in the ground. This method was originally developed for compacting loose sandy ground in 1957 but is also applied to clayey ground to reduce the ground settlement and to improve the ground stability (Fig. 13). When the shearing force acts on the composite ground, the shear resistance mobilized in the sand pile is frictional. Therefore, the material for the method should have a high internal friction angle, which means it should be easily compacted. In the case where drainage effect is expected for sand piles, the material should have high permeability.

This category includes other sand pile construction methods, such as “vibro-compaction” for sandy grounds and “vibro-replacement” and “vibro-displacement” for clay grounds, which have been widely applied in many countries. The procedure of constructing compacted sand piles in these methods is somewhat different from the SCP method: the sand piles in these methods are constructed by feeding sand in the cavity outer surface of the casing pipe. However, the shape and function of compacted sand piles in a ground are similar to those of the SCP method.

– (2) Approach to sustainable development

The sand compaction pile method has a double function of reinforcement for improving bearing capacity and drainage to accelerate the consolidation, requiring a well-blended granular material. The material appropriate for the method is granular soil with low fines content and high particle strength so that negligible crushing of soil particles takes place during pile installation. Similar to the sand drain method, a large amount of sand is required. It is desirable to reduce the amount of sand to minimize the environmental impact. Using granular materials from industry and construction has been beneficial for this method. Slag is a byproduct material in producing iron or nonferrous metals, which has a similar particle size distribution to sand and high permeability. Several kinds of slag were used as SCP materials, such as steel slag (Minami et al., 1997; Yasuda et al., 2004, Toki et al., 2004; Mizuno and Tsuchida, 2008). Coal ash solidification and granulation with cement have also been applied to the vertical drain method and sand compaction pile method (Hino et al., 2001; Murata et al., 2001; Uchida et al., 2001; Izumi et al., 2002). Oyster shell was also used for the sand compaction pile method where a mixture of shell and sand was used (Hashidate et al., 1993, 1994; Okumura and Kobayashi, 1995). These applications promote recycling and reduce the amount of sand material, which in turn minimizes the environmental impact on soil cutting sites.

3.4 Deep mixing method

– (1) Outline of method

The deep mixing method is a deep in situ admixture stabilization technique using lime-, cement- or lime-based and cement-based special binders. This method was originally developed in Japan and Sweden in the 1970s and has been widely applied to many kinds of infrastructures and purposes worldwide (Fig. 14). Compared to the other ground improvement techniques, the deep mixing method has advantages such as a large strength increase within a one-month period, little adverse impact on the environment and high applicability to any kind of soil if the binder type and amount are properly selected. The application covers on-land and marine constructions ranging from strengthening the foundation ground of buildings, embankment supports, earth retaining structures, retrofitting and renovation of urban infrastructures, liquefaction hazards mitigation, man-made island constructions and seepage control. In the field, a large machine with a mixing tool is used to supply the binder to the ground and mix it with the soil in situ.

– (2) Approach to sustainable development

A large amount of coal fly ash is produced from the electric power industry every year. The disposal of fly ash has become one of the headache issues in the industry. The fly ash gypsum cement-deep mixing method (FGC-DM method) was developed for the beneficial use of fly ash in which a mixture of cement and fly ash was used as a binder in the deep mixing method. The strength of soil stabilized by the method is generally less than that stabilized by cement alone, and a sheet pile can be installed in the stabilized soil column soon after the production of the column. The method was applied to several construction projects (Asano et al., 1996).

3.5 Ground improvements for reclaimed fill material

Large ground settlement and liquefaction risk in seismic areas often take place in reclaimed land, especially in the case where the reclaimed ground is constructed with dredged soil. As liquefaction causes a huge amount of infrastructure loss, liquefaction prevention is one of the critical issues in Japan. There are basically two approaches in ground improvement to prevent the liquefaction of reclaimed land: ground improvement after reclamation and before reclamation. Compaction methods such as the SCP method and the grouting method can be classified into the former category, and soil admixture techniques can be classified into the latter category. Many byproducts, wastes and dredged cohesive soils are beneficially used in these methods to reduce the amount of sand material for land reclamation.

3.5.1 Ground improvement after land reclamation

– (1) Sand compaction pile method

The sand compaction pile method is also applied to reclaimed land where loose sandy ground is compacted and densified by the installation of sand piles to reduce the ground settlement and prevent liquefaction (Okamura et al., 2003). The effect of the method is strongly dependent upon the ground condition, especially the fine-grained particle content of the ground. As described before, several types of slag and crushed concrete have been beneficially used in this method so that the amount of sand material could be reduced.

3.5.2 Ground improvement before land reclamation

– (1) Lightweight treated soil method

A large amount of dredged soil is produced annually to ensure the depth of the sea route and sea berth. These soft soils
used to be dumped at disposal sites constructed in coastal areas in Japan. However, it has become more difficult to construct disposal sites for dredged soil and subsoil because of environmental restrictions and economic reasons. These circumstances promote the use of dredged soft soils as a reclamation material, where they are mixed with binder to create high-strength soil material.

The lightweight treated soil method is one of the soil admixture stabilization techniques for the beneficial use of dredged soil and surplus soil from construction work. In the method, they are mixed with water, cement, air foam or expanded polystyrol beads and other cementing compounds to produce a very light foundation or back-filling material (Tsuchida and Egashira, 2004). The unit weight of the stabilized soil is 8 to 13 kN/m³ and can be effectively used to reduce the amount of consolidation settlement by properly controlling the density and strength of the material. Owing to its fluidity, the method can also be used as a self-compacting material.

The method has been applied to landfills or backfills behind newly constructed quay walls, reinforcement of existing structures, embanking of adjacent work, and submerged

Fig. 15. Application of the lightweight treated soil method at Tokyo/Haneda Airport.

Fig. 16. Group of barges for pneumatic flow mixing method.

Fig. 17. Application of pneumatic flow mixing method at Central Japan Airport.

Fig. 18. Application of Calcia material at Tokyo Port.
backfills and embanking on soft ground. The method was applied at Kobe Port, where a concrete-type quay wall was damaged by the Hyogoken-Nambu earthquake (Wako et al., 1998), and applied to the expansion project of the Tokyo Haneda International Airport (Fig. 15) (Watabe and Noguchi, 2011).

(2) Pneumatic flow mixing method

The pneumatic flow mixing method is a soil admixture stabilization technique in which dredged soil or surplus soil is mixed with a relatively small amount of cement in a pipeline. Figure 16 shows a group of barges, which consists of a pneumatic barge, a cement supplier barge and a placement barge. In Figure 17, the dredged soil in the soil transport barge is loaded into the hopper on the pneumatic barge at first and is transported to the reclamation site by compressed air. Cement is then injected into the soil on the cement supplier barge, and

<table>
<thead>
<tr>
<th>Port, site</th>
<th>Tidal flat (ha)</th>
<th>Beach nourishment (ha)</th>
<th>Total (ha)</th>
<th>Period</th>
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<tr>
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<tr>
<td>(11) Yokohama, Kanazawa</td>
<td>14.0</td>
<td>20.0</td>
<td>34.0</td>
<td>1988–1989</td>
</tr>
</tbody>
</table>

Fig. 19. Reproduction and beach nourishment projects.

Cement in the slurry or dry form is added to the soil, the slurry form being more common. The soil mixture is placed at the reclamation site through a cyclone on the placement barge. A tremie pipe is usually used to place the soil mixture under seawater and to avoid trapping seawater within the soil, which can cause a considerable decrease in the stabilized soil.

The method was applied to construct a large-scale man-made island for Central Japan International Airport at Nagoya in 2001 (Kitazume and Satoh, 2003, Kitazume and Satoh, 2005). After the construction of the airport, the method has been applied to many marine construction and land construction projects. In 2008, the method was applied to the expansion project of the Tokyo Haneda International Airport (Watabe and Noguchi, 2011).

(3) Beneficial use of Calcia reforming materials

Cement is widely used as a binder in soil admixture stabilization techniques. On the other hand, some industrial byproducts, such as coal ash and slag, have self-hardening characteristics and can be used as binders in soil admixture stabilization techniques. The FGC-DM method is one of the applications of fly ash, as introduced before.

The converter system steel slag calcia is produced by a process to refine pig iron manufactured from a blast furnace in a converter. Its major ingredients are lime (CaO), silicon dioxide (SiO₂), and iron oxide (Fe₂O₃), it has a similar shape to rubble and self-hardening characteristics, and it can be used as a binder by mixing dredged soil. Stabilized soil can be applied to land reclamation behind the caisson-type sea revetment and tideland and shallow fill (Fig. 18). Calcia was beneficial for use as a binder at Nagoya Port, where approximately 30% of Calcia in volume was mixed with dredged soil and transported to the reclaimed site by the pneumatic flow mixing method. The unconfined compressive strength of stabilized soil was on the order of 200 kPa, which is large enough for liquefaction prevention (Honda et al., 2015).

4 Natural reproduction and beach nourishment

Most of the reclaimed lands constructed in coastal areas change the shape of the shoreline and loose shoal and tideland, which affects the life of the creatures inhabiting these areas. It is necessary to harness the area’s natural ability to recover from environmental damage by land reclamation (Ohshima and Akimoto, 2003). Recovery is accomplished through three mechanisms: seawater exchange, sedimentation, and biological production. Many reproduction and beach nourishment projects have been conducted in the Tokyo Bay area, as shown in Table 2 and Figure 19 (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, 2006). Many tidelands were constructed by spreading sand near the reclaimed land area. In beach nourishment, sediment lost through long shore drift or erosion is replaced from other sources. Jonanjima Seaside Park is a seaside park located close to Haneda Airport, where airplanes landing in and taking off from the airport can be observed (Fig. 20).

Here, an application in the Tokyo/Haneda Airport area is briefly introduced. Airport was constructed in the 1930s and expanded on reclaimed land several times. To regenerate the shallow area lost due to airport expansion, reclaimed tideland and shallow place construction was carried out by the Tokyo Metropolitan government from 1988 to 2000. The shallow field was built with an area of 250 ha and a total length of approximately 7 km, as shown in Figure 21 (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, 2006). In the project, dredged sand excavated in Tokyo Bay was placed at a deep depth to the coastline to create shallow land to A.P. +1.5 m. This is followed by filling with mountainous soil for beach nourishment works. A sea embankment was also constructed 50 m from the revetment to secure the tidal flat. The subliminal embankments were constructed 170 m from the revetment to prevent flow out of sand and for fish.
5 Concluding remarks

As introduced above, many land reclamation projects were promoted to create new land areas for residential use, industrial use, port and airport facilities, etc. and for disposal sites of garbage, industrial wastes and construction subsoils. It is thought that the construction of reclaimed land is continuous. On the other hand, to meet growing environmental awareness, construction technologies for sustainable reclaimed land are needed to minimize adverse influences on the environment. These circumstances promote the reduction of the amount of mountainous soil cut and the beneficial use of dredged soft soil, waste materials and construction subsoils as reclamation materials to minimize the environmental impact.

The Sustainable Development Goals (SDGs) are a collection of 17 interlinked global goals designed to be a “blueprint to achieve a better and more sustainable future for all”. The SDGs were set up in 2015 by the United Nations General Assembly and are intended to be achieved by 2030. Among the 17 SDGs, land reclamation will be mostly related to (9) industry, innovation and infrastructure, (11) sustainable cities and communities, (14) life below water and (15) life on land. The sustainable land reclamation techniques regarding these SDGs can be summarized as follows:

– (9) Industry, innovation and infrastructure

Beneficial use of industry byproducts and construction waste, such as slags, fly ash, calcia, dredged soil, subsoil, etc.

– (11) Sustainable cities and communities

Ground improvement methods to improve ground stability, reduce ground settlement and prevent liquefaction, such as the sand compaction pile method, grouting method and deep mixing method.

– (14) Life below water

Non-dredged ground improvement methods, such as the sand compaction pile method, grouting method and deep mixing method, and reproduction and beach nourishment methods.

– (15) Life on land

Management and beneficial use of disposal sites and minimization of environmental impact on the soil cutting area.

In this manuscript, some techniques regarding land reclamation are introduced briefly. It is necessary to develop these sustainable landfill-related technologies and to promote sustainable landfill work in the future.

References


