New ground improvement technologies under restricted conditions in Japan

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ABSTRACT

It is commonly understood in Japan that “drainage”, “compaction” and “solidification” are principles for ground improvement. Many ground improvement techniques have been developed to meet the demands of the times i.e. “economic efficiency”, “reliability (improvement effect)” and “environmental-friendliness”. However, some drawbacks of the methods have been eliminated, like the implementation system developed recently under the restricted condition to improve the limited space around the existing structures. This paper describes the relationship between the conventional and the innovative ground improvement methods followed by their aims of development in Japan. Furthermore, technical aspect of each innovative ground improvement method is outlined, such as “sand-injection type sand compaction pile method” and “twin-flow cement slurry jet mixing method”. Finally, the effectiveness of ground improvement technologies evaluated on their application examples near existing structure for the purpose of seismic reinforcement against natural hazard is reported.

Keywords: ground improvement, compaction method, solidification method, restricted condition

1 INTRODUCTION

Due to the mountainous configuration in Japan, urban functions have centered on the low-lands of alluvial ground or reclaimed lands along coastal areas. Besides, such lands are relatively young, and in many cases, they are generally soft ground. Also, Japan as a country of frequent large scale earthquakes has suffered damages resulting from liquefaction by the earthquakes. Accordingly, at the time of construction of civil engineering structures, ground improvement technologies to turn such soft ground into the stable and firm one in a short period were essential, and it can be said that the development of technology to improve soft ground has been made to correspond to such a matter of problem-solving.

This paper explains about “operation of ground improvement under restricted conditions” as a recent technical subject as well as transition of the technical issues. Therupon, the summary and application examples of the new methods which were derived from the compaction method and the solidification method are introduced including the application of these two technologies for the purpose of seismic reinforcement against natural hazard.

2 TRANSITION OF GEOTECHNICAL SUBJECTS AND PRESENT SITUATION OF GROUND IMPROVEMENT

2.1 Transition of geotechnical engineering issues

Figure 1 shows the transition of geotechnical engineering issues after 1950s in Japan. With respect to the trends in Japanese ground improvement technology, solution to the ground stability issue occupied a main part of technological issues in 1950s, and subsequently the gravity of importance has shifted from stability issue to deformation issue, from deformation issue to earthquake resistance issue, and then to environmental issue. For the evaluation of ground improvement methods, three key-words “economy”, “reliability” and “environmental sensitivity” become important. Regarding achievement of “economy”, such means were taken as shortening a construction period by large scale construction and/or high efficient construction at the earlier stage on development of the methods. At the same time, the improvement in reliability has been attempted by enhancing the improvement effect and its quality. On the other hand, Environmental correspondence became essential combined with recent uplift of the consciousness for the environmental issue. Environmental correspondence herewith includes the environmental friendliness to minimize vibration, noise and deformation being caused by the improvement
works in urbanized area and the environmental conservation aiming reduction of environmental by such effective practical use of surplus soil at the construction fields. In addition to the above three key-words, demand to convert existing structures into earthquake resistant structures has been increased. Correspondingly, the mechanical improvement such as downsizing of a large-sized machine and/or pumped injection of sand-material, which formerly deemed unable, has been achieved.

| Engineering issues | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s |
|--------------------|-------|-------|-------|-------|-------|-------|
| Stability          |       |       |       |       |       |       |
| Deformation        |       |       |       |       |       |       |
| Settlemens         |       |       |       |       |       |       |
| Earthquake-resistance|     |       |       |       |       |       |
| Liquefaction       | | | | | | |

Fig. 1. Transition of the geotechnical engineering issues (Tsuboi et al., 2006)

2.2 The current state of ground improvement

The principle of ground improvement can be roughly classified into “replacement”, “drainage”, “compaction”, “solidification” and “water cut-off” and various methods were developed based on the principle. Technologies which are needed for the ground improvement differ depending on the ground properties, type of structures, scale, surroundings and so on. The main methods shown in figure 2 are the compaction method and the solidification method that can satisfy all kinds of purposes for ground improvement. The present situation of each method is outlined below.

(1) The compaction method

The sand compaction pile (SCP) method is to increase the bearing capacity and the liquefaction resistance by increasing in density of loose sandy ground, and to increase bearing capacity and shear strength by turning the original ground into composite ground composed of clay and sand piles. In Japan, there are the SCP method as a method applicable to both sandy and clayey ground, and there are rod compaction method, vibro-floating method and dynamic consolidation method applicable only to sandy ground.

The SCP method is the one which has been applied most widely and frequently since developed at 1956 owing to its diversified effectiveness of improvement. Accordingly, the execution technique and designing method were developed by assiduous efforts for many years, and now they became highly accurate ones. The accuracy of the execution was confirmed by check boring and/or excavating the ground and the reliability of the designing method was verified by collation with accomplishments and/or by full scale model tests, etc.

(2) The solidification method

One of the typical solidification method is the deep mixing (DM) method, which is capable of being roughly classified into two groups i.e. “mechanical type” group and “jet type” group. Both types have the principle to solidify the soft ground by the use of material like cement.

The mechanical type deep mixing (MDM) method was developed at 1974 in Japan. (At about the same time, this method was developed in Northern Europe, too.) Further, the MDM method evolved and was put to practical application as the deep lime mixing method by the use of lime based stabilizing agent. The MDM method has several strong points i.e. ① high possibility for rapid construction, ② minor deformation, ③ low vibration, and ④ easy availability of stabilizing agent, etc.

The jet type deep mixing method (hereinafter, referred to as the jet grouting method) is the method to inject binder slurry into the ground by the use of jet flow and to form rigidly solidified soil body with cement base agent as solidification material. This method was implemented in 1965, and the method has the jet types system consisted of grout jetting type (single nozzle), air grout jetting type (double nozzles), water air grout jetting type (triple nozzles). The strongest advantage of this method is that an execution machine can be as small as a size of a boring machine.

3 OUTLINE AND APPLICATION OF COMPACTION METHOD APPLIED TO EXISTING STRUCTURES

3.1 Developmental history of the method

Effectiveness of the SCP method as liquefaction countermeasure was firstly confirmed in Japan at the 1978 Miyagi-ken Oki Earthquake, and ever since it has the accumulative examples of confirmed effectiveness. In 1995, the non-vibratory SCP (trade-name; SAVE Compozer) equipped with the forced lifting/driving device was developed for the purpose of removal of vibration and noise generated by a vibration-hammer. In recent years, countermeasure against liquefaction for narrow place and/or right under the existing structures such as the existing river dyke and airport runway became required. However, because the largeness of
construction machines as shown in the figure 3 which are used on the vibratory-SCP or the non-vibratory SCP, hinders the methods from being applied to the ground under such limited conditions. Accordingly, the sand injection type SCP (trade-name; SAVE-SP method, hereafter called SAVE-SP method) that is able to inject sand using a small machine was developed and put into practical application.

![Scale of execution machines](image)

**3.2 Outline of the method**

(1) **Outline**

The SAVE-SP method is the method that compacts the surrounding ground statically by press injecting the fluidized sand into the ground through a rod being equipped to a small sized execution machine. Because of its smallness, the method can be applied to the narrow ground, and at the same time it can be said that the method achieves the same level of improvement effect with the one the conventional SCP methods originally have, and that the method is easily assimilated to the original ground and ecological owing to the fact that its major infilling material is sand.

(2) **Fluidized sand**

The fluidized sand is the one in the fluidized state that makes it easy to transfer by pumping. This material is made by mixing sand with special fluidizing reagent that was carefully chosen to be friendly to the sand and environment. The fluidized sand increases the viscosity of pore water due to its water-retention effect and restrains separation of water and sand, and made it possible to be transferred by pumping. Figure 4 shows actual fluidized sand being manufactured at a plant. On the basis of the principle that this method depends on the operation to inject sand into ground and to compact surrounding ground, the fluidized sand is required to have antipodal properties of the fluidity by keeping water-retainability to avoid pipe clogging and the modestly drainable characteristics to dissipate in order to obtain instantaneous high density of sand when pumped into the ground. Also, slow-acting retarding plasticizer is added to the fluidized sand to vanish the effect of fluidizing reagent after released into the ground.

![Fig. 4. Schematic view of fluidized sand](image)

(3) **Components for execution machine and process for implementation**

The execution machine for this method is, as shown in figure 5, consists of a small-sized execution machine to drive a rod, a conveying pump, a plant producing the fluidized sand, and a backhoe to put the material in the hopper. The small-sized execution machine covers an area about 3m x 6m and the rod has a diameter of about 100mm. The plant produces the fluidized sand with batch system, on which water, fluidizing reagent and retarding plasticizer are added to sand, and they are mixed together. The pump is piston/cylinder type that activates suction/discharge motion continuously, and its flow rate is adjustable by the change of piston speed. The distance between the machine and the pump can be as far as about 100m.

Figure 6 shows the flow chart for the implement process. The steps from ① to ④ below can perform the same quality of compaction as the conventional SCPs.

① Drive the rod to specified depth.
② Discharge and press the equal volume of liquidized sand to φ700 mm at the bottom end of the rod.
③ Lift up the rod to specified height of about 20cm.
④ Repeat ②~③ steps up to specified depth.

Figure 7 shows outline of the mechanism for compaction. The liquidized sand discharged from the rod into the ground is drained with pressure and enlarged as well as compacted. And surrounding ground is also compacted at the same time. Although some fluidizing reagent remains in voids therein, retarding plasticizer gradually effects to agglutinate it and the liquidized sand returns to normal sand.

(4) **Characteristics**

The followings are summary of characteristics of the SAVE-SP method.

1) Because of its small-sized execution machine, operation at narrow ground and/or on a pier is possible. Also, it can cope with emergency evacuation at the airport and others.

2) The operation with raking installing and/or penetration into hard obstacle layer can be corresponded by this method. Besides, the fast recovery after the treatment is easy, as the operation can be carried out through a small bore of about φ
150mm for existing pavement, revetments, and buried structures, etc.
3) As a vibration hammer is not applied, the method can compact the ground statically. High efficiency of operation can be achieved owing to its mechanism to repeat continuous movement of drilling and injection.
4) It is remarkably economic compared with conventional liquefaction countermeasures at narrow ground or right under the existing structures.
5) It is ecological and easily assimilates to the ground due to the application of the ultra mini equipment and natural material like sand.

(1) Outline of the construction plan and the improvement specifications
In regard to the site, 2–4 meters thick alluvial clayey layer is accumulated between the upper and the lower alluvial sand layer with SPT N-values from 3 to 20. The work was carried out on the temporarily filled land upon the inside slope of the river dyke. The width of temporary fill was 4–10 m and the method had arrangement of piles of 3–8 rows. Although length of drilling from the dyke crest was 9–21 m, the improvement length was 2–14 m. The spacing of columns was 1.2–1.9 m with square arrangement. This method applied 2 driving machines per a plant, and the plants pumped the fluidized sand to the driving machines for a distance of about 100 m at most. Photo1 shows the execution scene at the site.

(2) Confirmed result of the improvement effectiveness
Figure 9 shows the pre/post distribution chart of SPT N-values at the site. According to the figure, it was confirmed that SPT N-values of the site increased by the improvement work. Besides, at this site, a wide working area enough to arrange the large-sized non-vibratory SCP machines was applicable to the inner side of the river dyke, namely the dry riverbed, the comparison after the works between the SAVE-SP and the non-vibratory SCP method became possible, and it indicated almost the same increase in N-value. Herewith, the improvement effectiveness of the SAVE-SP was confirmed to be almost equal to that of the SCP’s.

3.3 Application example to the existing structures
The example of this method that is applicable to the existing structures is described herewith (Kubo et al., 2013). Figure 8 shows the construction cross section and the boring log of the site. The construction site for the river dyke’s seismic strengthening is located on the area close to private houses.
4 OUTLINE AND APPLICATION OF THE SOLIDIFICATION METHODS COPING WITH EXISTING STRUCTURES

4.1 Developmental history of the methods

Several compound types of mixing system by combining the mechanical mixing system and the jet mixing system have been developed for the purpose of forming the larger diameter of a column among the DM methods. The method called twin-flow cement slurry jet mixing method (Trade name; FTJ, hereinafter called F-twin jet method) is one of them. This method has two streams of highly pressured jet flow (cf. Fig. 10), which can form an improvement column with larger diameter and can carry out more faster and economically than the conventional jet grouting method. Regarding the execution machines, several types are available such as S-type machine using a boring machine, N-type machine that is self-propelled with high mobility and L-type machine that is conventional large-sized machine. Options on the machines are available according to the construction conditions.

In recent years, in accordance with the demand to make the existing structures earthquake resisting, the jet grouting method has become widely used, and the instances for the method to be applied right under the structures are being turned up. However, the conventional jet grouting method has difficulty in making an improvement column vertically through the structures. Thereupon, the swing type multi-flow cement slurry jet mixing method (Trade name; FTJ-FAN, hereinafter called FTJ-FAN method) was developed to carry out the improvement work without making a vertical hole through the structures by evolving the F-twin jet method.

4.2 Outline of the method

(1) Outline and execution method

The FTJ-FAN method, as shown in figure 11, can form the optionally angled fan-shaped or rectangular improved soil body by jetting the high pressured massive solidification slurry agent through multiple swinging nozzles which were mounted almost horizontally on the front surface of the mixing wings. It became possible herewith to improve under the existing structures without any loss. Normal jetting distance \( R \) of this method is \( R=3.5 \) m at sandy ground, and \( R=3.0 \) m at clayey ground. And it recorded an extremely long jetting distance of \( R=4.0 \) m, too. The fan shape can be formed within the optional range of swinging angle 0-180° and the standard specification provides the strength after improvement to be \( q_u \) (unconfined compressive strength)=3,000 kN/m² at sandy ground and \( q_u=1,000 \) kN/m² at clayey ground.

(2) Characteristics

The FTJ-FAN method has the following characteristics;

① The method can make the improvement body in the form having fan shaped section or rectangular section due to its swinging jet system.

② The method can reduce the number of improvement columns compared with the conventional jet grouting method with double steel pipe mechanism and can arrange the execution machines effectively in case of the improvement work for right under the structures.

③ The method has little influence on the neighboring ground and/or structures owing to the execution system using air simultaneously with double pipe mechanism.
4.3 Application examples to the existing structures

The application example of the FTJ-FAN method is explained herein as the method which is able to cope with the existing structures. The work (Akima et al., 2014) is for improvement of directly underneath of the river structure. Purpose of the work is seismic reinforcement for the existing structures.

(1) Outline of the work and improvement specification

The improvement work was carried out to meet the specifications that the swing angle=117° and 180°, the jetting distance of R=4.0 m. The work had the improvement length of 4.7 m as shown in figure 12, wherein the boring logs of both works are shown additionally. The work was for the treatment of the sandy layer having SPT N-value of about 25.

(2) Confirmed result of quality of improved soil body

The strength of the ground was confirmed by sampling the core at the improved grounds by the two works. The process for the confirmation was carried out in the way that nine test pieces in total were made from three improved soil cores each of which were divided into three pieces i.e. top, middle and bottom ones. And the unconfined compression test was held on those nine test pieces, and unconfined compression strength was provided. Figure 13 shows the test result, indicating that all of the improved soil bodies meet the design strength, although there exists some variation in their strength, thus satisfactory improvement of the soil was ascertained.

5 CONCLUSIONS

In this paper, current situation of the ground improvement technologies and transition of subjects for soil engineering and present state of several methods for the soil improvement in Japan were described. And the recent needs to provide proper measures for the existing structures having the limited conditions peculiar to Japan was presented. Specifically, the outline and application examples of the sand injection type SCP method and the swing type multi-flow cement slurry jet mixing method, which are the latest derivation technology from the compaction method being a main type and the solidification method so as to cope with the existing structures, were introduced.

Henceforth, the number of project to enforce the ground under existing structures is expected to go on increasing all the more, and such ground improvement technologies as mentioned above will become more needed to overcome the confined working area.

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