The 5th International Symposium on Robotics in Construction June 6-8, 1988 Tokyo, Japan

New Automated Operation and Feedback Control in Soil Improvement Method

Takahiro KAWAKAMI, Director, Machinery Center

Michio KATSUHARA, Manager, Development Division

Tomohiro ISODA, Chief Engineer, Geotechnical Division
Fudo Construction Co., Ltd.

1-2-1, Taito, Taito-ku,
Tokyo 110, Japan

ABSTRACT:

Soil improvement methods are an important mechanized field within the construction industry in Japan. As a representative soil improvement method, the Sand Compaction Pile Method has a 30-year history and has undergone many improvements in terms of both implementation and control.

In this paper, the latest improvements in the Sand Compaction Pile Method are described. These include automated operation and a revolutionary real-time feedback control system that contribute to greater precision and energy efficiency. The remarkable results of actual onsite applications are discussed.

1. Improvement Methods of Soft Ground in Japan

Because of Japan's mountainous terrain and scarce usable land, habital areas and locations for industry have been limited to coastal regions and areas between mountains and hills. The ground in these areas often lacks sufficient bearing capacity to support buildings, roads, harbor facilities and so on. In many cases, the ground is very soft. Soil improvement technique aims to improve the properties of soft ground and make it more suitable for use. It is a field of construction engineering, which has experienced a unique development in both quality and range in Japan. There has been a considerable mechanization of execution systems.

Various methods of soil improvement have been developed and carried out in correspondence to the properties of soft ground, workability, suitability for the site and greater economy. However, from the standpoint of basic principles of improvement, we can make a rough division into the following three categories.

a) Replacement: Digging up and removing soft soil and replacing it with soil which has a high bearing capacity, such as sand.

b) High densification: Promoting compression by removing the pore water in soft clayey soil or compacting loose sandy subsoil to increase the density of the soft ground, improving its geotechnical properties.

c) Solidification: Adding with or without pressurized insertion or mixing of some form of solidifier (such as cement) to the soft ground to chemically solidify soil particles.

Historically speaking, replacement and high densification were discovered and developed in that order. Engineers are now devoting themselves to making the solidification method available for actual use.

The Sand Compaction Pile Method draws on replacement and high densification as improvement principles. Since its development in 1956, it has been used for soft ground composed of both clayey and sandy soil. It uses vibration to form compacted sand columns in the ground. Both the application and the design standard were developed as techniques native to Japan. It is one of the most well-established methods yet developed.

2. Sand Compaction Pile Method

2.1 Outline of the Method

The Sand Compaction Pile Method (SCP) makes use of a hollow casing pipe outfitted with a vibrator on the head to supply sand or sandstone into soft ground and thus form compacted sand columns with relatively wide diameters. This improves soft ground in three ways. First, when used in soft clayey soil, the sand columns act as vents for pore water in the soil, compressing and strengthening the clay stratum. At the same time, the compacted sand columns produce a shearing resistance. The mutual effect of the soil and sand columns helps to increase the bearing capacity of the improved ground. Second, when used in loose sandy subsoils, compaction is done with vibration and forceful insertion of sand materials to increase the strength of the ground. This is most effective in preventing the liquefaction of the loose sandy ground when an earthquake occurs. Third, when used on an ocean-bottom clayey subsoils, installing the compacted sand columns with their wide diameters in close proximity to each other makes it possible to forcefully replace the sea-bottom clay stratum with good, usable material. Fig. 1 shows the typical examples of application.

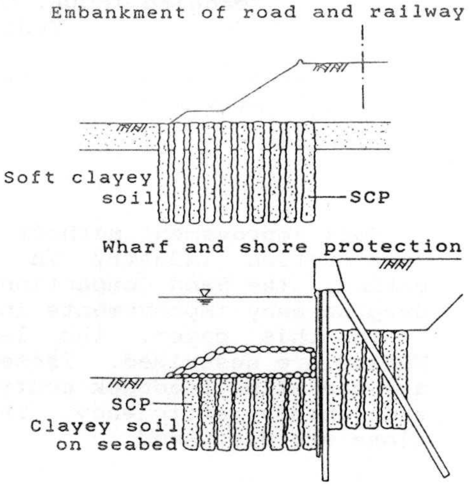

Fig.1 Typical Applications of SCP Method

2.2 Changes Over the Years in the Development of Execution Equipment

The SCP method had its start with the implementation of the hammering-type compozer method in Osaka in 1956. Ever since, further development of the SPC Method has been a consolidated development of the two areas of hardware (mainly the execution equipment) and software (mainly design theory and application technique). Fig. 2 shows the changes that have occurred over the years in hardware divided into two areas: development of execution equipment and development of execution control instruments.

The initial hammering-type SCP had many problems, including execution efficiency and durability. This limited application value. Attention therefore began to focus on a compaction mechanism using vibration, an area which at the time had seen little or no research in Japan. Research results were the basis for the development of the Vibro Compozer Method. This area continues to show the most improvements in the SCP method. The same period saw the development of the Mammoth Compozer Method, which made use of an execution ship for forced replacement. This meant the overall method was now suited for use on both land and sea.

The vibrator is an important section of the penetration device. Since the development of such early models as the VPD-50 and 100 and up to such recent models as the V-75, 120 and 300, there has been a constant attempt to improve penetration capacity, the ability to execute at greater depths and overall durability. In addition, the support device for the penetration body has undergone major changes, going from the initial wooden scaffolding to a two-shaft steel supporter (maximum depth: 13 m), truss steel leader (maximum depth: 35 m) and truss leader for maritime executions (maximum depth: 65 m).

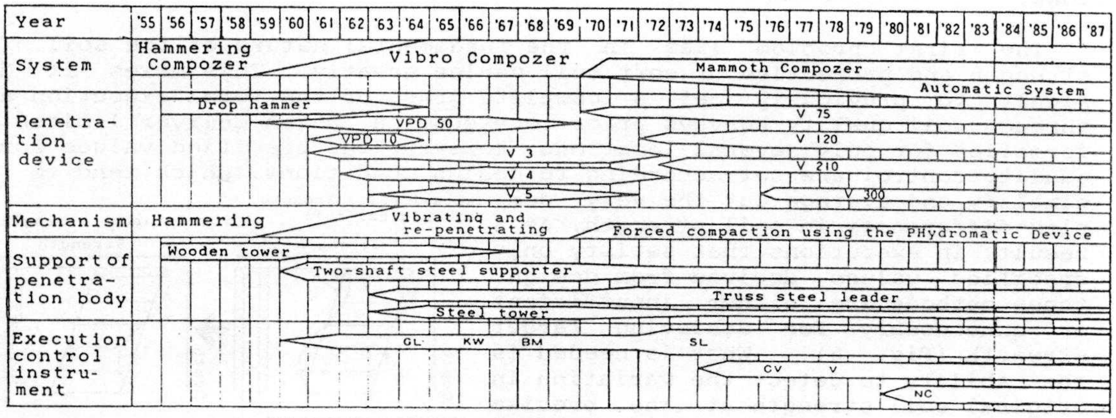

Fig.2 Development of SCP Method

2.3 Changes in Quality Control Instruments

Quality control in soft soil improvement is a matter of major importance because executions take place in subsoils that cannot be seen. Changes in quality control technique for sand columns and improving execution accuracy are shown in the development of execution control instruments. Execution control for sand columns includes the installation position of the sand columns, the space between them and their length. The following are of the greatest importance: i) Determining whether the required sand volume (or diameter of sand columns) is maintained for each depth; ii) Determining whether the strength of the sand columns fulfills the requirements.

First, the GL (depth) detector shown in Fig. 3 was developed to record the depth locus of the end of the casing pipe. Next, to show sand volume in earlier stages of development, the number of times sand thrown in the pipe with the bucket (BM) was recorded. Then, the sand level (SL) detector shown in Fig. 4 was developed to get an accurate grasp of the amount of sand released at each depth. The SL can continuously detect the sand level in the casing pipe. Since 1970 this has been used together with the GL gauge to control quality.

In order to ascertain the strength as explained in item (ii) above, it is necessary to check the strength of sand columns already installed or the soil between them. This is done by conduct-

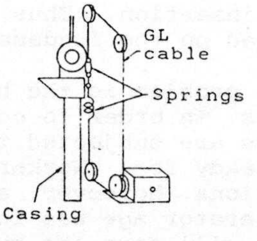

Fig.3 GL Detector

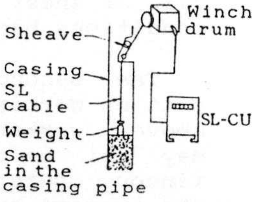

Fig.4 SL detector

ing a check boring survey at the end of execution.

3. Advancing Toward Automation

3.1 The Need for Effective Quality Control

Despite the implementation of the quality-control measures mentioned above, there were still a number of problems. Chief among them are as follows.

The first problem lies in the fundamental nature of the soil. The strength and properties of soft soil varies greatly. This makes it difficult to previously get a complete grasp of the total execution area through soil quality surveys prior to execution, which deliver limited information for only several locations. However, the specified values for quality control are set according to design conditions, which tend to simplify and average out the very complex differences in soil strength. As a result, in executions that satisfy only specified values derived from design, these methods are either insufficient or unnecessary for achieving target strength (Fig. 5). What is needed is the ability to detect the variation in original soil strength at the precise execution point and to make immediate adjustments in operation to meet different conditions.

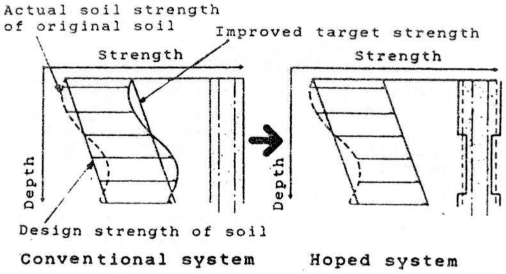

Fig.5 Concept of High Quality

The second problem is this: using a boring test to confirm strength means the confirmation can come only after improvement executions. But from the standpoint of execution control, it would be better to check strength constantly during execution. This need is particularly urgent when using forceful replacement in ocean-bottom clayey soil, where the strength of sand columns to be forcefully replaced is of great significance.

3.2 Striving for Better Economy

A number of factors have a direct or indirect bearing on efficiency and economy, and may affect quality as well.

The design process simplifies the complex characteristics of soft soil. This has resulted in a tendency to produce overdesigns, and execution based on them often result in partial excessive strengthening in parts of the improved soil. In these cases, the specifications are not just uneconomical. They also negatively affect such subsequent work as concrete pile or sheet insertion. Thus, it is desirable to scale down executive conditions based on the fundamental execution controls already described.

The second problem is the heavy work load that a lack of mechanization puts on workers. In order to conduct the executions and controls discussed above, workers are subjected to a work load that even experienced hands may not be ready for. Workers are often subjected to long hours of continuous operations. Moreover, as fewer young operators join the workforce, the average operator age has increased recently. Mechanization and energy-saving devices will ease the burden.

A third problem lies in summarizing records on operation results. Record-keeping requires a great deal of time and effort for a purpose other than the actual job. It is hoped that greater use of electronics will streamline record-keeping.

4. Automatic Execution System

4.1 System Flow

With these needs in mind, a new execution system was developed for the SCP method that makes use of automatic and feedback controls. This was one of the most dramatic advances in the thirty-year history of the method's development and drew greatly on recent advances in microelectronics.

The operational flow for the new system is shown in Fig. 6 together with overall views of the execution machine used on land and sea, shown in Photos 1 and 2, respectively.

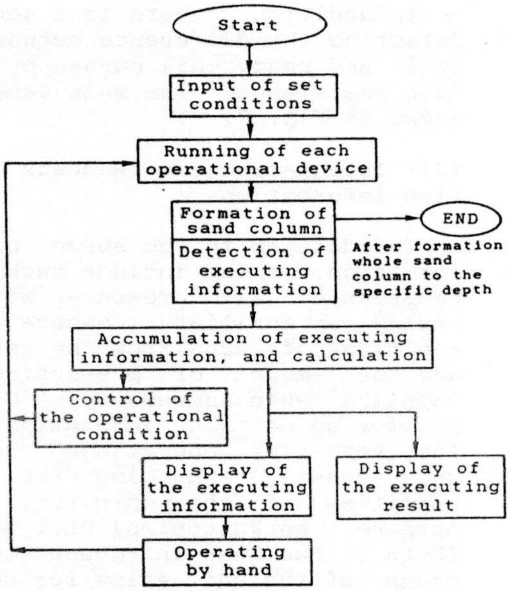

Fig.6 Flow for Execution System

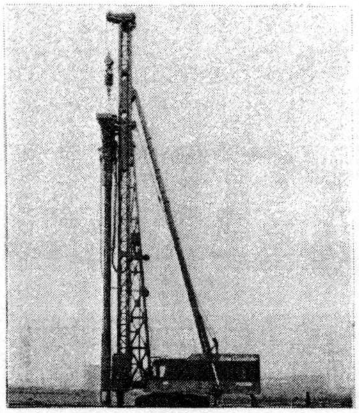

Photo.1 Execution Machine (onland)

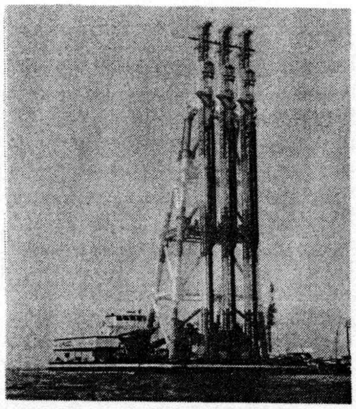

Photo.2 Execution Ship (Offshore)

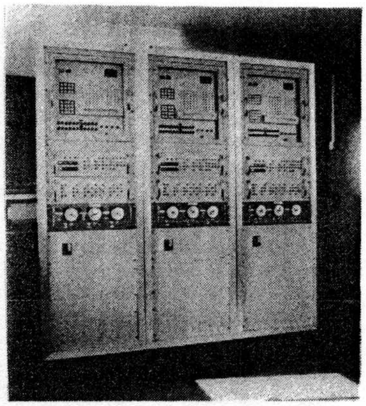

Photo.3 NC Control Unit

4.2 Characteristic Equipment and Functions

(1) Sensors

The depth of the casing end and changes in sand level within the casing are important operational factors. Other important sensor function includes detection of original soil strength or sand-column strength, which is done with a PHydromatic device attached to the casing end. The PHydromatic device contains a hollow cylinder that moves up and down, driven by hydraulic cylinders. When the cylinders move down, the sand packed in the end is forced out of the casing. At the same time, the sand column already ejected is broadened and compacted. The pushing power of the cylinders at this time is detected with an oil-pressure sensor. When there is a wide space between columns (low replacement ratio) this strength factor is made to correspond with the strength of the soil. Conversely, when the space is close (high replacement ratio), it is made to correspond to the strength of the column itself.

In addition, there is a sensor for detecting the difference between clayey soil and sandy soil caused by penetration resistance. The main sensors are shown in Fig. 7.

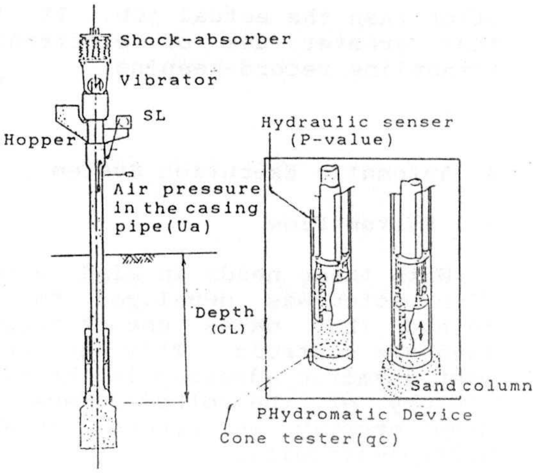

Fig.7 Main component and sensers

(2) Integration and feedback of execution information

In addition to the above basic information, we can include such items as compressed air pressure within the casing (an auxiliary measure for the ejection of sand from the casing end) and the amount of pressurized water (applied when necessary). Continuous monitoring of this information allows for real-time operational responses, thus greatly enhancing the control abilities of the operator. For this purpose, an NC control unit equipped with a microcomputer, as shown in Photo 3, has been introduced to the system. The concentrated control functions of the unit allow for continuous collation of the operational data, computation and conversion into a useful index, and determination of the appropriate response commands to be sent to the individual actuators of the control apparatus during execution.

As Fig. 8 shows, this unit also includes the "expert system for sand column formation" in the deduction logic section. This knowledge base includes design and execution theories required by the civil engineer and the know-how required by the operator.The software for computation and deduction is divided into 86 blocks connected by the main flow so a single process can be carried out in about 100 m. This means that computation and processing are carried out every 4 cm to 7 cm in depth of sand column forming, resulting in extremely detailed feedback and very accurate operational processing.

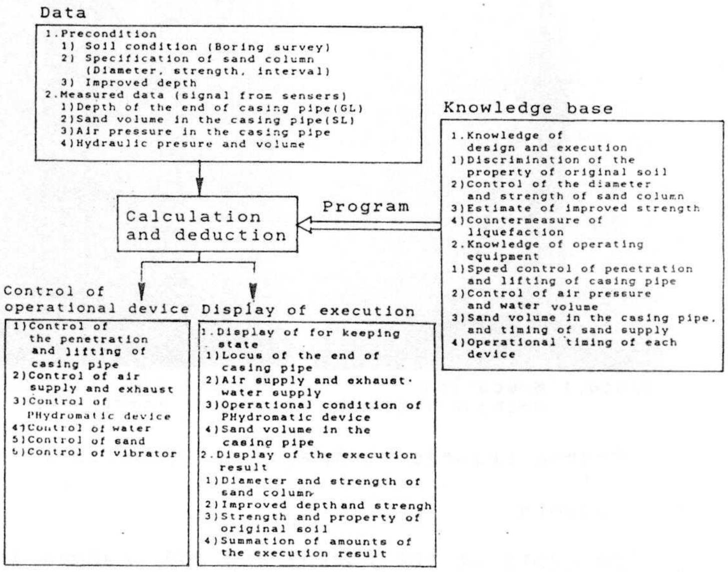

Fig.8 Expert System Forming Sand Column

(3) Quality display and summarization

The operational state of each sensor apparatus during execution is displayed continuously on the operation monitor, keeping track of operations. These include the locus of the casing end during penetration and formation of columns, information on air supply and exhaust,water supply and the movements of PHydromatic device as well as the sand level in the casing and operation of the sand-supply apparatus.

The quality that results from this tracking is also displayed continuously on the screen. As Fig. 9 shows, the following items are displayed moment by moment: (1) The depth locus of the casing end during penetration and formation of sand columns; (2) The continuous locus of the sand-column diameter at each depth; (3) A continuous locus showing the strength of the soil or columns at each depth. In addition, it is possible to display items for which geotechnical predictions can be made from the information.

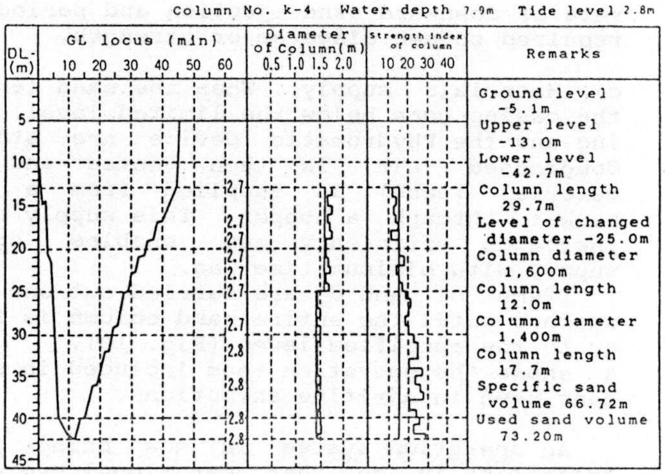

Fig.9 Display Example of the Execution Result

These various data are stored on a floppy disk, allowing the user to tally and provide report sheets of the execution results. This means greater energy savings.

4.3 Operational Procedure

The order of operation is as follows.

a) Input of set values: The results of the soil quality survey carried out prior to execution are used as the basis for converting into numerical values the data on soil strata, property and average strength. Design parameters including the standard diameter determined for sand columns, the space between them and the required sand-column strength are also used. These data are then input into the NC control unit. Because the soil-quality survey data include data on boring for several locations, it does not absolutely conform to conditions for the actual position of execution. This discrepancy is later corrected by deductions based on information from the individual sensors.

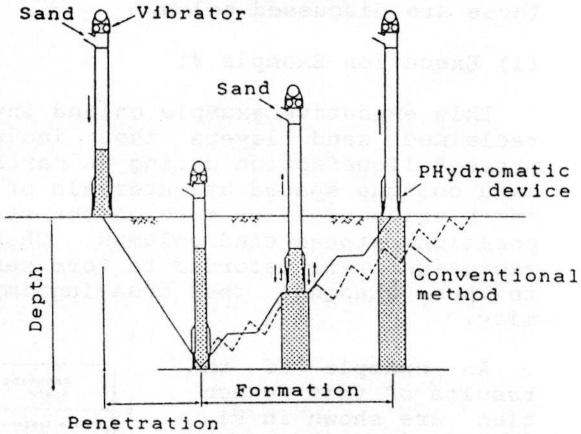

Fig.10 Execution Procedure of New System

b) Penetration: After the casing is set to the specified position and the sand is thrown into the casing, penetration is carried out by means of the vibrator down to the specified depth. When necessary, it is possible to generate information on strata divisions by detecting resistance values.

c) Formation of sand column: Following penetration, compressed air is supplied to the casing and the PHydromatic device operates. Then the casing is continuously lifted, otherwise the up-and-down operation of the PHydromatic device ejects and compacts the sand. This obviates the need for redriven-down operations of the casing required by conventional method, allowing for high-speed execution -- another special feature of this system. Lifting speed is controlled according to information on the rate of downward sand ejection and periods of vibration, resulting in the required column diameter or strength.

rate of downward sand ejection and periods of vibration, resulting in the required column diameter or strength.

d) Materials supply: When the sand level in the casing goes below the limited level, lifting and the PHydromatic device are stopped. Compressed air is then vented and more material (sand) is supplied from a large bucket through a hopper. This supply system increases efficiency and enables optimum supply with minimum time lag.

Items c) and d) are carried out one after another until the entire sand column is formed up to the specified level (Fig. 10). Photo 4 shows the operation room included in equipment used in maritime executions.

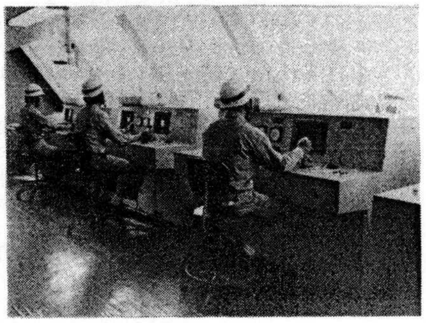

Photo.4 Operating Room in the Execution Ship

An operation system is now being prepared that can be processed automatically so that operational cycles b), c) and d) can be performed without requiring the operator to lift a finger.

4.4 Examples of Application

This new system has already been used in about 40 actual operations. These examples include both onland and maritime executions. Data from these are discussed below.

(1) Execution Example #1

This executive example onland involved ground consisting of loosely reclaimed sand layers that included a thin silty layer. In order to prevent liquefaction during an earthquake, this system was used to form sand columns spaced at intervals of 1.8 meters. The improvement target was an N value of 12 or more on the standard penetration test for the central position between sand columns. Changes in soil strength informed during execution were recorded to form sand column with a diameter corresponding to those changes, thus creating improved ground with outstanding uniformity.

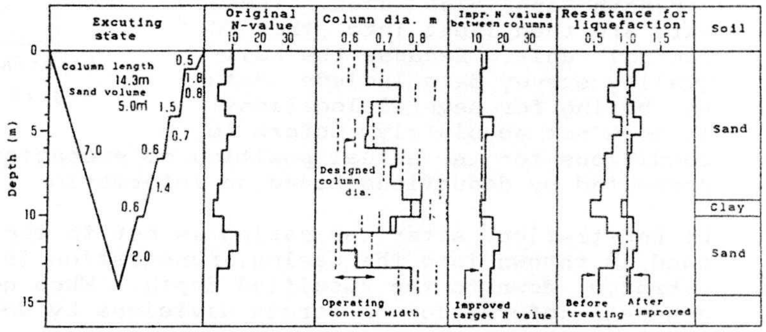

Fig.11 Display Example of the Execution Result (Prevention of Liquefaction)

An example of the results of this execution are shown in Fig. 11. The section with the original N value shows the strength values recorded continuously by the sensor. The section with the diameter of the sand column shows that the sand volume (column diameter), determined in response to the original soil strength to meet the improvement target (N>12), was computed immediately and displayed as the design column-diameter value. The results also show that executions were done within a control sphere where the indicated values formed the center. The section featuring improved N values between sand columns shows post-improvement strength that was predicted based on geotechnical knowlege derived from the original soil strength and the column diameter.

(2) Execution Example #2

This execution was also undertaken to prevent liquefaction in loose sandy subsoils. It consisted of sand columns at intervals of 2 m where the improvement target was an N value of 20 or more. As in the former example, changes in the original N value were obtained to form a sand column of the proper diameter. Fig. 12 shows a comparison of actual boring data obtained before and after executions. The post-improvement N values meet the target strength and are concentrated around the target N value. For your reference, other execution results using the conventional SCP method with a target N value of 20 at a district adjacent to this site are included. As the Fig. 12 shows, the results gained with this new system are characterized by an extremely uniform improvement.

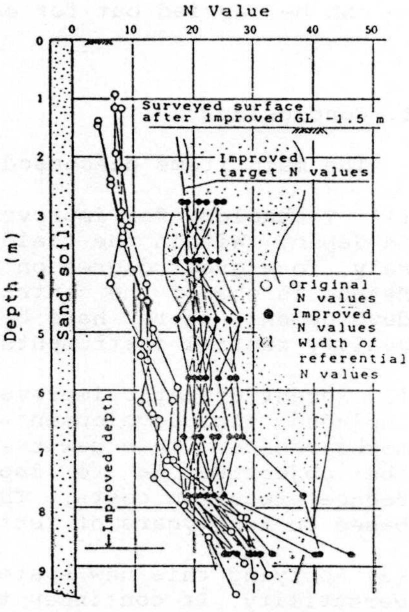

Fig.12 Comparison of Untreated and Improved N Values (Prevention of liquefaction)

(3) Execution Example #3

In this maritime improvement, the new method was used to stabilize the clayey sea-bottom soil prior to shore-protection work. It is an example of "high replacement ratio" (sand columns placed at 1.7 m intervals with diameters of 16 m - 1.4 m). The strength index of sand column S predicted by the sensors on the equipment and the N values obtained by the actual boring survey after the execution are compared in Fig. 13. Because there are errors in both values, there is not absolute one-to-one correspondence. However, the correlation between the two is clearly recognizable in Fig. 13. A method making good use of the S value as a real-time executional control index is explained below. First, instead of using the average line S=(1/1.18)N as the control index, the method uses value, x (average)- σ (standard deviation), on the safety side, or, in other words, S=(1/0.9)N. Next, if the control target in the specifications is, for example, N>10, operations are carried out to satisfy S>10/0.9=11. In this way quality control during executions -- the original meaning of execution control

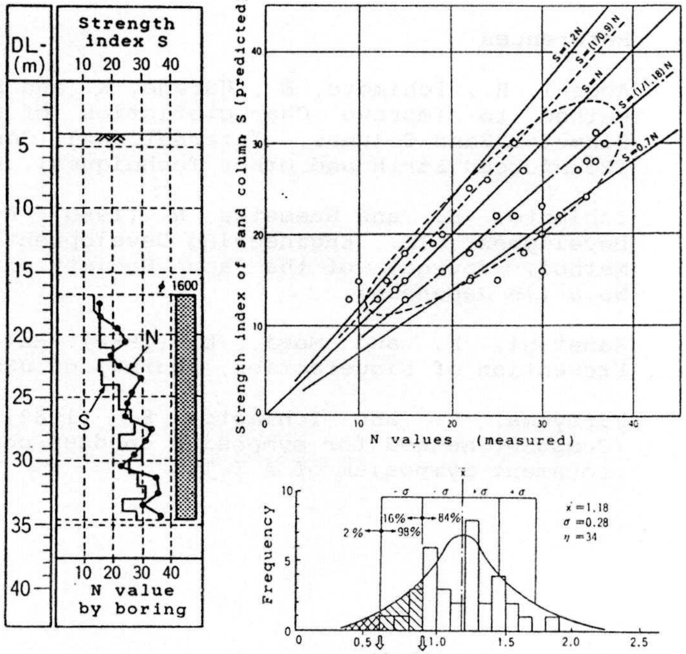

Fig.13 Comparison of the Strength Index of Sand Column S and the N Values by Actual Boring Survey (maritime, high replacement ratio)

-- can be carried out for each sand column.

5. Conclusions

The main items discussed in this report are as follows.

(1) Technology for improvement of soft soil has reached a very high level in Japan. Within the field of construction, it is one of the areas that rely to a great degree on mechanical equipment. The Sand Compaction Pile Method is one of the central methods for soil improvement. Throughout its development there have been many improvements in execution equipment and quality control instruments.

(2) Recent dramatic improvements in the Sand Compaction Pile Method have included the development and implementation of automatic operation using mechatronics. This new execution system allows for feedback control where the objective is to improve overall response in quality control and to reduce execution costs. The result has been an outstanding expert system based on long years of testing and experience.

(3) Applying this new system to a wide variety of situations has shown its versatility. It continues to meet the prescribed objectives, and proposals for new control indices are regularly submitted. Demands for higher quality and lower execution costs are constant factors to be reckoned with in construction. It is our hope to continue developing this technology and putting our best efforts toward advancing every aspect of soil improvement.

References

Aboshi, H., Ichimoto, E., Harada, K. and Enoki, M. (1979): THE COMPOZER, A Method to Improve Characteristics of Soft Clays by Inclusion of Large-Diameter Sand Columns, International Conference on Soil Reinforcement (Reinforced Earth and Other Techniques), Paris.

Ichimoto, E. and Suematsu, N. (1980): Frontiers of Execution Engineering Development, II. Engineering Development Examples in Japan, 3. COMPOZER Method, Journal of the Japan Society of Civil Engineers (JSCE), Vol.65, No.8 (in Japanese).

Kanatani, K. and Mori, K. (1986): Rational Soil Improvement Works for Prevention of Liquefaction, Journal of JSCE, Vol.71, No.2 (in Japanese).

Murayama, S. and Ichimoto, E. (1982): Sand Compaction Pile Method (Compozer Method for symposium on deep compaction), Proc. The Ground Improvement Symposium of A.I.T.