Development of Unmanned Deep Foundation Construction Method in Shaft

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Abstract

Deep foundations, because of their economical merits, are frequently used as foundation for steel transmission towers and bridges which are provided in mountain areas, as well as for landslide-restraining pile at scarps. However, the most of the works such as excavation are implemented in a narrow circular vertical shaft by human labor, with extremely severe work environment. Improvement of work environment, enhancement of safety, labor saving, shortening of construction period and cost reduction for deep foundation works by mechanization and automation are of primary concern. To overcome these difficulties, we have successfully developed a comprehensive unmanned construction system which is very innovative in conception and able to cover, from excavation to concrete placing, that is, "unmanned deep foundation construction method in shaft".

The paper outlines various technology elements, including the deep foundation excavator, the results of field tests, as well as its applicability to the foundation for steel transmission tower and the expected improvements.

1. Introduction

The deep foundation is a cylindric foundation of about 3m in diameter and 20m deep, having a large load resistance and able to be constructed in a relatively small space. Having the advantage of being constructed at low cost, it has being used in many cases for foundations of steel transmission towers, of road bridges, and as landslide preventing piles which are provided in mountain areas. Generally, deep foundations have been largely constructed by manual labor, because it is constructed in geographically disadvantageous spots with various restrictions in transportation and site space, in such mountain areas, introduction of large scale construction machine is difficult. Since the works are conducted in a circular space restricted in space with severe work environments, recruitment of quality manpower is harder and harder, on the background that the labor population of Japan decreases dramatically.
Therefore, improvement of work environment, enhancement of safety, labor saving, shortening of work periods for the construction of deep foundations and cost reduction through the mechanization and automatization are the topics of deep concern.

2. Summary of the unmanned construction method in shaft

Fig. 1 illustrates a series of process steps from excavation to concrete placing. This method aims to implement various works using no manpower in the shaft when constructing deep foundations, for the works such as excavation , bar arrangement and concrete placing . For this purpose, a comprehensive construction technology together with its elemental procedures was investigated and confirmed for its feasibility, setting up the following target items:

(1)In-shaft unmanned excavation by full face deep foundation excavator.

(2)Reinforcement cage-placing method, including assembling of cage outside the shaft and placing of cage in shaft.

(3) Development of concrete of self-filling type for deep foundation, including compaction-free concrete-placing technology

(4) Study on possibility of omitting temporary earth retaining

3. Excavation system

3.1 Composition of the excavation system

The excavation system consists of a main body of excavator, mucking system, suspension unit , remote controller and power unit . The configuration of the excavation system is shown in Fig. 2. The main specifications and performances are shown in Tables 1 and 2.

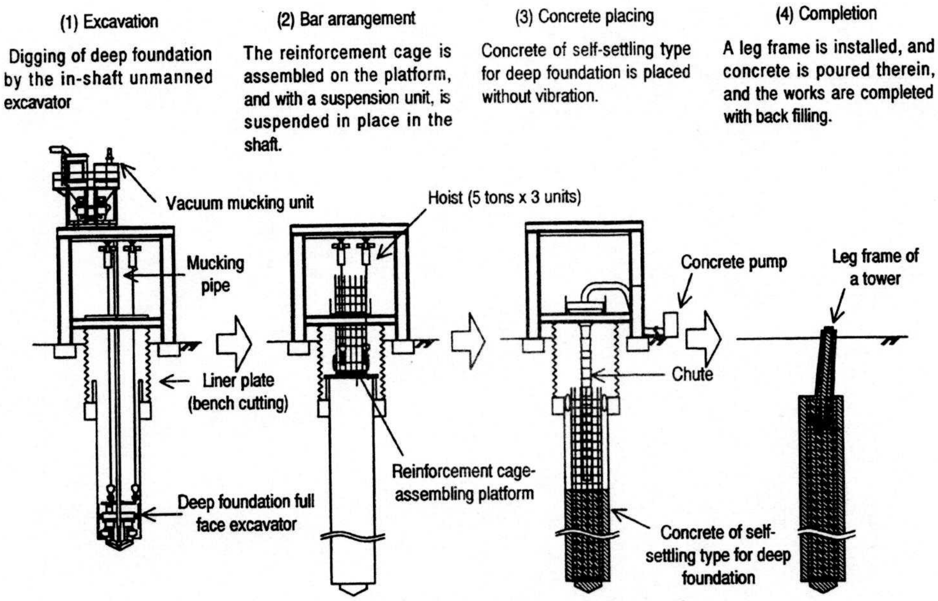


Fig. 1 Work steps for the in-shaft unmanned excavation

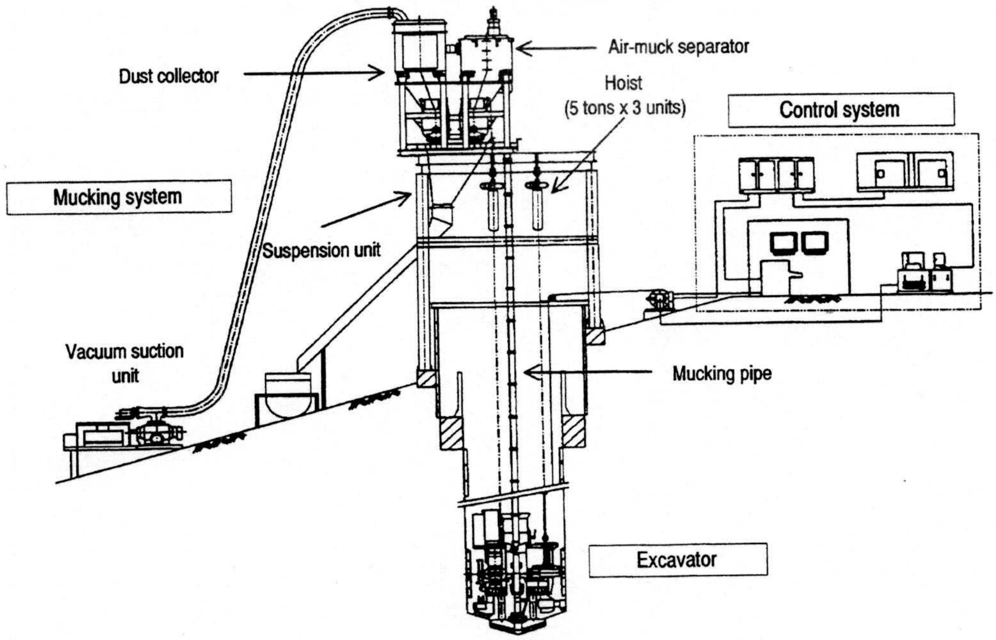


Fig. 2 Diagram of the entire deep foundation full-face excavator

Table 1 Main specifications of the excavator

Item				Specifications
Excavator main body	Cutter		rpm of cutter	Central cutter 4.7 rpm Circumference cutter 3.3 rpm
Excavator main body	Cutter		Cutter torque	Central cutter 55.9 kN m Circumference cutter 79.4 kN m
Excavator main body	Cutter		Motor	18.5 kW x 4p, 220V x 60Hz, 3units
Excavator main body	Shift jack			78.5 kN x 550mm, 3 jacks Total propelling force, 235.5kN Telescopic speed (Max) 5.6cm/min
Excavator main body	Gripper jack			240kN x 300mm, 3jaks
Excavator main body	Hydraulic unit	Shifting	Hydraulic pump	0.28L/min x 3 x 15.7MPa
Excavator main body	Hydraulic unit	Shifting	Motor	0.4kW x 4p 220V x 60Hz, 1unit
Excavator main body	Hydraulic unit	Gripper	Hydraulic pump	6.4L/min x 3 x 15.7MPa
Excavator main body	Hydraulic unit	Gripper	Motor	7.5kW x 4p 220V x 60Hz, 1unit
Vacuum suction unit	Vacuum suction unit		Engine	Air cooled diesel engine 76kW 2300rpm
Vacuum suction unit	Vacuum suction unit		Vacuum pump	250A Root blower
Vacuum suction unit	Vacuum suction unit		Theoretical treatment capacity	98kN/h
Vacuum suction unit	Air / muck separating collector		Motor	1.5kW x 4p 220V x 60Hz 1unit
Vacuum suction unit	Air / muck separating collector		Dust removing	Air pulsation
Vacuum suction unit	Air / muck separating collector		Required air volume	360NL/min x 0.5MPa(G)
Vacuum suction unit	Mucking unit of continuous operation		Motor	0.75kW x 4p 220V x 60Hz 2units
Vacuum suction unit	Mucking unit of continuous operation		Maximum mucking capacity	0.3 m^3/min

Table 2 Performance of the excavator

Item	Performance
Excavation diameter	from 2.50m to 3.35m
Excavation ground	Ordinal soil to rock of middle hardness (unconfined compressive strength : up to 50N/mm^2)
Excavation depth	35m or less
Weight of each of the elements constituting the system	2.0 ton or less
Total weight	About 12 ton (excavator only)
Excavation speed	Sand stone : 60cm/h Soft rock : 50cm/h Rock of middle hardness : 35cm/h

3.2 Main body of the deep foundation full face excavator

Photo 1 and Fig. 3 show the appearance and structure of the excavator.

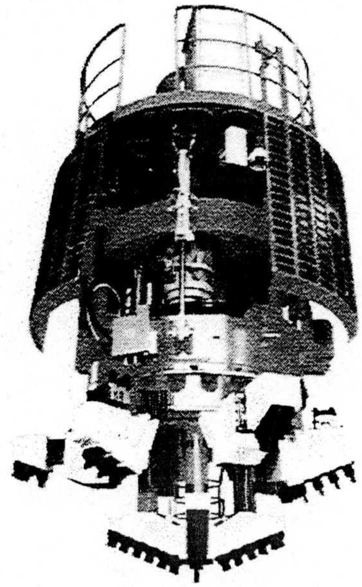


Photo 1 Appearance of the deep foundation full-face excavator

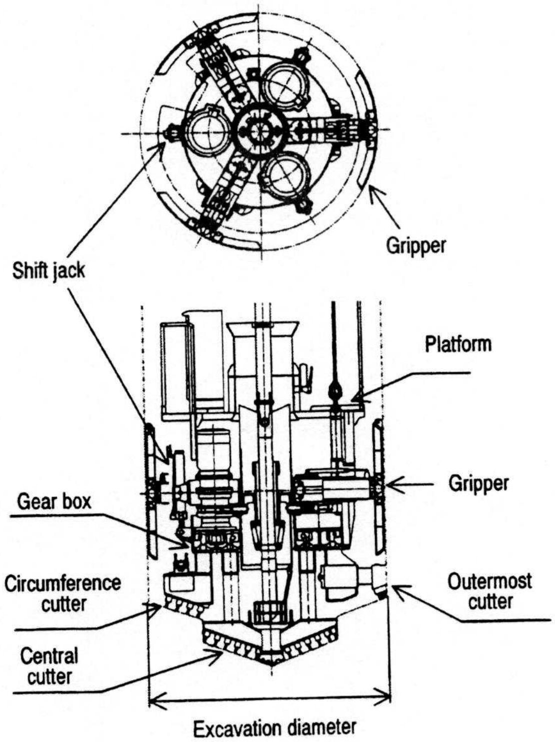


Fig. 3 Structure of the excavator

Fig. 4 shows the excavation steps, they are

Step1: The excavator presses its three gripper plates to the shaft wall with hydraulic jacks to secure its body against the wall.

Step2: For the full face excavation, the excavator extends its propelling jacks to press the rotating cutter to the cutting face.

Step3: After each stroke of jacking for propelling (1 shift : 50 cm) ,the grippers release their holding.

Step4: The propelling jacks retracted to let the excavator body descend.

Next cycle: The grippers are extended again to secure the excavator body by reaction from the wall to perform the excavation of the next shift.

The excavator repeating four steps in order, can advance with a cycle length of 50 cm.

The excavator is given the following features:

(1) All the in-shaft operations from excavation to mucking can be remote-controlled with a single operator on the surface, without human intervention.

(2) The cutter is composed of a center cutter and a circumference cutter which are designed so as to turn inversely to each other for cutting. Use of this mechanism allows us to miniaturize the main frame, with the possibility to compensate torsional moment generating by rotation of the cutters in opposite direction.

(3) The central cutter is arranged with a level difference with the circumference cutter, by which the cutting surface created is slanted so that muck gathers by gravity to the center of the cutter face; therefore, the muck gathered can be carried out easily through a mucking pipe running in the spine of the excavator.

(4) The system is designed with an outermost cutter of telescopic type so that the cutting diameter can be adjusted from 2.65 m to 3.35 m.

(5) The whole assembly can be divided into elements weighing respectively 2.0 tons or less; even if the site concerned is located in a mountain area, their hauling is easy on cableway or on helicopter.

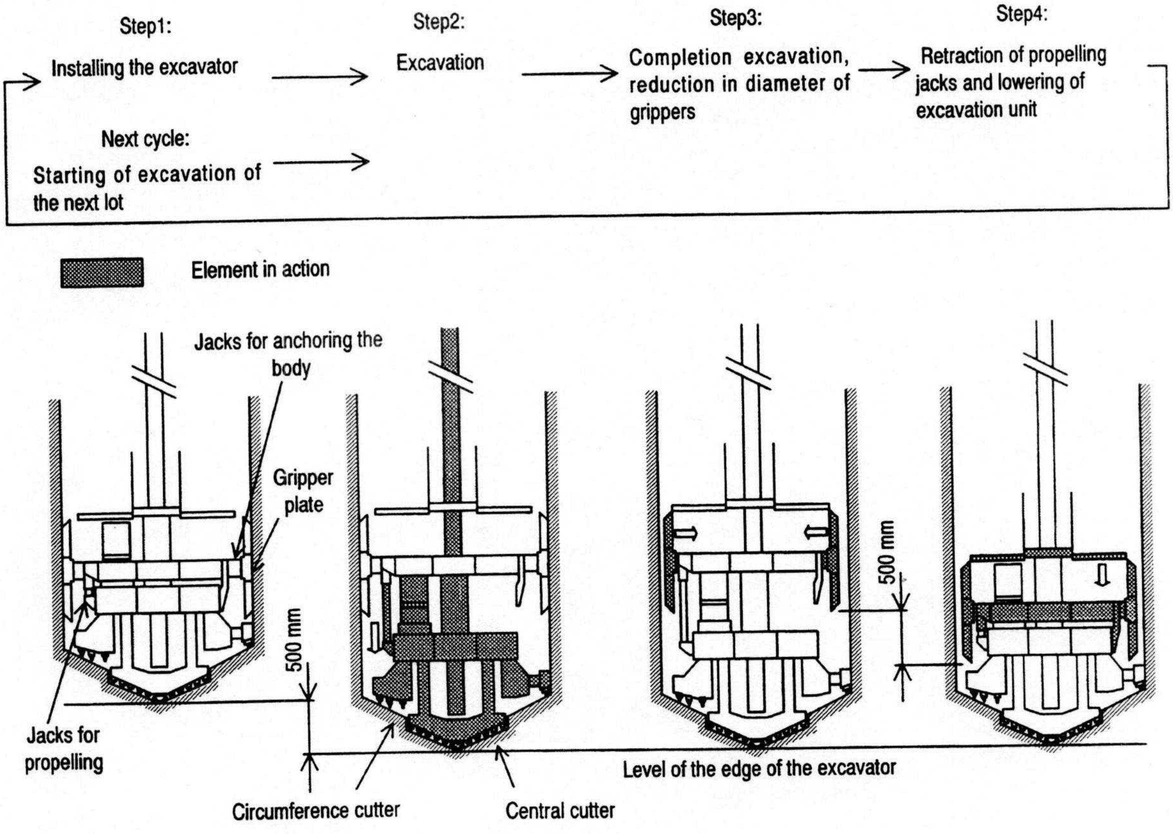


Fig. 4 Propelling steps of the deep foundation full face excavator

3.3 Vacuum suction mucking system

For mucking, the shaft excavator, which is provided with a vacuum suction system of pneumatic type to discharge to the surface the muck collected at the center of the cutting face, is able to perform mucking continuously during excavation. The mucking system consists of a pipe to collect muck, a soil or a dust/air separating dust collector and a vacuum suction unit which generates suction force (rotary blower).
The mucking system is shown in Fig. 5.

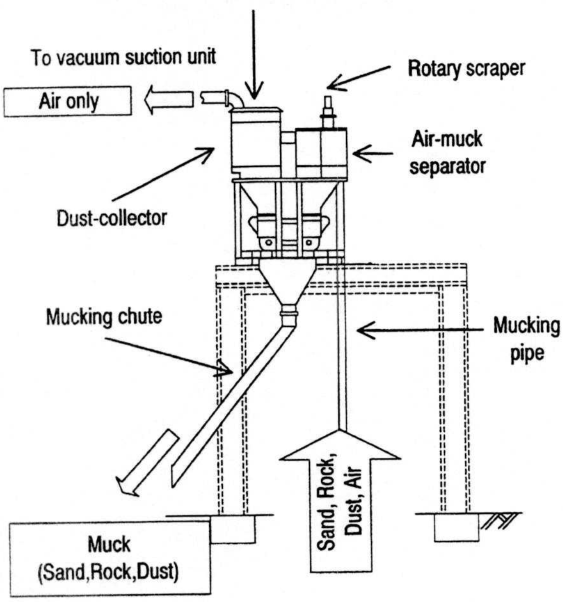


Fig. 5 Mucking system

3.4 Control system

Operation of the excavator is performed by a single person from a remote control unit (Photo 2) in the control room on the surface, referring to the data below:

(1)Muck sucking from the mucking pipe inlet, rock mass conditions of the cutting face and of the shaft wall. (monitored by 3 CCD cameras mounted on the excavator)

(2)Hydraulic pressure and shitting speed stroke for shift jacks and gripper jacks.

(3)Inclination of the excavator from horizontal plane. (monitoring by biaxial inclinometer mounted on the excavator)

(4)Cutter load amperage.

(5) Suction force by vacuum suction unit.

Photo 2 Remote controller

3.5 Suspension unit

The suspension unit is composed of a gantry type platform with 4 legs provided above the shaft, and three 5 tons hoists; with this suspension unit, it is possible to carry in and out the excavator, and to place the reinforcement cage into the shaft. The platform is designed with additional leg elements so that it may be installed on an inclined ground surface.

4. Omission of temporary earth retaining

Usually, temporary earth retaining is provided to prevent shaft wall from collapsing, with the purposes: (a) security of workers in the shaft, (b) protection of materials and machines and (c) protection of the equipment provided in site.
Since the in-shaft unmanned excavation method is designed especially for the rock mass of a sufficient self-standing force, as far as the ground concerned is sufficient in these condition, this method can be applied without problem, omitting temporary earth retaining; therefore, we can expect a considerable cost down and shortening of construction period.
The self-standing capability of a shaft wall can be estimated based upon the nature and physical properties of the rock mass in site, as well as on the depth of the excavation level.

For this work, a chart of shaft-standing sections was prepared using the boring survey data of the site to determine the areas needing no temporary earth retaining; the use of this chart enables to locate the section having self-standing force, on the results of boring survey which are available for many points in the site, and on the FEM-data in terms of the behaviors of the site under excavation.
This procedure needs to implement a preliminary geological review of the site by boring survey on the construction site, so that for the sections of sufficient self-standing force, we may proceed with excavation resorting to no earth retaining.

5. Placing of reinforcement cage

This procedure is to place reinforcement cage in the shaft ; first of all , a cage is assembled just above the shaft , lowered and set in place with a suspension unit. The placement of a cage into the shaft is shown in Photo 3 . This procedure's steps are illustrated in Fig.6.
The assembly of the reinforcement cage are divided into several lots according to their placement depth; they are jointed sequentially on the surface before being lowered into the shaft. The main reinforcement bars of the cage are of screwed type, and coupler-joints used for connecting the lots, enabling continuous construction of plural lots and simplifying the coupler joints-related works.

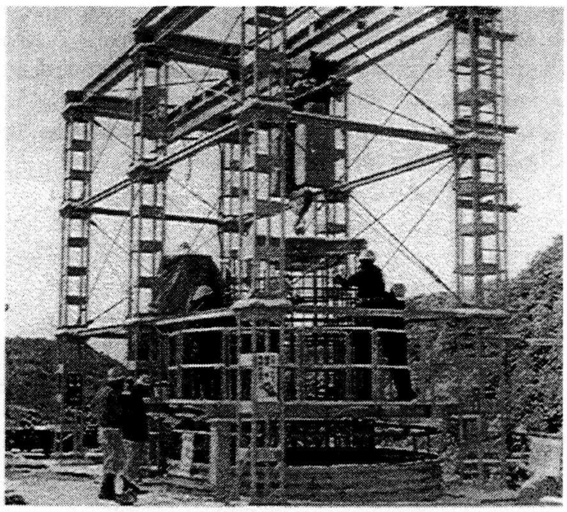


Photo 3 Reinforcement cage-placing method

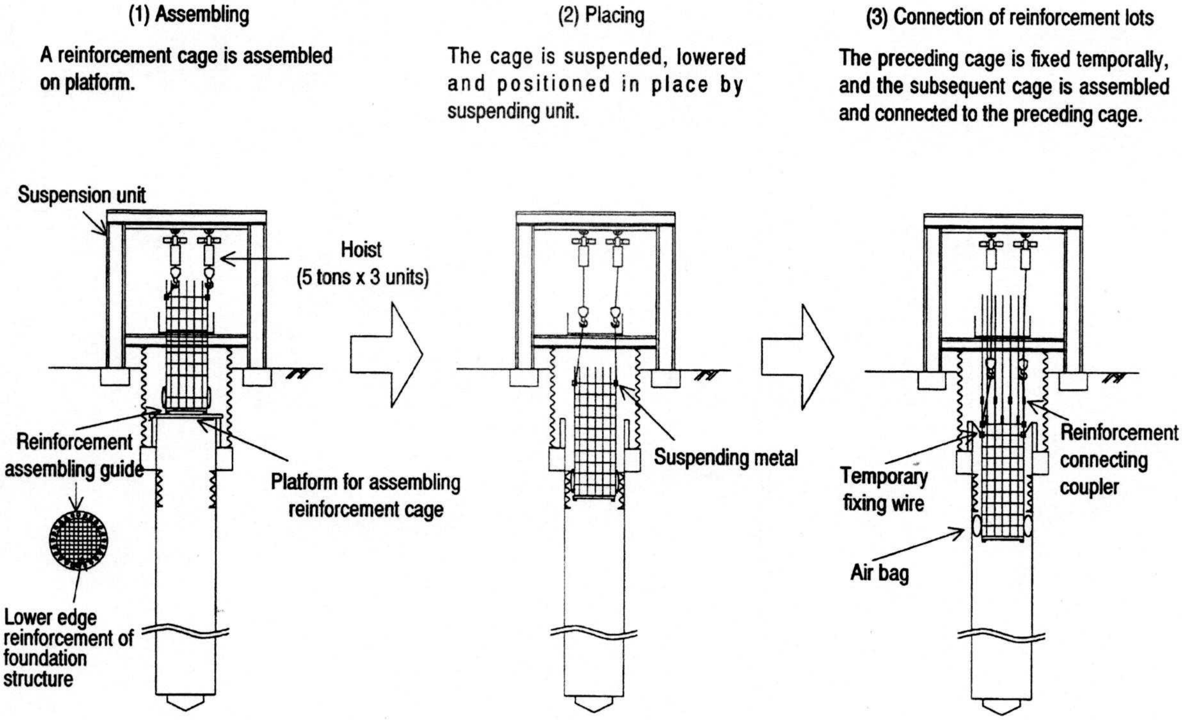


Fig. 6 Steps of placing reinforcement cages in shaft

6. Self-settling concrete

In order that concrete placing in the shaft may be performed unmanned, it is necessary to establish a new concreting procedure needing no filling nor compaction . To meet this requirement, use of one of the high performance concretes recently developed is considered to be effective; however, since this type of concrete is composed of not only cement but also other powder agent, it cannot be prepared by an ordinary butcher plant and is costly.

Paying attention to the fact that the density of bar arrangement is not so high in the case of the deep foundation for steel transmission towers, we have developed a new type concrete, "self-settling concrete for deep foundation", which is smaller in flowability than the concretes of high flowability, but has an excellent resistance in segregation.
This concrete is given the desired flowability and the desired segregation resistance, by use of AE water-reducing agent and mix-proportion regulation. Use of this material enabled to omit filling and compaction of concrete in the shaft. Tables 3 and 4 show the performances and mix proportion of the concrete required for this project.

Table 3 Required performance of self-settling concrete for deep foundation

Item	Performance
Nominal strength	21 N/mm^2
Slump flow	50 cm
Time during which concrete keeps its flowability	90 min.
Air content	4.5 %
Bleeding rate	5% or less

Table 4 Mix proportion of the self-settling concrete for deep foundation

Water cement ratio (%)	Aggregate ratio (%)	Specific material content (kg/m^3)					Admixture rate (C x %)
		Cement	Water	Fine aggregate		Coarse aggregate	
				Coarse sand	Fine sand		
41.6	48.9	375	156	687	170	896	1.90

7. Demonstration tests

For the purpose of putting this method into practical use, its applicability to actual use was tested at factory and at field. The test was conducted in two steps; the first step is an element test for each of all the elementary procedures, and the second is a comprehensive test to verify the overall process of the system.

7.1 Test of the full-face excavator for deep foundation

(1) Preliminary test
At the factory having manufactured this system, test grounds were provided to testify, as preliminary experiment, six cases to simulate excavation performance by the excavator. The excavation diameter was 2.6m. The excavation propelling speed was 90 cm/h in gravel-mixed cohesive soil and 30 cm/h in rook mass of middle hardness; the speed achieved was about 3 times larger than conventional excavation methods.

(2) Field-excavation test
To confirm performance, required manpower, processes and safety by excavation system, a demonstration test was conducted at a field through construction of a 500 kV steel transmission tower. The test was conducted for two cases different in ground properties, as shown in Table 5.

(3) Improvement of the excavator
The excavator was improved based upon the test results.

-Use of lime water-absorbing agent
As far as generation of mine water is limited, the viscosity of soil was confirmed to be reduced by using lime water absorbing agent to prevent the mucking pipe from clogging.

- Reviewing the mucking system
The structure of the mucking system was redesigned so as to collect earth and dust separately, resulting in the reduction of the dust which is discharged into the atmosphere.

-Reviewing the structure of the mucking pipe inlet
A large screen cage was provided at the suction inlet to prevent large pieces of stone from entering directly into the mucking pipe.

7.2 Comprehensive test of the system

For the unmanned deep foundation construction method in shaft, its field test was conducted to verify all the aspects in applicability of the system at a site of a 500 kV steel transmission tower. The results of the test were shown in Table 6. Photo 4 shows the appearance of the comprehensive test site. Through this comprehensive test, we have verified: performance of each type of work, consistency between work types and consistency with temporary equipment; their applicability to practical use are confirmed positively.

Table 5 Operation tests of the deep foundation full-face excavator

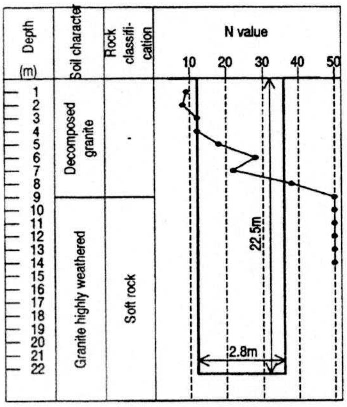
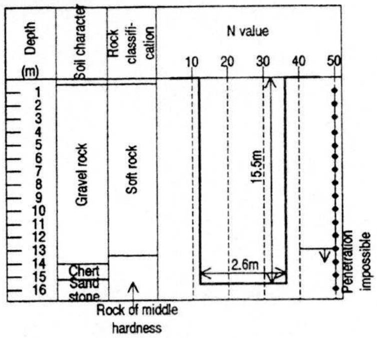
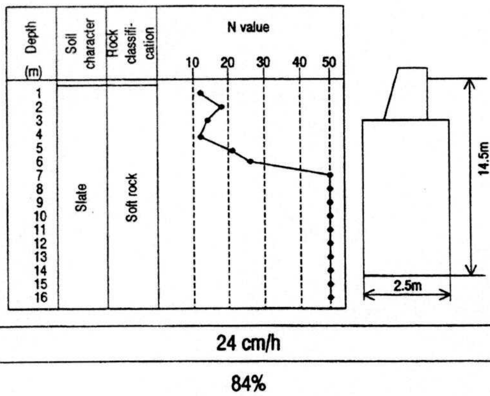
	Case-1	Case-2
Ground soil property	Soft rock highly weathered (granite)	Soft rock Rock of middle hardness(chert)
Construction condition		
Summary of results	Although there were some mine water, excavation and mucking could be performed successfully.	The inlet of the mucking pipe clogged because of some gravel-like pieces of rock. Good excavation.
Excavation speed	Decomposed granite: 60 cm/h Granite: 50 cm/h	Chart: 35 cm/h

Table 6 Result of comprehensive test for the in-shaft unmanned excavation method

		500kV Etumi Trunk Line No.10 Tower	
Ground soil property		Soft rock (slate)	
Construction condition			
Excavation speed		24 cm/h	
Omission of temporary earth retaining		84%	
Construction period	Temporary work	4 days	(3 days)
	Excavation	10 days	(15 days)
	Bar arrangement	1 day	(2 days)
	Concrete placing	1 day	(1 day)
	Sum.	16 days	(21 days)

( ) : by usual construction method

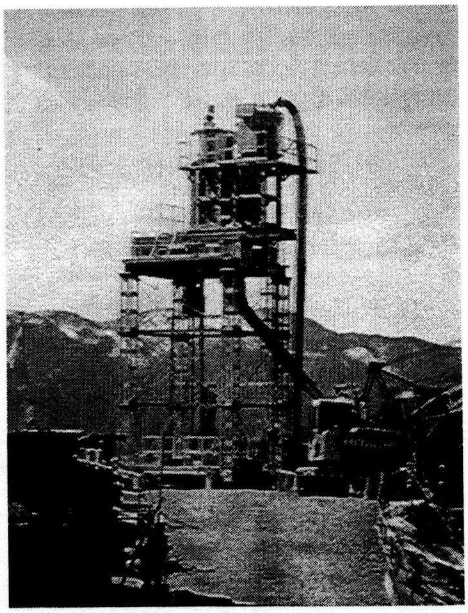


Photo 4 Comprehensive test of the system

8. The effects expected by the introduction of the system

When introducing the in-shaft unmanned deep foundation construction method, the following strengths can be expected

(1) Improvement of working environment: attenuation of working load, shifting from in-shaft work to on-surface work.

(2) Enhancement of safety: unmanning of in-shaft works, needing no explosive.

(3) Labor saving: reduction of manpower for a working group. (from 8 persons to 5 persons)

(4) Shortening of the working period: from 4 months/tower to 3 months/tower

(5) Reduction of cost: 2~3 % (when 80 % of the temporary earth retaining can be omitted).

9. Conclusion

All the procedures constituting the system from excavation to concrete placing are confirmed for their respective applicability to practical use, through their field tests.

Based upon the demonstration test results, we prepared a manual of execution for the method of the in-shaft unmanned deep foundation construction, covering operation procedures, setting of individual machines and equipment, method of transportation and quality control standards.

This method has been used from April, 1996 at various construction sites of trunk line transmission towers, including those on 500 kV Etsumi trunk line, and with additional improvements and reformations, will be extended in application.