NONSHORED FORMWORK SYSTEM FOR TOP-DOWN CONSTRUCTION

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ABSTRACT: Recently, the top-down construction method has been applied to building construction to secure excavation safety by providing rigid diaphragm walls. Usually, proper and economical formwork systems need to be selected for successful top-down construction. This paper proposes a nonshored top-down formwork system (referred to as NSTD) as a modified formwork system for top-down construction. The NSTD method provides sufficient workspace for excavating under the suspended forms. Upon completion of concrete placement and curing on the ground level slab, the formwork system is lowered to the next floor, and the process is repeated down to the lowest underground floor. The advantages of the NSTD method include a reduction in the excavation duration and an improvement in the quality of the underground concrete work by the hanging-type formwork. A case study was performed to verify the validity of the NSTD by comparing its schedule and cost effectiveness with those of traditional top-down methods.

INTRODUCTION

In recent years, the need for deeper underground parking structures in urban areas has made for complex and difficult excavation work (Jung 1995). In restricted urban sites, high-rise buildings and underground facilities are so congested that new building constructions often pose safety problems during the construction process, particularly during the excavation work (Ng and Lings 1995). Therefore, the selection of proper foundation construction methods is important, to prevent accidents and traffic problems.

Top-down methods have improved the safety and efficiency of work in many major construction projects in Korea (Song 1992). In traditional substructure construction methods, the structural frames of buildings are erected after the completion of foundation construction, but top-down methods function in the opposite direction (Paek and Ock 1996). Because top-down methods are aimed at substructure construction, proper substructure construction methods require careful consideration. Among these, the development of proper and economical formwork systems for the successful performance of top-down methods is essential.

The main objective of this research is to propose a new formwork system that enables the underground excavation work to be executed in safe conditions, while still providing significant savings in the overall project schedule. The feasibility of the new formwork system is presented, through a case study, in terms of both time saving and cost-effectiveness. The objectives were met through (1) an intensive literature review; (2) problem analysis of traditional top-down construction methods; and (3) a case study to illustrate and validate the formwork system in an actual construction field.

PROBLEM STATEMENT

Characteristics of Top-Down Methods

In the construction of high-rise buildings with an open-cut excavation method in an urban area, the uncertainty and increasing depth of the excavation may cause public discontent and safety problems irrespective of how carefully planned the design and construction progress (Whittle et al. 1993). As a result, a considerable amount of losses in time and cost to the construction projects are incurred. Usually, top-down methods are applied to substructure construction to avoid accidents that result largely from unsafe excavation work. However, the size of the construction site, excavation depth, and soil conditions should be carefully considered to select a proper top-down method for substructure construction.

Generally, a top-down method is performed via sequential steps. First, permanent underground walls, columns, and footings are installed using perimeter diaphragm walls. Second, upon completion of concrete placement and curing of the ground level concrete slab, which functions as a strut for supporting the underground perimeter walls, the formwork system is lowered to the next lower floor. Third, this process is repeated down to the lowest floor, while constructing the substructure from the top to the bottom down. In this method, both the substructure and superstructure of a building are constructed simultaneously and completed at the same time. Therefore, it is also called an up-down method or the Sakauchi method (Samwhan 1991).

In the top-down method, permanent structures are constructed by rigidly combining previously constructed steel columns and concrete slurry walls with concrete slabs (Peurifoy and Oberlender 1996). The slurry walls are commonly used as a retaining wall. Therefore, temporary facilities such as struts are not required in this method because the slabs and beams of the substructures function, in part, as struts against underground soil and water pressure (Tatum and Bauer 1989). Upon completion of ground leveling and pouring of lean concrete, reinforcing bars and concrete are placed on the slab. At times, a temporary truss, suspended formwork, or metal deck plate are used to support the slab.

Types of Top-Down Methods

Various top-down methods have been developed in the construction industry. This paper describes typical top-down methods, such as concrete-on-grade, form-on-support, and go-over-next-slab, and analyzes the problems that are associated with these methods.

Concrete on Grade

This method is applied directly to the slab on grade. After stabilizing the subgrade, polyethylene film or plywood sheeting is laid on the ground surface and lean concrete placed over it. Then, reinforcing bars and concrete are placed, which requires curing prior to excavating. Therefore, formwork is not usually required for the construction of a slab because the slab concrete is placed directly on to the lean concrete surface.

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However, a drainage or dewatering system must be installed to overcome difficulties in the control of underground water. In the case of pouring concrete without control of underground water, particularly in silt or clay layers, the concrete structure can be damaged severely by ground-water pressure or consolidation settlement. In addition, this method is appropriate for simple flat-type slabs because of its convenience in construction but not for complex slab-beam type structures. In this case the thickness of flat slab should be at least 30 cm to ensure adequate stability, thus increasing the quantity of concrete. In addition, the installation of a concrete slab on subsurface rock is not possible, because of damage to the concrete structure during the excavation of the rock.

Form on Support

This method is applied to a concrete slab that is constructed on relatively rigid soil layers. The concrete is placed after excavating to the necessary depth and then installing the shored formwork. Due to the fact that shoring under the forms is required during concrete curing, the excavation crew and equipment must wait until the completion of the curing. In addition, shoring materials for the forms must be removed before the excavation proceeds. This is also a cause of losses and delays for the formwork crews. For these reasons, in this method, the time and cost of the construction work will inevitably increase.

Go over Next Slab

In this method, the excavation work for two floors is simultaneously performed, and the lower slab is then constructed beforehand by the concrete-on-grade method without shoring. The upper slab is constructed subsequently by the form-on-support method, and as a result, shoring is required for concrete curing. The concrete-on-grade method can be applied to grounds composed of soft soil layers. If construction is performed with this method on solid rock layers, the concrete structure can be easily damaged when excavating in rock below the slabs. This method may increase cost because retaining walls with high strength need to be designed to support the simultaneous excavation of two floors against lateral movement.

Problems in Top-Down Methods

In typical top-down methods, excavation is not possible during concrete curing. That is, the excavation work must wait until the completion of curing, resulting in schedule delays and discontinuity of the work process. Therefore, the overall project schedule is delayed, causing an increase in the total cost. In addition, the safety of the slab concrete cannot be guaranteed when the forms are removed early.

With completion of each slab of the substructure, slurry walls are stabilized by being braced by floor slabs. However, since the outlets for moving materials or equipment are not sufficient, the removal of the excavated soils from the workplace is not an easy task. In addition, lighting and ventilation equipment for the underground workplace must be installed and, if the ground layers are too loose or if the levels of the basement slabs are different, special consideration in design and construction is necessary. These problems would cause a decrease in efficiency, schedule delays and cost increases to the typical top-down methods.

DEVELOPMENT OF NSTD METHOD

Introduction to NSTD Method

This research proposes a new top-down method called the nonshored formwork system for top-down construction (hereafter, NSTD), which may resolve some of the problems in traditional top-down methods. The NSTD method provides sufficient workspace for excavating under the suspended forms. Upon completion of the concrete placement and the curing of the ground level concrete slab, the forms of the NSTD are lowered to the next lower floor and the process is repeated down to the lowest floor. Due to the fact that the NSTD method is performed entirely within the perimeter of the site, it is well suited for projects where jobsite conditions are restricted.

In addition, the NSTD method provides a safe workspace because the constructed slabs cope with the soil pressure under uncertain soil conditions. Moreover, under hard soil conditions, this method can reduce cost, time, and hazards by permitting the excavation and slab installation to be simultaneously carried out. Under rock conditions, this method can reduce cost, time, and hazards by an even greater degree.

The steps of construction operation using the NSTD method are as follows; the conceptual sequence of the operation is illustrated in Figs. 1(a–d):

1. After the concrete slurry walls (retaining walls) are constructed, steel columns are installed in the subgrade surrounded by slurry walls.
2. When the steel columns are installed, the ground surface is stabilized for pouring lean concrete.
3. The NSTD deck forms are fabricated on the finished grade after the lean concrete is placed over it.
4. Reinforcing bars for the concrete slab are placed on the deck forms, and rock bolts (screw-type steel bars) are installed vertically through dual sleeves as shown in Fig. 1(a).
5. Concrete is placed on the forms at the ground level. While the concrete is curing, the soil under the suspended deck forms fixed to the ground level slab is excavated as shown in Fig. 1(b).
6. After the excavating work for the first basement floor is finished, the deck forms are lowered to the next lower floor using hydraulic lifting devices, as shown in Fig. 1(c).
7. The main retaining assembly is installed on the ground level slab, and the deck forms are fixed at the first basement floor.
8. Reinforcing bars are placed on the deck forms of the first basement floor. Checking the sleeves in which the rock bolts are inserted, concrete is placed on the forms at the ground level and then cured. This step represents the part of the operating cycle. The process is repeated down to the lowest basement floor, as shown in Fig. 1(d).

Quality Control of Slurry Walls and Steel Columns

Accuracy in the construction of slurry walls and steel columns is very important in the top-down method to which the NSTD method is applied, and the NSTD method depends upon the quality control of them for successful performance. In general, about 100 mm of plumb variation (under 1:200) is allowed when the slurry wall is constructed. A large deviation of plumb is likely to induce leakage of water in the joints, boiling and inflow of soil, and problems in safety. Accordingly, the slurry walls should be aligned in actual construction by proceedings as follows.

A computerized monitor is installed in the excavation equipment of the slurry wall itself, and the operator excavates vertically by adjusting the flap installed in the lower part of the excavator while watching this monitor. In addition, the excavation equipment is taken out every 10 m of excavation, and alignment is checked by taking photographs of the excavated walls with an underwater ultrasonic detector, thus preventing

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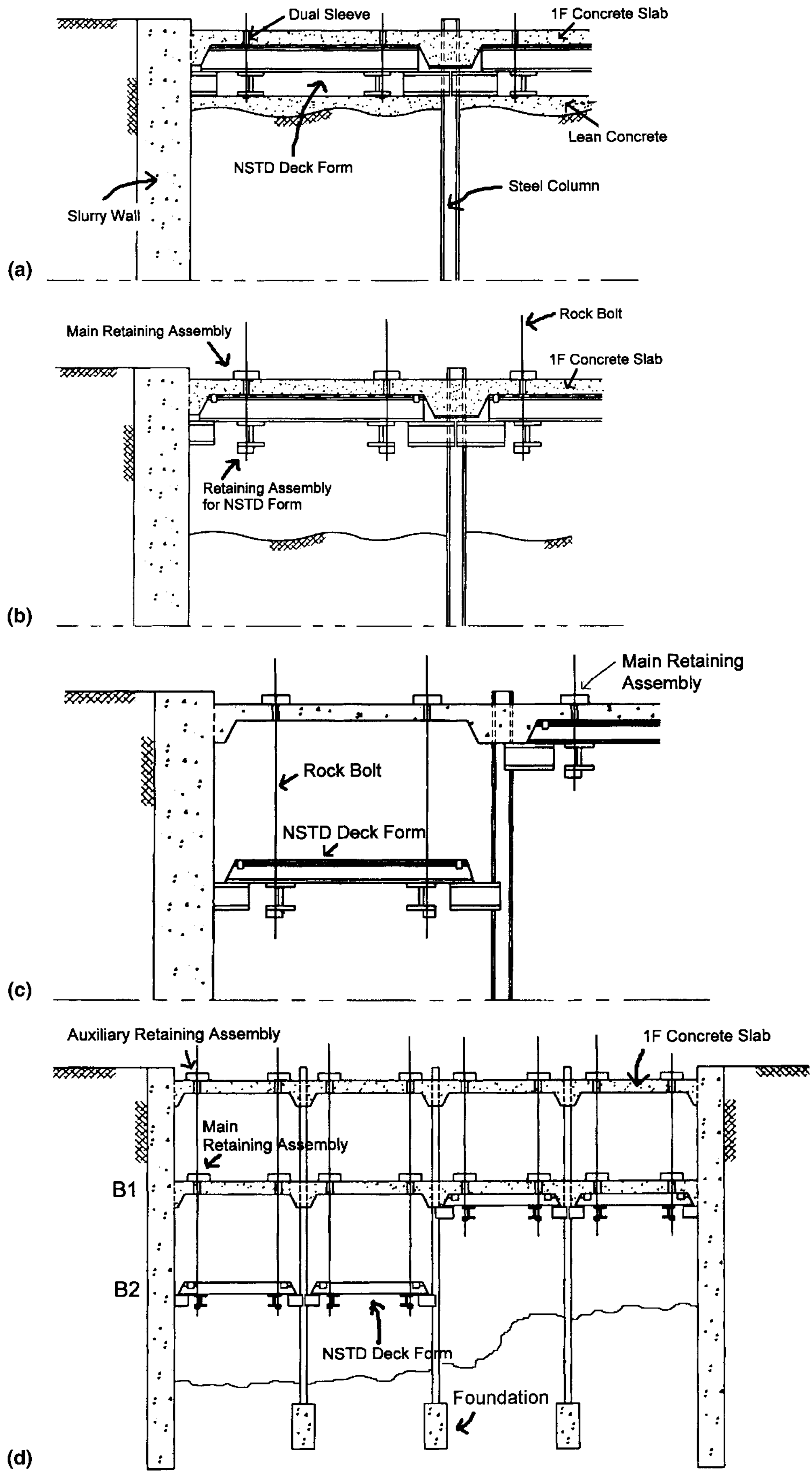

FIG. 1. Sequence of Operations Using NSTD Method: (a) Initial Assembling of All Deck Forms on Finished Grade; (b) Excavating under Suspended Forms; (c) Lowering of Forms under Slab to Next Floor; (d) State of NSTD Method

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possible wrong excavation. In case it is found out that the excavation was performed inaccurately, excavation is to be performed again with the flap. Accordingly, the slurry wall is built with excellent alignment.

More than 100–150 mm of deviation in the alignment of the steel columns produces no problems in slab construction. However, it is likely to cause serious impacts on structural stability due to the eccentricity of the steel columns. In general, steel columns shall be allowed a variation of 1:300 from the alignment.

Therefore, field supervisors of the actual project set four points of survey around the upper casing pipe of the excavation hole to which the steel column is inserted and confirm the location of the steel column. Steel columns are checked of their verticality with 2 units of digital tilt meters.

In some cases, if the deck forms are lowered in a situation where slurry walls and steel columns are out of alignment, problems may occur. But that problem can be solved as follows.

Because the NSTD deck forms are designed to allow a space of about 100–150 mm for the protective concrete cover of steel columns, there is no problem in lowering the deck forms even though the steel columns are out of alignment. It is also designed to have an extra 50–100 mm of space, taking into account variations in construction at the joint between the slurry walls and the slabs.

Main Components

The NSTD forming system consists of several components. The main components include a deck form, a main retaining assembly, an auxiliary assembly, a retaining assembly for the NSTD deck form, clamps, a rock bolt, and a hydraulic lifting device. Figs. 2 and 3 show the details of these main components.

The main retaining assembly is installed on the floor where the NSTD deck form is set up to support the live and dead loads. An auxiliary assembly is then installed with the extension of a rock bolt on the upper floor, where the main retaining assembly is set up. To prevent the collapse of the concrete slab with the main retaining assembly, an auxiliary assembly is installed on an upper floor slab for the safety. As a result, safety is ensured even if the concrete slab collapses, because the auxiliary assembly on an upper floor slab bears a portion of the loads whereas most of the loads are distributed to the concrete slab with the main retaining assembly. The retaining assembly for the NSTD deck form is fixed at the NSTD deck form to transfer the live and dead loads to the rock bolts.

The clamp for the beam connects the stringers with the joists. The stringers and joists are mostly H-beams that vary in size according to the design loads but are generally composed of H-beam (W 8 × 24). The clamp for the C-shape channel is used to connect the C-shape channel with the joist. The C-shape channel supports the live and dead loads, transfers the loads to joists, and provides the face to fix the plywood decking. Specially designed ''hydraulic lifting devices'' are developed to lower rock bolts to hang the NSTD deck forms exactly at the fixed place while maintaining roughly equal tension distribution in the rock bolts. This device consists of a hydraulic cylinder, pulleys, a stranded wire rope, casters, and two auxiliary cylinders to support the eccentricity.

NSTD Deck Form

The NSTD deck form is composed of H-beam stringers, H-beam joists, clamps for the beam, C-shape channels, and clamps for the C-shape channel, as shown in Fig. 3. Plywood decking is installed on the NSTD deck form. After the NSTD deck form is fabricated, the retaining assembly for the NSTD deck form is installed. The main retaining assembly and auxiliary assembly fix the rock bolts at the upper floor slab. The NSTD deck form is lowered slowly while the rock bolts are being strained by hydraulic lifting devices.

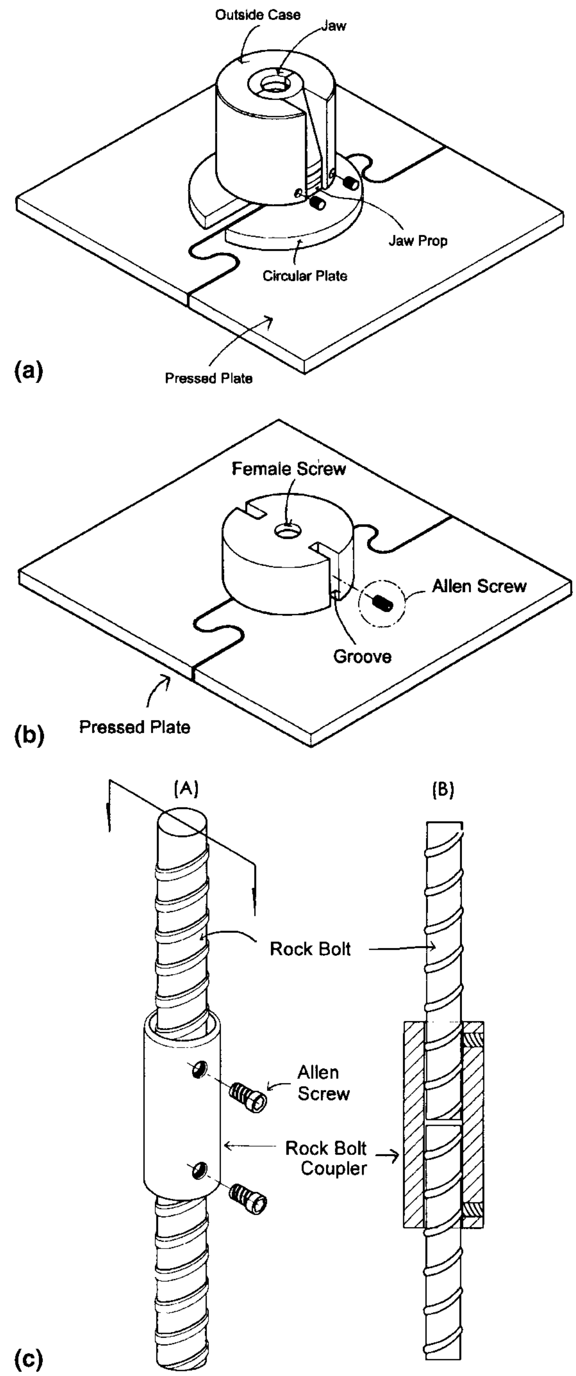

FIG. 2. Main Components: (a) Main Retaining Assembly; (b) Auxiliary Retaining Assembly; (c) Splicing of Rock Bolts

Properties and Advantages of NSTD Method

The NSTD method is developed to reduce time and cost of the substructure construction and to provide safe work conditions. The properties and advantages of this method are as follows:

1. The concrete work on the deck forms and the excavating work under the deck forms are performed simultaneously. Therefore, this method can reduce time for installing formwork, placing reinforcement, and pouring concrete.

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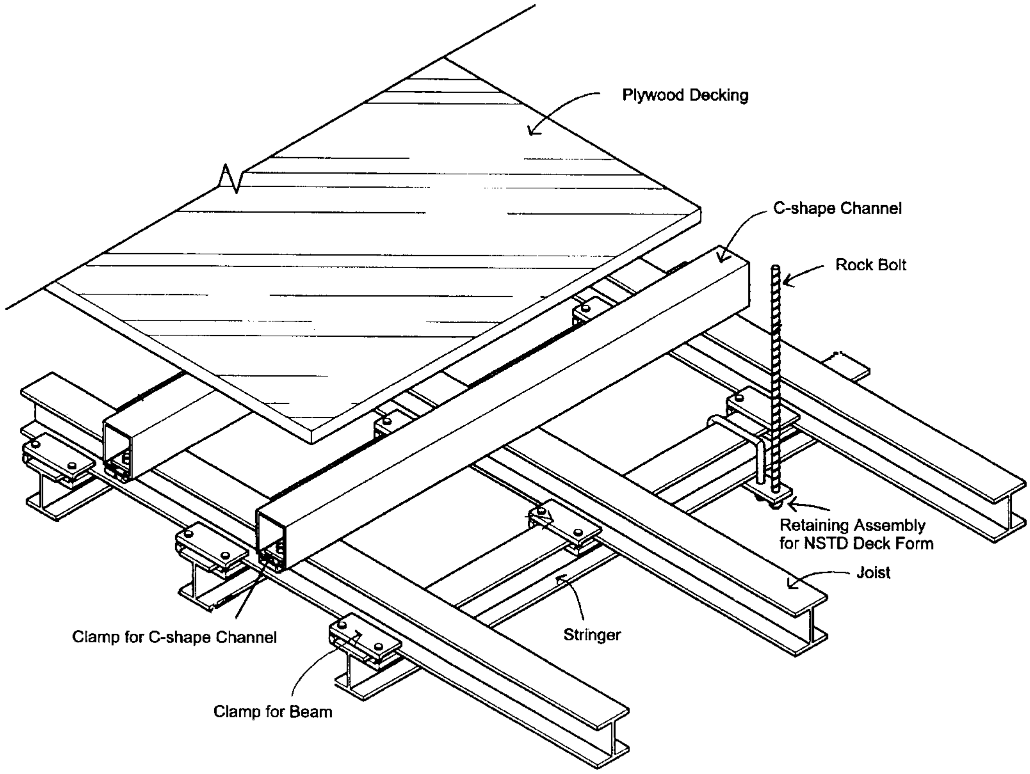

FIG. 3. NSTD Deck Form

2. The deck forms used for the ground level slab are lowered to the next lower floor. In this fashion, the forms can be used repeatedly for the slabs concrete in the basement floors.
3. There is no need to support the forms with shores or to erect/remove the forms during the work process. Thus, the construction project can be accomplished faster with less cost.
4. When the deck forms are hung, excavation for the next lower floor can proceed without any obstacles. There is no waiting time for equipment and labor for excavation. In addition, there is less need for temporary materials such as scaffolds.

Checking Structural Safety

The computer program was developed and coded using Visual C++ programming language for checking the structural safety of the NSTD deck forms. This program enables the users to compare the moment, shear, and deflection of each member of the forms with allowable values, providing the exact dimension of the forming system (decks) by inputting the design load and live load. Meanwhile, shown below are the grounds for determining whether or not the number of rock bolts suspending the NSTD deck form is appropriate. The load on the upper part of the deck forms (8×8 M as a standard) totals 83.04 tons with 12 tons of the deck forms load, 61.44 tons of freshly placed concrete (T = 400 maximum thickness as a standard), and 9.6 tons of the live load of workers, tools, and equipment (150 kg/cm^2 as a standard). The breaking strength of the rock bolts is calculated as 10 ton/EA in design, although it was proved to be 15 ton/EA from the strength test. Accordingly, it can be sustained with 9 rock bolts in calculation, but 16 rock bolts are installed to assure safety, taking into account the possible impacts to the adjacent rock bolts in case one rock bolt is broken.

Comparison with Top-Down Methods

The applicability of the NSTD method was compared with that of other top-down methods. As shown in Table 1, the NSTD method can be applied to any type of soil conditions and slab types. In addition, the NSTD method is superior to the other methods in terms of reducing excavation time, particularly in hard rock conditions. The slurry wall construction in hard rock is generally possible depending on the excavation equipment; however, it is not widely used when consideration is given in terms of the economic factor and construction time due to its slow excavation speed. Thus, in the case of hard rock, slurry walls are usually constructed up to the upper part of the soft rock (1–2 m or so is inserted into soft rock), and underpinning or counterwalls are constructed to the lower part.

Because the NSTD method gives a load on the upper slab of the floor where concrete is placed, this system is not influenced at all by the soil conditions on the lower part. That is, a large size of the excavation equipment can be put under the NSTD deck forms to shorten the excavation time as shoring is not installed. In the case of rock conditions, both rock frac-

TABLE 1. Properties of NSTD Method

Descriptions (1)	Method: Concrete-on-grade (2)	Form-on-support (3)	Go-over-next-slab (4)	NSTD (5)
Clay, till, soil	×	×	×	○
Soft rock	○	×	○	○
Hard rock	×	○	×	○
Slab type				
Flat	○	□	○	○
One-way	□	○	□	○
Slab with beam	×	○	×	○
Construction duration saving effect	Low	Very low	Medium	High

Note: Applicability (×, impossible; □, possible; ○, applicable).

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ture and soil excavation is possible, using a large size breaker. In addition, the upper part of the structure and concrete curing are not influenced by the impacts of vibration, for the case where blasting or the rock splitter method is used.

APPLICATIONS

Example Project

To illustrate and validate the NSTD method, an actual project that was built using NSTD was selected for a case study, which is an office building, located at Yeoksam-dong, Kangnam-gu in Seoul. The original construction process in this project was planned using the top-down method with diaphragm walls and underpinning techniques. Fig. 4 summarizes the principal features of this project.

Application of NSTD Method

To apply the traditional top-down method, such as form-on-support, the work area needs to be divided into four portions [zones A, B, C, and D in Fig. 5(a)] for the work process and concrete curing. The excavation of each zone then proceeds successively from zone A to zone D. Each zone consists of 615 m^2 (zone A), 704 m^2 (zone B), 650 m^2 (zone C), and 537 m^2 (zone D) in area, respectively, and requires 7–8 days of excavation work with a total of 29 working days. In addition, the excavated soil must be removed through three outlets.

However, in this project, the NSTD method was actually applied instead of the traditional method. The work area was divided into only two portions [zones A and B in Fig. 5(b)]. The excavation areas were 1.067 m^2 (zone A) with 11 working days and 1,367 m^2 (zone B) with 15 working days, and required a total of 26 working days. The project required only two outlets for the removal of the excavated soil. Therefore, the excavation time was reduced significantly (3 days) compared with the traditional method.

The excavation work for the next floor could proceed after 4 or 5 days (initial concrete curing for 4 or 5 days) with hanging-type formwork, taking a total of 15 days before form removal. With the help of the suspended deck forms, the concrete was sufficiently cured while excavation was in progress. Therefore, a time saving of about 10 days for each story was achieved with this simultaneous work schedule.

In the case of the actual project, which was comprised of

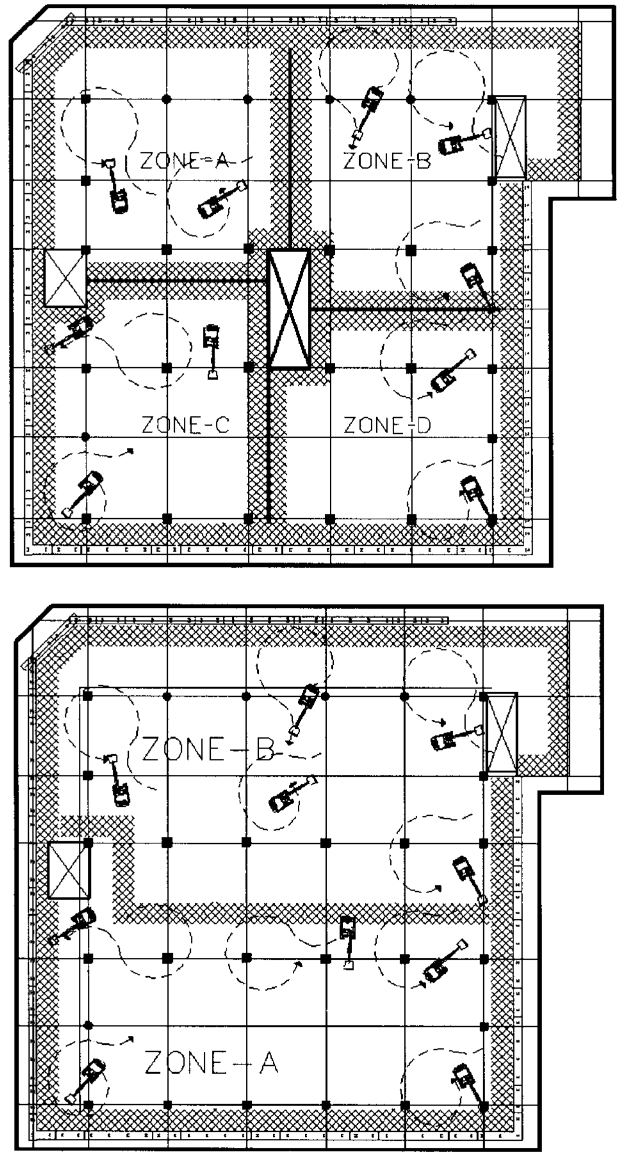

FIG. 5. Zones of Excavation: (a) Traditional Method; (b) NSTD Method

Items	Principal Features				
Project Name	○ ○ Building Project				
Address	Yeoksam-dong Kangnam-gu, Seoul, Korea				
Usage	Office, Neighbor convenience facility				
Duration	1995.12.1 – 1998.11.30 (1,095 days)				
Design Parameter	Area of Site	2,876m^2			
	Area of construction	1,818.8m^2			
	Gross enclosed floor area	48,638.66m^2			
	Typical floor	1,684m^2			
	Number of stories	20-stories (above ground), 8-stories (below ground)			
Type of Structure	SRC				
Earthwork Method	Top-down method (Slurry wall + underpinning) R.C.D Pile Teo-Grouting Rock Bolt + Shotcrete				
Condition of Strata	Type	Fill	Sand	Weathered rock	Soft rock
	Thickness (M)	0.5 ~ 4.0	2.5 ~ 5.0	1.0 ~ 4.0	2.5 ~ 6.8
Ground-water level	Testing date	1995.12		1998.4	
	Depth (M)	GL –6.2 ~ –6.3		GL –30.35 ~ –31.44	

FIG. 4. Principal Features of Example Project

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eight stories below grade, it was found that the construction time could be considerably reduced by 80 days in comparison with the traditional method.

Monitoring the NSTD Method

When applying the NSTD method to an actual project, safety control was performed as follows. The worker frequenting on the lower parts was aggressively controlled to prevent accidents by falling materials when the NSTD deck forms are lowered. Because excavation is to be carried out on the lower part and the NSTD deck forms are lowered panel by panel, safety handrails were immediately installed on each panel. In addition, safety precautions could be assured with various activities including the installation of exhaust fans, because the NSTD method is carried out with the underground excavation work at the same time.

RESULTS AND ANALYSIS

The actual NSTD method was compared with the originally planned traditional method such as form-on-support in terms of the time and cost of the excavation and underground structural work in the example project. The results and analysis are as follows.

Time

Fig. 6 shows a comparison of the results of the expected duration using the traditional method with the actual duration using the NSTD method in the excavation and the underground structural work. If the traditional method had been applied to the example project, the total duration would have been 360 days. However, the actual duration using the NSTD method was 298 days. Therefore, the difference between 360 days and 298 days, or 62 days, was saved with the NSTD method. Moreover, the traditional method such as form-on-support has many unprofitable points compared with the NSTD method. These are as follows:

1. Lean concrete is required for each floor.
2. Supplementary perimeter beams near the slurry wall are required, because of the soil pressure.
3. The excavation of the lower level cannot proceed until the entire frame is dismantled.
4. The excavation of the lower level cannot proceed until the concrete is sufficiently cured.

Cost

Table 2 shows the costs for excavation and underground structural work, when the original traditional method and the actual NSTD method are applied, respectively. The construction cost for the NSTD method was reduced by about 12.6% compared with the traditional method. However, when the effect of time saving is considered, the amount of the cost saving will be in an excess of 12.6% because of the indirect effects of financing costs.

TABLE 2. Cost Estimates: Traditional versus NSTD

Item (1)	Construction cost (2)	Cost of temporary work (3)	Job site overhead (4)	Sum (5)
Traditional method (A) (U.S.$)	1,856,841	2,019,637	2,468,882	6,345,360
NSTD method (B) (U.S.$)	1,311,500	1,905,284	2,329,092	5,545,876
Reduced cost (A and B) (U.S.$)	545,341	114,353	139,790	799,484
Reduction (%)	29.4	5.7	5.7	12.6

Note: Exchange rate is based on US$ 1 = 1,000 KRW (Korean Won).

CONCLUSIONS

In the implementation of large and complex building projects, when the excavating works are performed in parallel with the structural work above the ground, the top-down construction has been considered economical in terms of time and cost.

(a)

(b)

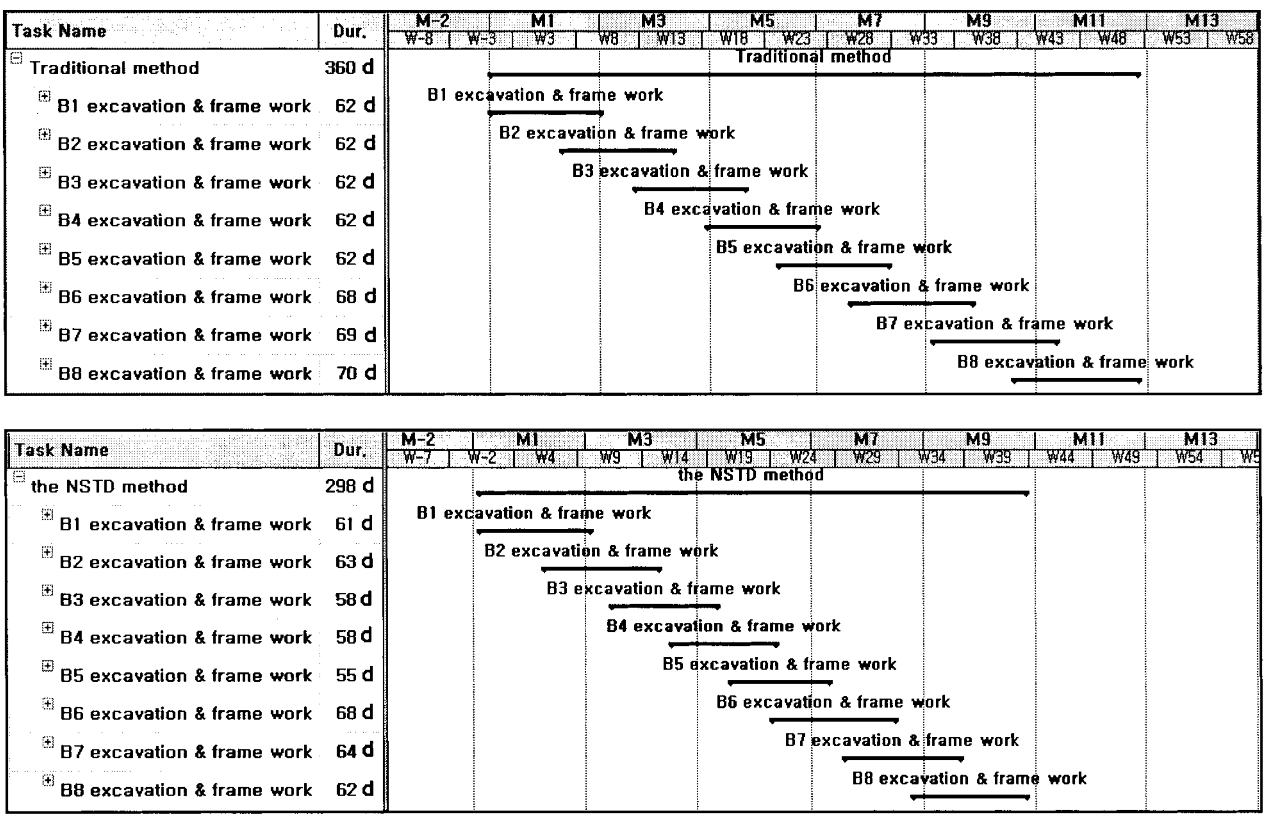

FIG. 6. Schedules; Traditional versus NSTD: (a) Schedule for Traditional Method; (b) Schedule for NSTD Method

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However, traditional top-down methods such as form-on-concrete have many problems, such as time loss and cost increase caused by time lag between concrete curing and excavation. Therefore, a systematic formwork method is required in order to improve the problems in top-down methods.

This research proposes the NSTD method as a new formwork system for the construction of structures below grade, which may resolve some of the drawbacks in traditional top-down methods. The excavation work with the NSTD method can be executed continuously without any interruption of work during concrete curing. A case study was performed to illustrate and validate the NSTD method by applying it to an actual construction project.

After assembling the NSTD deck forms on the ground surface after pouring lean concrete, concrete work on the ground level proceeds and then, using suspension materials such as rock bolts, excavation of the first basement floor can be carried out. The NSTD deck forms are lowered to the next lower floor using hydraulic lifting devices. The above process is repeated cyclically down to the lowest floor. Therefore, this method could reduce construction time and cost by carrying out continuous excavation and slab construction simultaneously.

By applying the NSTD method to an actual project, its capability and utility are verified. The result verified the application validity with the findings that the construction time was reduced by 17.2% (62 days) and the cost by 12.6% (about $800,000) in comparison with the traditional top-down method such as form-on-concrete.

ACKNOWLEDGMENTS

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