Development of Expert System–Supported Construction Planning for a Shield-Tunneling Method

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Our expert system aims at the optimum and fast plan making for shield-tunneling works. It is an expert system of applied design problems that integrates such advanced technologies as relational databases, AI, and computer-aided design (CAD). This expert system is able to design and draw a suitable shield machine with an automatic output of design calculations and also specify an optimum control range for the operation of shield-tunneling works. It is possible for a user to quickly make the construction plan for the shield-tunneling works, taking full advantage of the expertise stored in the expert system.

The shield-tunneling method is a tunneling method in which soft ground is excavated by a shield machine with a segment lining. In recent years, this method has been widely used in areas where the ground is soft, or the site is in a densely populated area.

For shield work, a shield machine and construction plan must be considered for various ground conditions, such as soft ground, gravel, sand

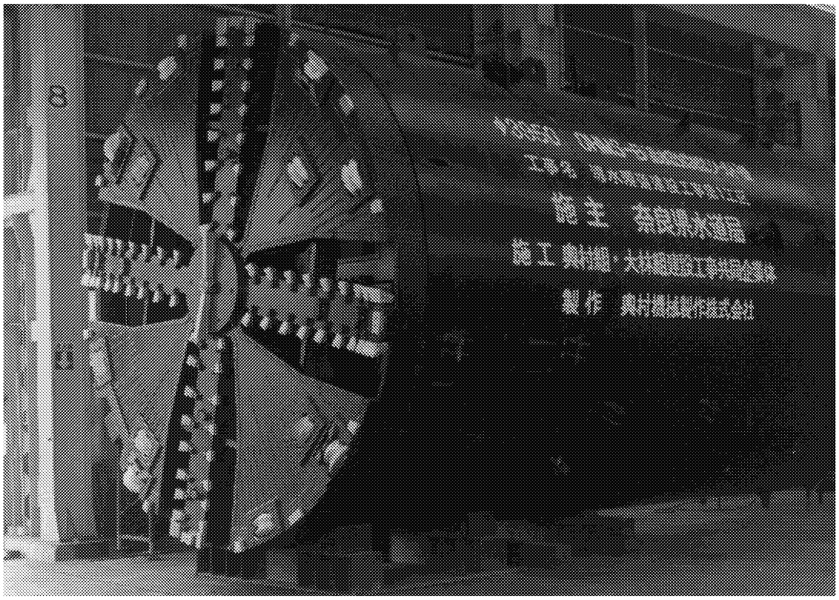


Figure 1. Photograph of Shield Machine.

layers, and so on, as well as other conditions such as high water pressure or curved alignment. In addition, the growing regulatory concern about environmental protection from ground settlement, vibration, and so on, has made it more difficult to adopt the shield-tunneling method.

Conventionally, a construction plan was jointly drawn by experts from the specialized fields, but this approach consumes a large amount of time and labor. Our expert system makes optimum specifications for the shield machine. When we only input construction conditions—such as the tunnel diameter, design alignment, and contract period as well as the condition of the ground soil, the status of the underground water, and so on—the system automatically leads to the drafting of an optimal shield machine based on its knowledge base. The system also analyzes ground settlement using the finite-element method and selects an optimal code of construction and supplementary construction methods. It then outputs design specifications and design calculations accordingly.

Background

In shield-tunneling projects, a higher level of planning is required because of the advanced construction technology. Such planning is usually done by experienced specialists. However, their know-how is individ-

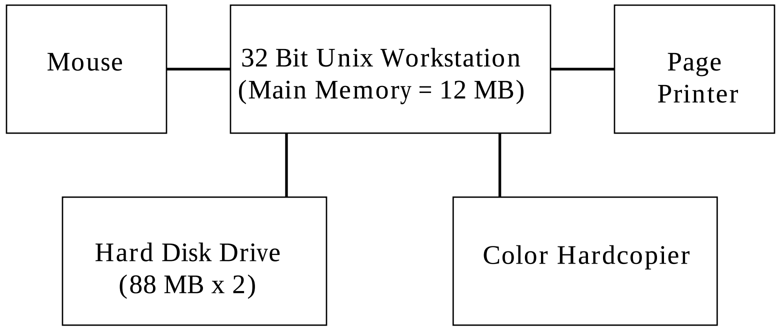


Figure 2. Hardware Component.

ual and not systematized, and planning depends on the collaboration of individuals from the civil engineering and mechanical and analytic fields. Therefore, there are always differences in opinion on the part of the specialists, resulting in much lost time.

We developed our expert system to eliminate these problems and enable planning that could be done quickly and reasonably. In other words, the objective of systematization is to bring together all the expertise and varied experiences into a knowledge base so that definitive design programs and construction methods can be realized.

Applicable Range

Our expert system applies to tunneling work using the Earth Pressure Balanced Shield, which is one of the close-face–type shield machines, as shown in figure 1, and to the design of a shield machine (outside diameter of 2000 to 6200 mm). The reason we selected this method is that it is increasingly being used. It is new and is synthesized in its code of construction.

Composition of Hardware

The expert system can be used on a 32-bit workstation (Hitachi 2050/32). The hardware is shown in figure 2. Because of the software, the main memory has to have 12 megabytes. The operating system is equivalent to Unix System V. We adopted a workstation approach because of its convenience at the site or in a branch office.

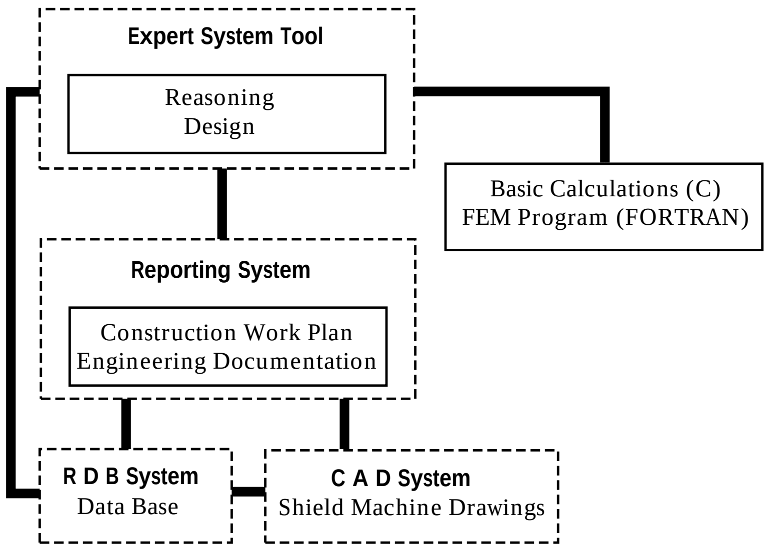
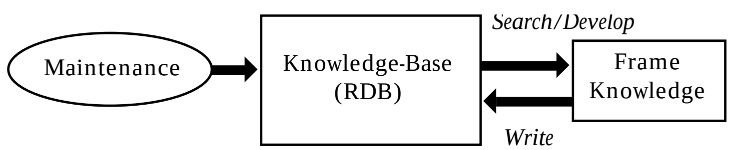


Figure 3. Software Component.



Region	Product A		Product B	
	Sales	Profit	Sales	Profit
A	1500	800	200	12
B	1300	600	400	8
C	700	240	60	2

Table name = Results

RESULTS

Super - class System

Product A: Sales (data-type int)

Profit (data-type int)

Product B: Sales (data-type int)

Profit (data-type int)

Class - Frame

Figure 4. Utilization of Relational Database.

Composition of Software

As shown in figure 3, the software combines a relational database system (Exceed2), an expert system building tool (ES/Kernel), a CAD system (Hicad), and a documentation system (Ofis/Report).

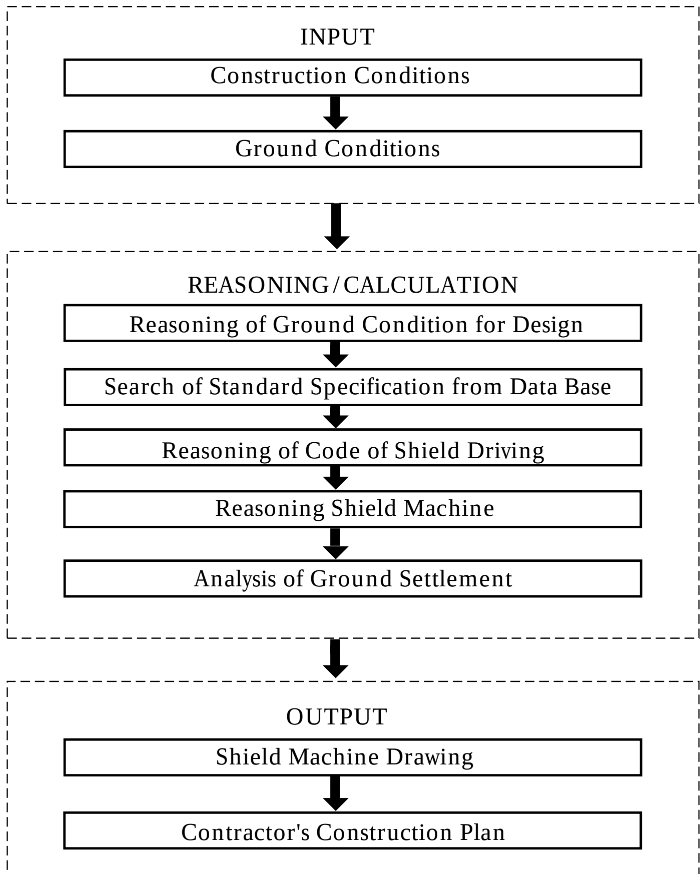


Figure 5. Process Flow.

The systems are assigned the following functions: The relational database keeps the specialist's knowledge in a graph form and develops only the knowledge required for reasoning. This function, as shown in figure 4, is dynamically executed in reasoning, reducing the reasoning time and improving storage capacity. The expert system building tool performs forward reasoning on the basis of given information and the facts extracted from the relational database. The calculating process is written in the C language. The CAD system automatically drafts the shield machine and various drawings based on the results after reasoning. The documentation system outputs the results of the reasoning as a configuration of design specifications or calculations. For complex engineering calculations, C and Fortran are used.

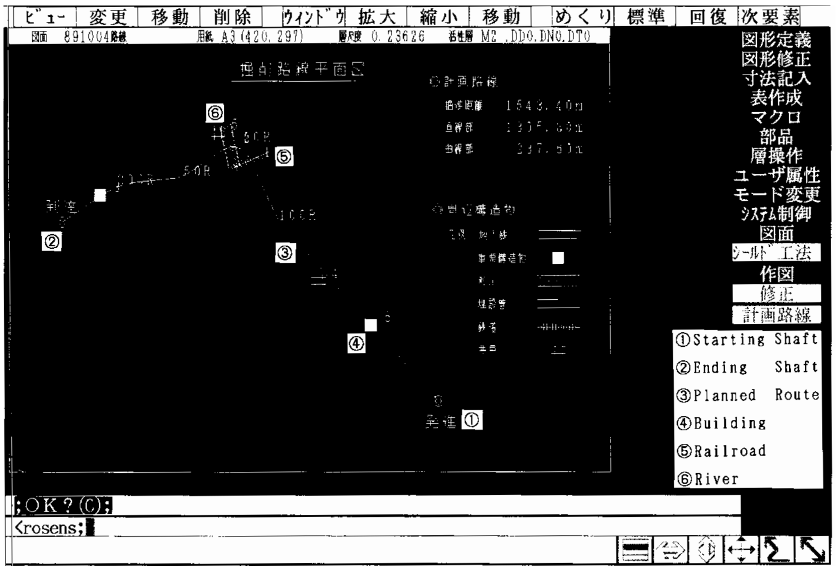


Figure 6. Drawing of Planned Tunnel Route.

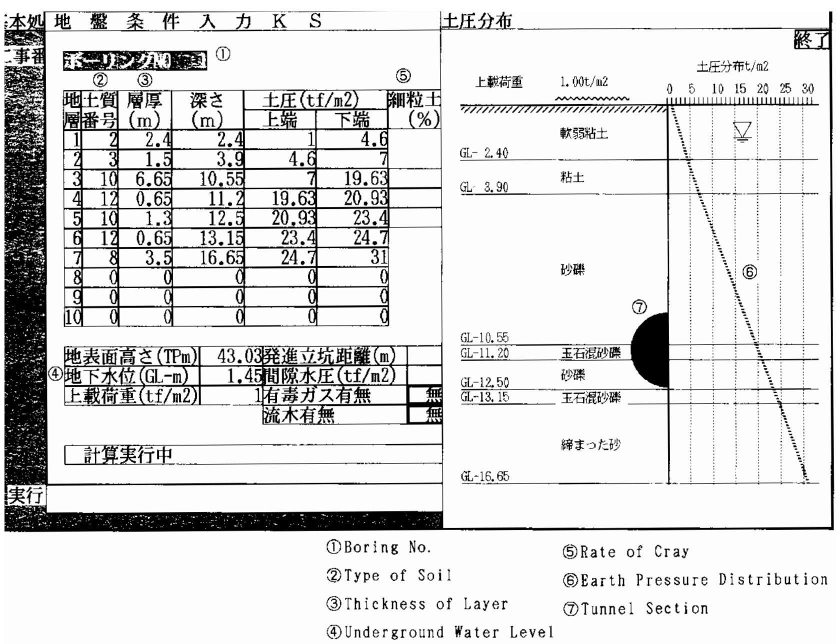


Figure 7. Input Screen for Ground Conditions.

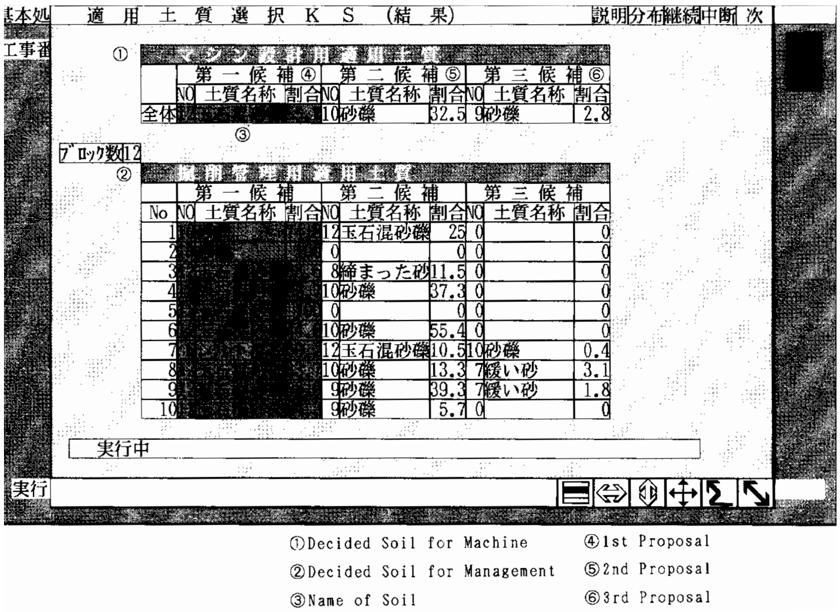


Figure 8. Decision Screen for Ground Conditions

General Aspects of the Applications

The expert system, as shown in figure 5, comprises 3 phases: input, reasoning and calculation, and output. The phases are summarized as follows.

The Input Phase

During input, data about construction and ground conditions are entered. To input construction condition data, three input screens—construction conditions, configuration of the planned route, and conditions around the planned route—are prepared.

The construction condition data include the project's name, the shield machine diameter, the period of construction, and segment types. The configuration of the planned route by distance, curve radii, and inclines from the beginning to the end of the tunnel are input. Data for the surrounding area, the location of important buildings, the existence of railroads, the condition of crossed rivers, and so on, are also input. These data are used to forecast the influence of tunneling. The CAD system can draw the surrounding area and planned route configuration from the information input and check for input mistakes as shown in figure 6.

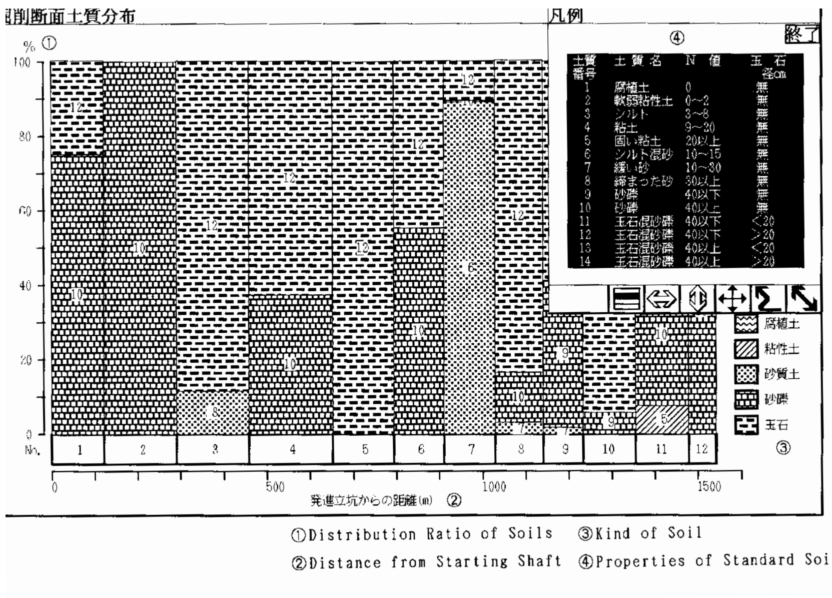


Figure 9. Distribution Chart of Ground Conditions.

For ground condition data, the composition of the ground layer, underground water levels, and loading weights based on the data compiled during the boring investigation are fed into the computer. The input condition is immediately drawn by the system to assure the layer composition and ground pressure, as shown in figure 7. This process is repeated for each boring investigation.

The Reasoning-Calculation phase

In this phase, three reasonings are executed to help make decisions about ground conditions, help design the shield machine, and determine the construction method. Also calculations for forecasting the ground settlement are performed.

During ground condition reasoning, the ground conditions are determined to aid in designing the shield machine and in managing construction. Figure 8 shows the results of reasoning for determining ground condition. The upper part of the screen shows the ground condition aspects used for shield machine design, and the lower screen shows those used for construction management. Each set of results has three proposals, ranked from first to third.

Users can change the results of reasoning with the system by using the ground condition distribution chart shown in figure 9 and with

```
{`発進部Ａ型粘性土`}                                     ・・・・・ group name of rules
(発進部A1ﾀｲﾌﾟ設定_rule_1                                 ・・・・・ name of rule
if
(発進部坑口   の   @`坑口タイプ名`     が      "A"     であり
                   @適用土質番号       が      1       以上であり
                   @適用土質番号       が      5       以下である)
then
施工管理検討中  0.1。
(send    `Ａ型粘性土`     assign(`補助工法タイプ`,`Ａ型粘性土`))
(send    `Ａ型砂質土`     delete_frame)
(send    `Ｂ型発進坑口`   delete_frame)
(send    `Ｃ型発進坑口`   delete_frame)
explain 発進部坑口の補助工法は、適用土質番号が粘性系である^
ためＡ型粘性土タイプとする
)
(A型粘性土発進坑口_rule_1                                ・・・・・ name of rule
if
(`ブロック1`  の   @土被り             を      ?x1      とし
                   @地下水位           を      ?x2      とし
                   @間隙水圧           を      ?x3      とし
                   @上載荷重           を      ?x4      とし
                   @地層数             を      ?x5      とする)
(?frame       の   @class              が      発進部坑口   であり
                   @`補助工法タイプ`   が     `Ａ型粘性土`  であり
                   @`シールド土被り`   が      0            である)
(発進部坑口   の   @`シールド外径`     を      ?x           とする)
then
(send   ?frame   assign(`シールド土被り`,?x1))
(send   ?frame   assign(地下水位,        ?x2))
(send   ?frame   assign(間隙水圧,        ?x3))
(send   ?frame   assign(上載荷重,        ?x4))
(send   ?frame   assign(地層数,          ?x5))
(send   ?frame   assign(`下端深さ`,      ?x1+real(?x*0.001)))
)

comments;
 * Rules are written in Japanese in this system.
 * Literals with @ mark are slot name in frame.
 * Literals with ? mark are variables.
```

Figure 10. Example of Production Rules.

their own experience. With these changes, various ground conditions are easily examined.

To look up standard specifications, various shield machine designs and construction management possibilities based on a determination of the ground condition and input conditions are automatically looked at within the database and are converted to frame knowledge by the system. During construction management reasoning, an examination is automatically done of management items for the tunneling shown in table 1. During reasoning for shield machine design, examinations are automatically done on items shown in table 2, and the compositions of the cutter head and the main body of the shield machine are automatically designed. Figure 10 shows an example of the knowledge (production rule) used during reasoning.

During the calculation of ground settlement, it is possible to do a detailed analysis using the finite-element method at the location where

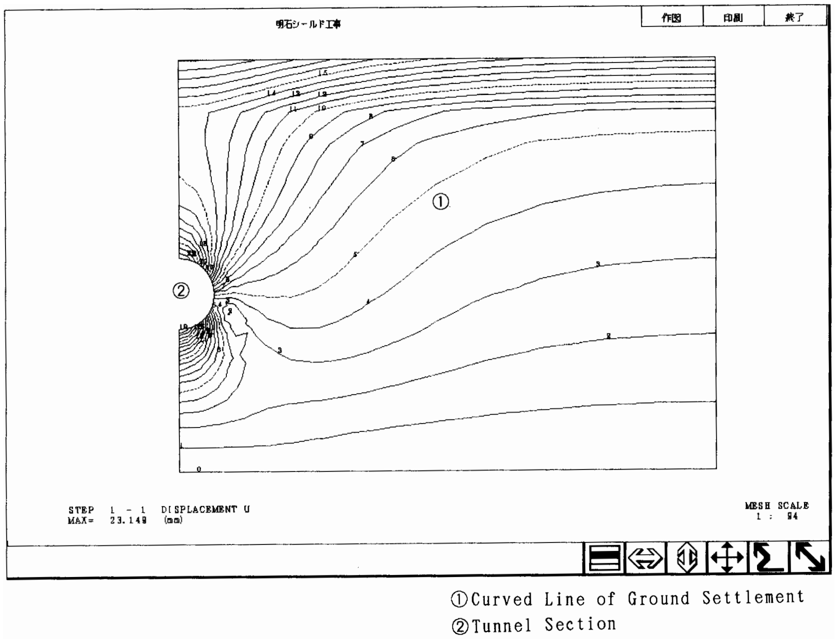


Figure 11. Displacement of Ground Layers.

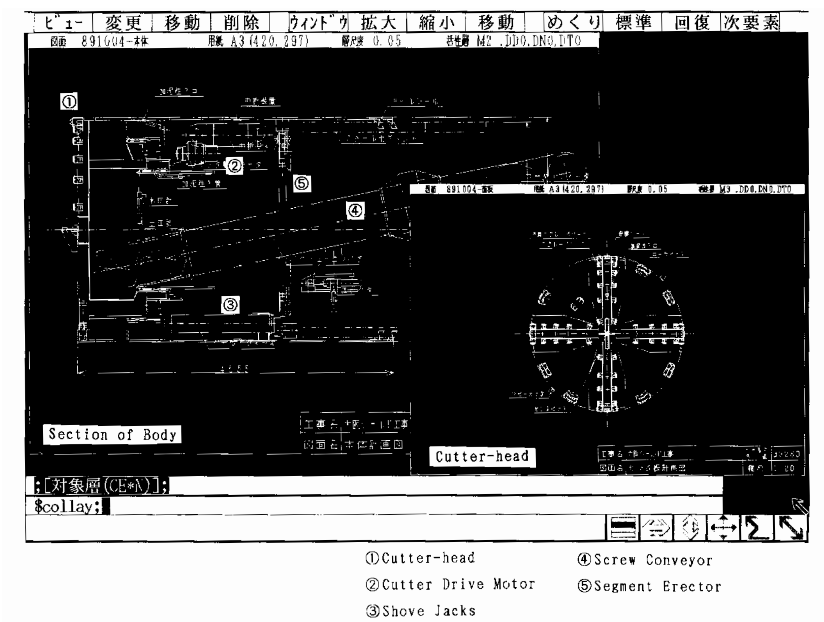


Figure 12. Drawing of Shield Machine Structures.

Items	Remarks
Mud Injection	Material, Volume, Grouting Method
Earth Pressure at Excavation Chamber	Control Code
Backfill Grouting	Material, Volume, Pressure
Schedule of Tunnel Driving	Required Schedule for Shield Driving
Supplementary Construction Method for Shaft	Method, Scale, Volume
Ground Settlement	Analyzing Settlement
Ground Water	Assessment for Environm ent

Table 1. Control Items for Tunneling.

Items	Remarks
Excavation	Cutter Head, Cutter Teeth, Cutter Drive Motor, Mud Injection pipeline
Mucking System	Screw Conveyor, Rotary Feeder, Belt Conveyor
Thrust Force	Shove Jacks
Water Tightness	Cutter Head, Bulk Head, Tail Seal
Curve Alignment	Over Cutter, Shove Jacks, Articulate Shield Body
Segment Lining	Segment Erector, Segment Adjuster

Table 2. Design Items for Shield Machine.

there is a high possibility of ground settlement after the construction management reasoning. These input data for the analysis are automatically created by the system based on the ground condition data. Figure 11 shows the contour chart of ground settlement.

The Output Phase

The drawing of the shield machine is automatically done by the CAD system. Three drawings are made: the cutter head, the main body, and the support equipment. These drawings are made to the correct dimensions, and it is possible to manually modify them with the CAD system. Figure 12 contains examples of cutter head and main body drawings.

When making the construction planning sheet, it is possible to output the final plan, including various specification forms and calculation forms, as shown in figure 13. Also during this phase, information can be output, for example, about what procedures were taken under what conditions that could affect the reasoning of the system. This capability makes it possible to easily evaluate the propriety of the reasoning results.

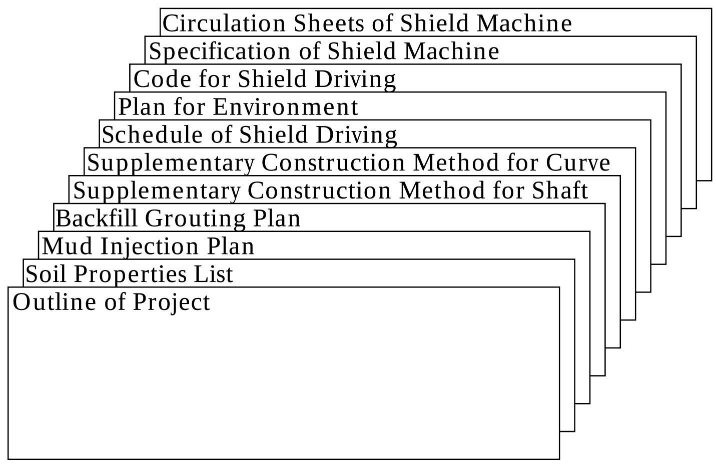


Figure 13. Output Lists for Construction Plans.

Scale of the System

The number of rules, frames, and program steps needed for the expert system is generally as it is in table 3.

Personnel and Term of Development

Three knowledge engineers, 4 system engineers, and 3 to 4 specialists were charged in developing the expert system. The time required for the development of the prototype was about 18 months and for transition to a practical system about 6 months. Total time was about 60 person-months.

The costs incurred were about 14 million yen (US$100,000) for hardware and software and about 48 million yen (US$343,000) for personnel expense. The expert system was jointly developed by Okumura Corporation and Hitachi Ltd.

Use and Effect of the System

This system is used when construction technicians at design divisions or construction sites have shield-tunnel construction operations to present to government offices or construction consultants.

Construction technicians only have to input the basic construction and ground conditions to have the system return a detailed construction planning sheet. It is possible that work that was previously done by a number of experienced special technicians can be done by one not so experienced construction technician.

This system offers judgment data for users at points of important rea-

Items	Number of Data
Database Items	15,000
Kind of Frames	100
Number of Rules	850
Calculating Program Steps	5,000
Drawing Program Steps	5,000
Parts of Shield Machine	250
Commands	A Large Number

Table 3. Scale of System.

soning, steps such as determining ground condition and the basic specifications of the shield machine, and also asks users for their judgment. The system continues reasoning based on these judgments, so that the user's thoughts are reflected in the reasoning. Thus, this system becomes more human in character.

Also, this system lets technicians other than specialists easily calculate and judge ground settlement, which previously was only done by analytic specialists; so, savings in personnel are also large. Moreover, the automatic drawing of shield machines and the documentation functions for completing specifications and calculation forms lightens the simple workload of the technician in charge and results in higher-quality data for the customers.

This system has been used for actual construction plans since October 1989 and has executed 13 construction plans. It is difficult to evaluate the payoff in using this system, but it has received the following comments from the technicians who used it: (1) Standardized construction planning became possible (fewer plans were made by various people). (2) Construction planning could be quickly done (work that used to take at least one week now takes a couple of days). (3) It is now easy to make alternative construction plans. (4) Detailed examinations can be done by non-experts. (5) Even a technician with little experience can make detailed construction plans. (6) The appeal of the system to customers has increased.

Postscript

The expert system supporting a shield-tunneling plan was developed based on an experience of shield tunneling that exceeded 250 km. We are confident that it can help in such plans. In the future, we intend to expand the functions to include cost estimation and the planning of shaft construction, plant facilities, and secondary lining. The knowledge base will also be made applicable to a wider range of sites.