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STUDY ON PRACTICAL EXPERT SYSTEM FOR SELECTING THE TYPES OF RIVER-CROSSING BRIDGES

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This paper describes an expert system for selecting the types of superstructures and substructures of river-crossing bridges, and deals with the knowledge of expert designers and rules of Japanese codes as the knowledge base. This expert system can automatically determine span arrangements satisfying the River-Crossing Structure Law, and uses the fuzzy set theory for pile type selection to express the ambiguous knowledge of expert designers. Moreover, in this system, the online data communication system between workstation and host computer is utilized for more accurate evaluation of substructure construction costs.
Keywords : expert system, fuzzy sets, data communication, bridge type selection

1. INTRODUCTION

Selecting the proper types of superstructures and substructures of bridge holds a very important position in the series of processes from design to erection. Unless a designer has many years of experience and a wealth of knowledge, it is not easy for the designer to select an adequate type. If the designer can use the integrated knowledge of expert designers, he will be able to obtain various advantages. Therefore, the authors have developed a practical system for selecting bridge types as an application of the expert system[1].

To develop a fully efficient expert system, the authors have utilized a workstation (Nihon UNISYS KS-303) for the exclusive use of LISP programming language. Also, an expert shell (Intelli Corp. KEE)[2] has been applied in order to easily establish the knowledge base in this system.

Design conditions for the superstructure and substructure vary significantly depending on the location of a constructed bridge, for example, in a mountainous area or urban region, across a river, etc. It seems that a type selection system applicable to all construction locations becomes bulky and difficult to develop. The authors, therefore, have limited the scope of this system to river-crossing bridges.

Some expert systems[3)~6)] with the same aim as this system have already been presented, and obtained useful results. Paying attention to the methods for span arrangement in Ref. 3) ~5), related data is directly input by designers. A designer can easily determine a span arrangement when river width is narrow. However, the designer takes a long time to determine a span arrangement satisfying the River-Crossing Structure Law[7] when river width is broad. On the other hand, in the method in Ref. 6),

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span arrangement can be automatically determined, but can not be completely satisfied with the law.

Pile type selection apparently influences the economy of substructure, but involves many ambiguous elements. There are two methods to express ambiguous knowledge : the Certainty Factor (CF) and the fuzzy set theory. Shiraishi *et al.*[5] and Mikami *et al.*[8] used CF, and obtained useful results. However, Shiraishi *et al.* pointed out the necessity of using fuzzy sets because the final CF value obtained by combining individual CF values might differ from the actual degree of certainty. On the other hand, Iwamatsu *et al.*[3], Leelawat *et al.*[4] and Kawakami *et al.*[9] used fuzzy sets. However, they pointed out that practical membership functions of these fuzzy sets should be concretely expressed, taking into consideration the practical experience of expert designers.

In the systems of Ref. 3) and 6), construction costs of substructure can be calculated by using some charts of design manual. However, when calculating pile construction costs, it is possible to make serious errors by disregarding of complicated soil conditions. This is because pile construction costs are easily calculated by using the charts in the Steel Bridge Design Planning Manual[10], but this manual does not consider the effects of the number of piles and pile type.

To solve the above problems, the authors have developed a system that involves original methods. This paper first outlines this system. Then, the methods of automatically determining span arrangements, pile type selection by using fuzzy sets, and evaluating pile construction costs by using an online data communication system will be proposed in order. Finally, by using an application example and its considerations, the feasibility of this system will be discussed.

The authors believe that this system can applicable to foreign specifications by replacing Japanese specifications with others.

2. OUTLINE OF THIS SYSTEM

(1) Process flow

Fig. 1 shows the type selection procedure of this system. In this figure, the number of production rules used in this system are also shown.

Superstructure types (span arrangement and bridge type) are selected first. Span arrangements are automatically determined to satisfy the River-Crossing Structure Law. Applicable bridge types are assigned to these span arrangements by using manuals[10),11)]. **Fig. 2** shows the bridge types used in this system. Combinations of bridge type are decreased by structural restrictions and heuristic rules of expert designers. The construction costs are calculated by using the charts in design manuals[10)~12)].

Substructure types (abutment, pier and foundation) are selected based on the results of superstructure type selection (height, reaction force and support condition). Pile type is selected by using fuzzy sets. The construction costs are calculated not only by using the charts in the Steel Bridge Design Planning Manual[10], but also by online data communication between the workstation and a host computer (Nihon UNISYS series 2200).

Then, the total construction cost of the bridge can be obtained by summing up the construction costs of the superstructure and substructure. All cases are ranked according to total construction cost.

(2) Feature of use

It seems that production rules in this system use more than 90 % of the expert designers' knowledge, but not 100 %. This is because of the difficulty in making all rules that can perfectly express their knowledge.

All span arrangements and bridge type selections are displayed. A designer can remove undesirable span arrangements according to his own judgement. If the designer is not satisfied with any of the span arrangements or bridge type selections proposed, a routine will allow the designer to enter his desired span arrangement and bridge type. This work will eventually reduce total calculation time. Therefore, basic knowledge about bridges is regulated for the designer to interact with this system.

Generally, in the expert system, the maintenance of a knowledge base that unfortunately keeps on

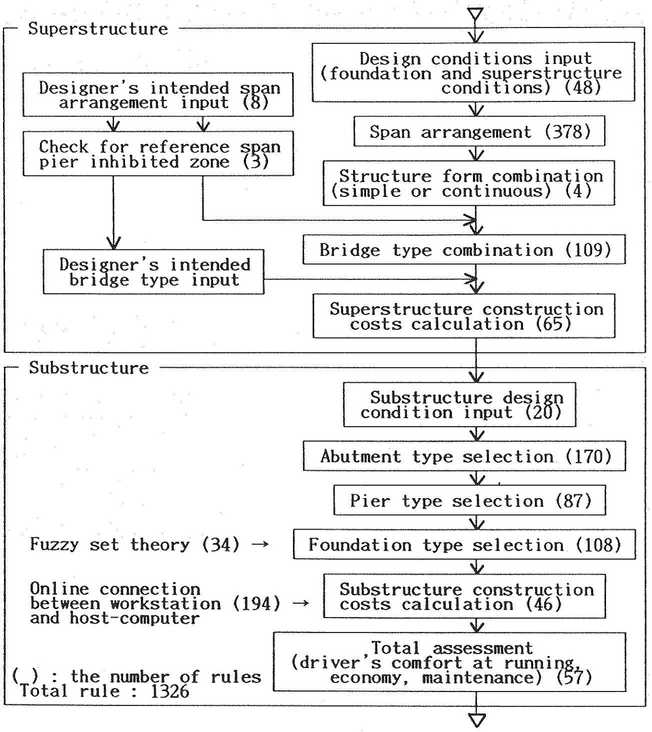

Fig. 1 Flow-chart of type selection procedure.

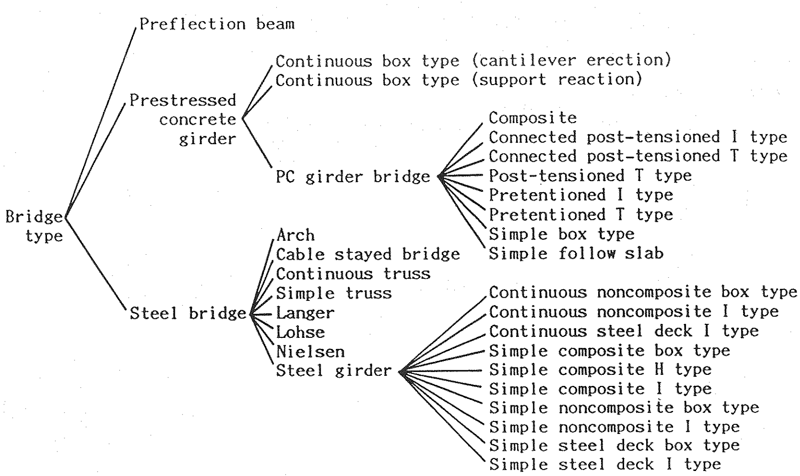

Fig. 2 Bridge types used in this system.

changing is the most important theme. Therefore, in this system, much consideration has been given to maintenance. For example, a designer can easily input the latest data on construction costs.

3. AUTOMATIC SPAN ARRANGEMENT

After entering the data (i. e., topography, river discharge, overall bridge width, and bridge length) for selecting the type of superstructure, the following regulations of the River-Crossing Structure Law must be considered.

① Reference span length (Minimum span length is decided to prevent any disturbance to river flow due to flooding).

② Pier-inhibited zone (The zone is prepared to protect the pier from anomalous scour).

③ 5 m relaxation regulation (This is to relieve the condition of span lengt being much longer than the reference span length).

④ Exception to high river bed (This is to shorten the reference span length on a high river bed to reduce the girder height of the side span).

⑤ Small or medium river width (This is to shorten the reference span length for small river discharge).

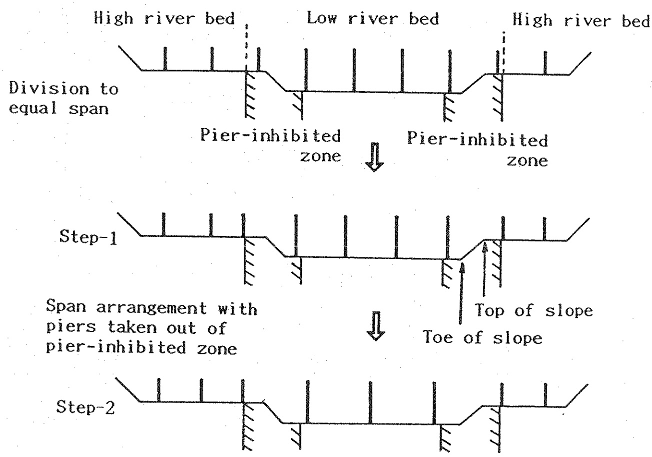

Fig. 3 An example of taking piers out of pier-inhibited zone.

⑥ Hindrance to cross-sectional area of river (The width of pier is decided to prevent any disturbance to river flow due to flooding).

⑦ Exception to neighboring bridge (The location of pier is decided to prevent the disorder of flow line due to flooding).

Now, these regulations are applied for determining the span arrangement, and are used in the form of production rules in this system.

When the total bridge length is divided by the reference span length (minimum span length), the maximum number of divisions (N) is obtained. For example, if the total bridge length is 300 m and the reference span length is 35 m, N is 8 and the equal span length is 37.5 m.

In this system, span arrangement is done based on the number of divisions that induce N, $N-1$, $N-2$, of course, equal span length from $N-3$ to 1 are clearly longer than the reference span length, but these lengths are generally too long for river-crossing bridges and not economical.

```
;;;
;;; Check routine for the length of left high river bed
;;; longer than reference span length
;;;
(defun koul-kijyun-check (a b)
  (koul-kijyun)
  (if (and (= sw1 1)(= koul 1)(< (+ lenl 0.005) skijyun-1))(setf sw1 2))
  (if (and (= sw1 1)(> koul 1)(< (+ lenl 0.005) skijyun-1))
      (prog nil (setf koul (- koul 1))
            (kou-tei-keikanchou (- a (first nn)) koul (- b a) tei
                                (- (first (last nn)) b) kour) (koul-kijyun))))
;;;
;;; a : The coordinates for the outside boundary of left pier inhibited-zone
;;; b : The coordinates for the outside boundary of right pier inhibited-zone
;;; koul : The number of span on left high river bed
;;; tei  : The number of span on low river bed
;;; kour : The number of span on right high river bed
;;; lenl : The length of left high river bed
;;; skijyun-l : Reference span length
;;; nn : The coordinates for abutments and piers when dividing into equal span length
;;; kou-tei-keikanchou : The function to get the coordinates
;;;                      for abutments and piers after moving piers

;;;
;;; Subroutine for koul-kijyun-check
;;;
(defun koul-kijyun ()
  (if (< (+ lenl 0.005) skijyun-l)
      (sent sw1 (incf sw1)))
  (if (>= sw1 2)(setf sw1 2)))
```

Fig. 4 The production rules for Fig. 3.

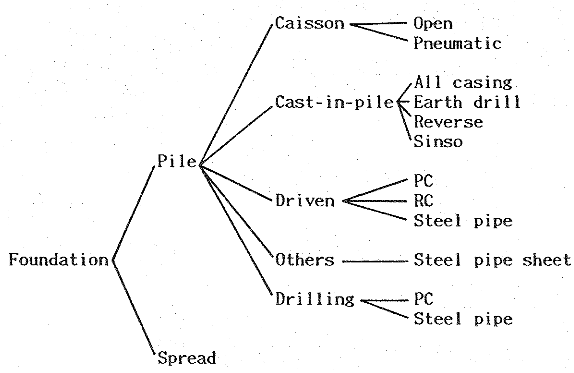

Fig. 5 Foundation types used in this system.

Table 1 Representative items and their categories about the foundation type selection table.

Item	Category
Foundation work depth (m)	2 ~ 5 5 ~ 15 15 ~ 25 25 ~ 40 40 ~ 50 50 ~ 60
Gravel diameter (cm)	~ 5 5 ~ 10 10 ~ 50
Vertical load (span length) (m)	~ 20 20 ~ 50 50 ~

If division into equal spans causes some piers to fall into the pier-inhibited zone, these piers are taken out of the zone and this may render unequal span lengths. This system provides, through the experience of the expert designer, 20 kinds of rules that completely satisty the River-Crossing Structure Law to take piers out at the boundary of the pier-inhibited zone. Fig. 3 shows an example of taking some piers out of the pier-inhibited zone, and Fig. 4 shows sone the production rules regarding the example in Fig. 3.

4. PILE TYPE SELECTION BY FUZZY SETS

Fig. 5 shows the foundation types used in this system. A pile type is usually selected by an expert designer by referring to the chart for selecting types of foundation in the Specifications for Highway Bridges[13]. Table 1 lists representative items and their categories in the specifications. However, the results of soil tests are only average values of foundation work sites, and these values are ambiguous.

These differences may greatly affect the total construction cost. Therefore, the authors have used fuzzy sets[14] for pile type selection to express the ambiguous knowledge of the expert designer.

(1) Selection possibilities regarding foundation work depth

First, the method of pile type selection by using fuzzy sets is described here by using foundation work depth as an example.

a) Fuzzy representation of selection factors

Fuzzy set A in universe of discourse (X), is defined by membership function μ_A as follows:

$$\mu_A : X \rightarrow [0,1] \quad \cdots\cdots (1)$$

Foundation work depth is classified into six categories according to the chart for selecting types of foundation in the Specifications for Highway Bridges as follows: "very shallow (2 to 5 m)", "shallow (5 to 15 m)", "intermediate shallow (15 to 25 m)", "ordinary (25 to 40 m)", "deep (40 to 50 m)", and "very deep (50 to 60 m)".

To use the example of "deep", the applicability of "deep" is abruptly zero when the depth is less than 40 m or more than 50 m in the chart. These definitions do not exactly express the idea of the expert designer. "Foundation work depth is deep" can be represented with a fuzzy set as expressed by Eq. (2) or Fig. 6.

$$A=\sum_{i=1}^{n} \mu_A(X_i)/X_i=0/0+0/1+\cdots+0/36+0.2/37+0.35/38+0.5/39+0.66/40+0.85/41+1.0/42$$
$$+\cdots+1.0/48+0.8/49+0.64/50+0.5/51+0.34/52+0.15/53+0/54+\cdots+0/70 \quad \cdots\cdots (2)$$

where the term to the right of '/' denotes elements of the universe of discourse that correspond to a set of foundation work depth (m), and '+' denotes 'or'. Eq. (2) or Fig. 6 can almost express the idea of the expert designer. Fig. 7 shows the membership functions of other categories regarding the foundation work depth. These functions are based on the experience and knowledge of the expert designer.

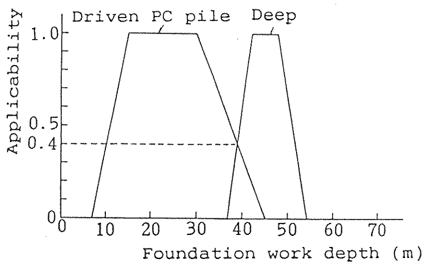

Fig. 6 Selection possibility of driven PC pile type when "foundation work depth is deep".

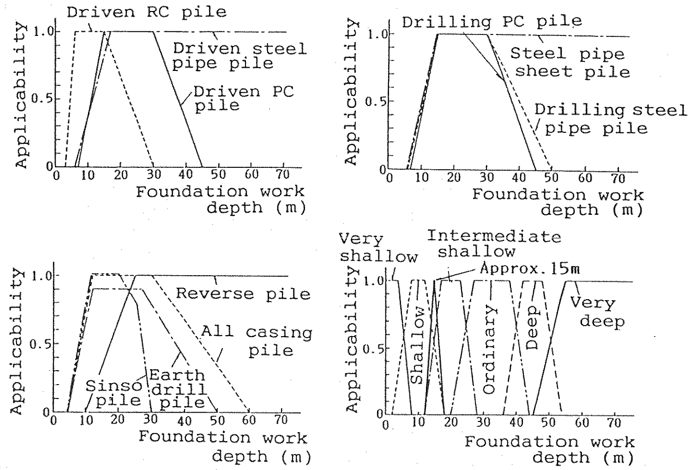

Fig. 7 Membership function of foundation work depth.

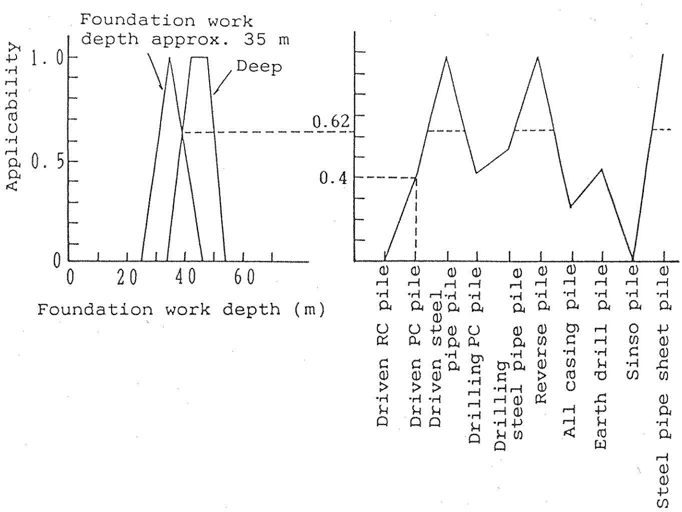

Fig. 8 Selection possibilities of pile types when "foundation work depth is approx. 35 m".

b) Fuzzy relation between selection factor and pile type

The selection possibility of each pile type with respect to the fact that "foundation work depth is deep" must be represented with fuzzy sets. However, the expression of this fact is very ambiguous, and it is difficult to directly obtain the selection possibility of each pile type with respect to this fact. The authors, therefore, adopted the following procedure :

For foundation depth (X) and a set of piles (Y), the fuzzy relation R between X and Y is also a fuzzy set expressed by Eq. (3). The membership function of the fuzzy set is expressed by Eq. (4).

$$R = X \times Y = \{(X_i, Y_i) \mid X_i \in X,\ Y_i \in Y\} \quad (3)$$

$$\mu_R : X \times Y \rightarrow [0, 1] \quad (4)$$

where "$\times$" denotes the cartesian product.

The fuzzy relation R is combined with fuzzy set A to obtain the applicability of each pile type. This is expressed as follows :

$$B = A \circ R \quad (5)$$

where '$\circ$' denotes composition. The membership function of fuzzy set B (made up of A and R) is defined as follows :

$\mu_B(Y_i) = \vee\{\mu_A(X_i) \wedge \mu_R(X_i, Y_i)\}$ ………………………… (6)

where "$\vee$" denotes maximum and "$\wedge$" denotes minimum.

According to Fig. 6, the applicability of driven PC pile is 0.4. In the same way, the selection possibility of each pile type can be obtained as shown in Fig. 8.

c) Fuzzy inference

When the selection possibility about specific selection factors has been obtained, fuzzy inference is made to obtain the selection possibility of each pile type for optional selection factors. For example, it is represented by

Proposition $A \Rightarrow B$	Selection possibility (B) with respect to "foundation work depth is deep" (A)
Observation A'	Foundation work depth is approximately 35 m
Conclusion B'	Selection possibility with respect to "foundation work depth is approximately 35 m" ?

The above relation is expressed as follows:

$B' = A' \circ (A \Rightarrow B)$ ………………………… (7)

Fuzzy inference is usually applied Zadeh's method or Mamdani's method[14]. In this system, the latter is applied. The following conversion formula of Mamdani's method[14] is used.

$A \Rightarrow B = A \wedge B$ ………………………… (8)

Fig. 8 shows the selection possibility of each pile type when the "foundation work depth is approximately 35 m" on the condition that the "foundation work depth is deep". Namely, the selection possibility of each pile type is less than 0.62. In this figure, it means that the information of "foundation depth is approximately 35 m" is more clear than that of "foundation work depth is deep". Moreover, the membership function of "foundation work depth is 35 m" becomes a straight line due to unambiguity, and it corresponds to the expression that fuzzy sets need not to be used.

In the same way, other selection possibilities are obtained for the "very shallow", "shallow", "intermediate shallow", "ordinary" and "very deep" categories. The final selection possibility of each pile type with respect to "foundation work depth is approximately 35 m" is taken as the highest selection possibility all six categories.

(2) Other selection items and averaging selection possibility

Figs. 9～12 show the membership functions of other items. These functions have been similarly obtaine based on the experience and knowledge of the expert designer. However, contradictory results were sometimes obtained by inferring these functions at first, although the functions appeared appropriate. Because the expert designer never arranges his own experience and knowledge, the authors and the expert designer arranged these functions as agreeing with reality.

Selection possibilities regarding other items (i. e., N-value, gravel diameter) are also obtained by similar treatment as for the foundation work depth. Finally, the best type of pile is selected with the highest score among the averaging selection possibilities of each pile type for all items.

(3) Trial calculation for confirming of usefulness

To confirm the usefulness of fuzzy sets, both the results of pile type selection by using the chart and membership

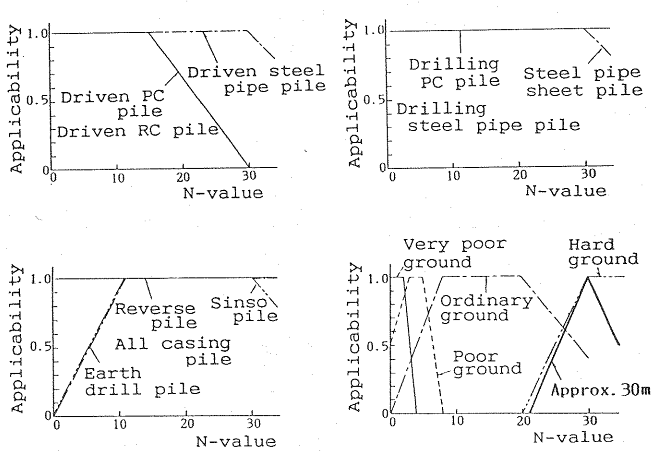

Fig. 9 Membership function of N-value.

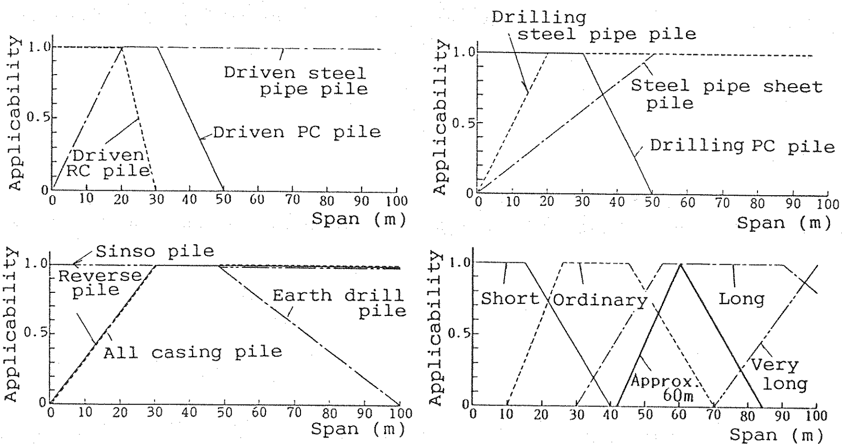

Fig. 10 Membership function of Span length.

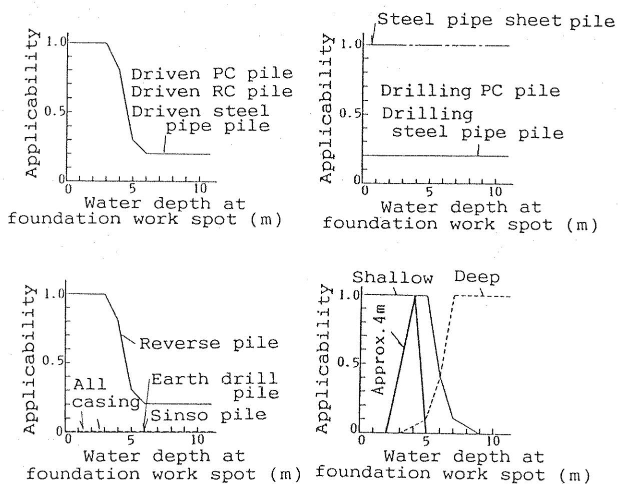

Fig. 11 Membership function of water depth.

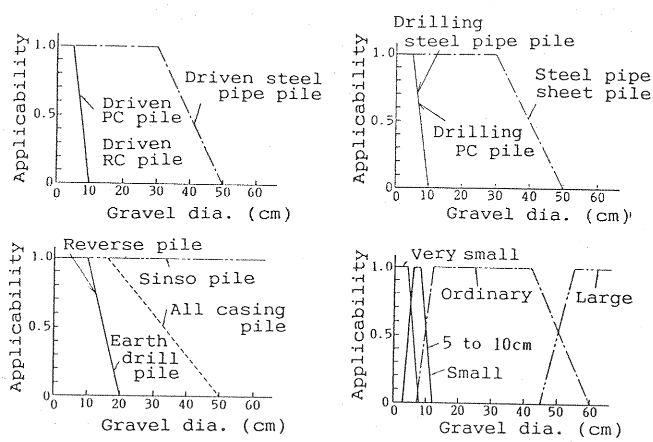

Fig. 12 Membership function of gravel diameter.

functions are derived and compared as listed in Table 2. It can be said from the results of this table that pile type selection by only using the chart is difficult and may be contradictory. On the other hand, fuzzy sets are not contradictory. A designer can easily trace the results of selection by using fuzzy sets because

Table 2 Differences between fuzzy sets and the chart for selecting types of foundation in the Specifications for Highway Bridges.

Pile type \ Result	Fuzzy sets	Table (Upper side)	Table (Low side)
Driven steel pile	1.000	1.000	0.905
Reverse	1.000	0.823	0.829
Driven PC	0.905	0.823	0.905
Driven RC	0.863	0.705	1.000
Sinso	0.767	0.705	0.625
All casing	0.767	0.941	0.835
Earth drill	0.709	0.530	0.470

Geological and foundation work conditions at fuzzy sets and the chart

o Hardness of intermediate layer	Slightly poor ground
o Stage of gravel	Approx. 10cm
o Vertical load (span length)	Approx. 50m
o Foundation work depth	Approx. 15m
o Water depth at foundation work	Approx. 5m

When stage of gravel is about 10 cm
State
5 ~ 10 cm → Low side
10 ~ 50 cm → Upper side

◎, ○, △, and × in the chart for selecting types of foundation in the Specifications for Highway Bridges is scored below.

◎ Actual results : Many → 5
○ 〃 : Usual → 3
△ 〃 : Few → 1
× 〃 : Almost none → 0

the operation is very simple.

5. EVALUATION BY USING HOST COMPUTER

After selecting the types of abutment, pier and foundation, the substructure construction costs are calculated according to the charts in the Steel Bridge Design Planning Manual.

In this system, the charts are online data communication between the workstation and the host computer are utilized to calculate the construction costs. In other words, the pile construction costs are calculated based on the results of structural analysis by the host computer.

Table 3 Pile diameters used in calculation by host computer.

Pile type	Diameter(mm)
Driven RC Driven PC Driven steel pipe Drilling PC Drilling steel pipe	600,800
Reverse All casing Earth drill Sinso	1000 1200 1500

Based on the result of pile type selection with fuzzy sets, the three pile types with rather high scores are selected. The diameters of these pile types are then assigned as listed in Table 3. Footing dimensions for abutments and piers, and the required number of piles are calculated for each combination of pile type and diameter by using a structural analysis program which runs on the host computer to determine abutment and pier stability. The exact excavation and cofferdam costs, therefore, can also be calculated.

The input data for structural analysis is automatically created at the workstation and is sent to the host computer. Then, the results obtained from the host computer are sent to the workstation where the pile construction costs are calculated by multiplying pile unit construction cost by the number of piles and pile length for rach combination of pile type and pile diameter. Finally, the most economical pile type and diameter are selected.

6. APPLICATION EXAMPLE AND ITS CONSIDERATIONS

Fig. 13 shows input data that are the same design conditions as in the actual design plan. The results of selection obtained from the usual design process and those obtained from this system are compared in order to verify the accuracy of this expert system.

(1) Span arrangement and combination of bridge types

The results for span arrangement (10 combinations in total) obtained from this system are approximately the same as those of the actual design plan. The inappreciable difference in the example of results shown in Fig. 13 is due to the following : when a pier is taken out of the pier-inhibited zone in the usual design

Input data

BASIC DATA	SUPERSTRUCTURE DATA	SUBSTRUCTURE DATA
Bridge length(m) : 307 River width(m) : 300 Skew angle(deg) : 80 Overall bridge width(m) : 10.75 Planned high water level(m) : 2 Hindrance to river improvement : No River discharge(m^3/s) : 4350 Storm tide area : No Backwater area : No	Effective bridge width(m) : 9.75 Restruction on girder height : Not considered Steel composite girder : Not used	Horizontal seismic coefficient : 0.2 N-value of high river bed(left) : approx.30 N-value of low river bed : approx.30 N-value of high river bed(right) : approx.30 Stage of gravel(mm) : from 5 to 10 Water depth at foundation work depth(m) : approx.4 Foundation work depth(m) : approx.15 Vertical load (span length(m)) : approx.60 ....

An example of results

① Selection from the usual design process

Number of span	2	3	2
Span length(m)	2 @ 30.6 = 61.2	3 @ 60 = 180	2 @ 32.9 = 65.8
Bridge type	Continuous noncomposite steel I-girder	Continuous noncomposite steel box-girder	Continuous noncomposite steel I-girder

② Selection from this system

Number of span	2	3	2
Span length(m)	2 @ 30.4 = 60.8	3 @ 60.333 = 181	2 @ 32.6 = 65.2
Bridge type	Continuous noncomposite steel I-girder	Continuous noncomposite steel box-girder	Continuous noncomposite steel I-girder

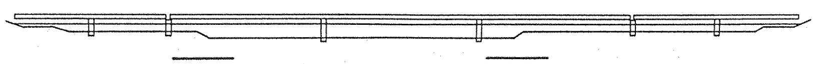

Fig. 13 Design conditions of actual plan and example of results by this system.

process, an expert designer world move the pier based on his own judgement by considering the balance of the span arrangement. This problem can be solved by entering the span arrangement data again that the designer desires after referring to the results from this system. As far as the bridge type combination is concerned, the same results are obtained from both methods.

According to the results of selection by this system, the PC simple post-tensioned T-girder bridge with span arrangement of 7@ 43.86 m is the cheapest. This type, however, was not adopted due to driver's comfort at running based on the actual design plan.

(2) Pile type selection

The actual design plan involves five ambiguous conditions as shown in Fig. 13. That is, N-value, stage of gravel, water depth at foundation work depth, foundation work depth and vertical load (span length).

When a condition corresponds to the boundary value between two categories for each item in the chart for selecting types of foundation in the Specifications for Highway Bridges as listed in Table 2, it is difficult for a designer to judge which category the condition would belong to.

Table 4 lists the results of selection by using fuzzy sets. As a result, a 1 200 mm reverse pile is selected. This result agrees with the pile type selected from the usual design process. Thus, from this fact, the method using fuzzy sets for pile type selection appears to be sufficiently practicable.

(3) Calculation of construction cost

Table 5 shows a comparison between both construction costs of superstructure and substructure, and the total construction costs obtained from this system and those from the usual design process. Table 6 lists the differences in construction costs of pier P3 and the substructure between both calculation methods using the host computer and charts in the Steel Bridge Design Planning Manual.

The construction costs of superstructure and substructure calculated by the charts are not certainly accurate, but the calculation

Table 4 Results of pile type selection by using fuzzy sets.

Driven steel pile	0.934
Steel pile sheet	0.934
Reverse	0.894
Sinso	0.734
All casing	0.734
Driven PC	0.632
Driven RC	0.632
Drilling steel pipe	0.614
Earth drill	0.554
Drilling PC	0.542

Table 5 Comparison of construction costs.

Calculation method \ Details of construction cost	Superstructure (million yen)	Substructure (million yen)	Total construction costs (million yen)
① The usual design process	597.0	264.0	861.0
② This system	628.5	270.0	898.6
(|① − ②| / ①) × 100	5.3 %	2.3 %	4.4 %

Table 6 Differences of substructure construction costs between calculation methods.

Calculation method \ Details of construction cost	Pier P3 (million yen)	Substructure (million yen)
① Calculation by host-computer	23.13	270.0
② Calculation by chart and table	24.75	287.1
(|① − ②| / ①) × 100	7.0 %	6.3 %

time of this method is very short. Consequently, for rough estimation, this method is also practicable.

(4) Effects on design work time

In this plan, the total calculation time is about 8 hours. Most of the calculation time is used by the host computer. This is because the stability of all abutments and piers are calculated for all combinations of bridge types and span arrangements, by changing their pile type (3 type) and pile diameter (2 or 3 types).

For the actual design work according to the usual process, the work time needed by an expert designer to achieve same accuracy level as achieved by this system was about one week. Therefore, it can be said that selection by using this system can significantly reduce the design work time.

7. CONCLUSION

(1) For selecting the types of river-crossing bridges, it is important for a practical expert system to consider not only the Specifications for Highway Bridges, the River-Crossing Structure Law and other manuals, but also the integrated knowledge of expert designers.

(2) By applying the knowledge of an expert designer, it is possible to develop an expert system that can automatically determine span arrangements to completely satisfy the River-Crossing Structure Law.

(3) By using fuzzy sets to express the ambiguous knowledge of an expert designer, the pile type can be selected by a process based on theoretical grounds, and the results of selection through this process are sufficiently reliable. Moreover, a designer can easily trace the results of fuzzy sets. Therefore, selection by fuzzy sets is more reasonable than selection by using the chart in the Specifications for Highway Bridges.

(4) By utilizing an online data communication system between the workstation and host computer, the evaluation of substructure construction costs can be made more accurate and certain.

(5) It seems that a designer can signiticantly reduce the work time for comparison design by using this system.

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