Soil Investigations and the Determination of Geotechnical Parameters for Highway Bridge Foundation Design in Japan

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ABSTRACT

A questionnaire survey was conducted in the spring of 2001 to investigate the present situation regarding the determination of soil parameter values in a process from ground investigation through to design. The questionnaire survey was designed to assemble fundamental information for the revision of the Japanese Specifications for Highway Bridges with the introduction of an LRFD (Load and Resistance Factor Design) format and a reliability design concept. The questionnaire investigated which ground investigation/testing methods were employed and how soil parameter values used in a design calculation were determined, because, in order to develop the LRFD foundation structural design, it is necessary to consider not only how resistance factors are calibrated but also how the characteristic values of soil parameters are defined. In the present paper, the authors describe the major findings of this questionnaire survey.

INTRODUCTION

The Japanese highway bridge design codes, i.e., the Specifications for Highway Bridges (SHB, Japan Road Association, 2002), are regarded as a performance-based design code as well as a limit state design code because the limit states of individual structural components such as superstructures, piers, footings, foundations, etc., are defined and verified in accordance with the required bridge performance for each design situation. However, a global safety factor format is still used. The background of most global safety factor values is ambiguous, and additional safety margins are occasionally included in design formulas. These actions tend to hinder the introduction of technological advances in design models, design concepts, materials, and so forth. In considering the adoption of a new technological development, the development should be compared to conventional designs in terms of the required performance and safety margin. However, it is not easy to assess the safety margin that is supposed to be built into conventional designs. As a result, the NILIM and the PWRI have been revising the codes with an LRFD format, considering that a reliability design concept will provide the benefit of organizing the manner in which safety margins are arranged in design and the sources of uncertainty involved in design.

A secondary objective with respect to the adoption of the reliability design concept is to harmonize the SHB with other major international standards. According to ISO 2394: General principles on reliability for structures (1998), structural design shall be based on the limit state concept in conjunction with a partial factor method. The partial factor format in which safety factors are applied to material parameters or the resistance of the structural elements has been introduced in European and North American standards/codes, such as Structural Eurocodes, i.e., EN 1990: Basis of

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Structural Design (prEN 1990, 2000) and AASHTO LRFD (2nd Edition, 1998).

In order to develop the LRFD foundation structural design, it is necessary to study not only how resistance factors are calibrated but also how the characteristic values of soil parameters are defined. In addition, the determination of soil parameter values depends not only on geotechnical knowledge but also on the design, that is, the types of foundation and calculation method. The values of load and resistance factors and the validity of design resistance formulas, such as pile bearing capacity formulas, depend on the definition of the characteristic values of soil materials, in which the characteristic values of soil parameters are a sort of unfactored value that are input into design calculation. However, such soil characteristic values are assessed via ground investigation at individual sites by individual engineers, and typical ground investigation/testing methods and a typical definition of the characteristic soil parameter value are vague. Accordingly, it is necessary to know the current practice in ground investigation and the manner in which soil parameter values are usually estimated.

Therefore, in the spring of 2001, the authors conducted a questionnaire survey to investigate which ground investigation/testing methods are employed and how soil parameter values used in design calculations are determined.

QUESTIONNAIRE SURVEY

The target respondents in the questionnaire survey were in-house engineers, geotechnical investigators, designers, and contractors who usually participate in the design and construction of highway bridge foundations. In the questionnaire survey, respondents were requested to consider common highway bridges with lengths shorter than 200 m. The questionnaire considered the following seven topics:

Q1: Information about the respondents
Q2: Who currently plans geotechnical investigations?
Q3: What are the current and ideal investigation or testing methods?
Q4: Who determines the parameter values for detailed design?
Q5: How are the parameter values determined?
Q6: Usefulness of statistical approaches in geotechnical design
Q7: Comments on the present situation regarding the procurement system.

Regarding topics Q2 through to Q4, the respondents were requested to give their views on the current and ideal situations.

The questions are categorized into two types. The first type involves the selection of an option and/or the ranking of several options in order of priority, and the second type asks for comments (e.g., Q7). The questions belonging to the first type can be evaluated by ranking using an inverse proportion approach, as shown in Table 1.

CURRENT PROCUREMENT SYSTEM

First, we outline a typical procurement system in Japan, because some of the respondents replied to the questions in the context of the Japanese procurement system. Figure 1 shows a simplified typical procurement system for highway bridge construction works. One feature of the procurement system is that in-house engineers in charge supervise the geotechnical investigation, design, and construction through individual contracts with geotechnical investigation companies, consultancies, and construction companies. The authorities themselves also plan projects and conduct maintenance work directly.

In general, before the start of design, a ground investigation company receives a contract from the entity in charge (in-house engineer), investigates the ground, and submits a ground investigation report (GIR). A design consultancy carries out the design based on the GIR and then submits a structural design report to the entity in charge. In a project, the investigation and design work should be conducted twice, namely during the preliminary design stage and during the primary (or detailed) design stage.

GENERAL FINDINGS

Respondents' positions

A total number of 314 questionnaires were returned by 63 organizations, including three principal authorities (the Ministry of Land, Infrastructure and Transport, the Japan Highway Public Corporation, and the Hanshin Expressway Public Corporation, at that time), 14 ground investigation companies, 26 consultancies, and 20 construction companies. The returned questionnaires were completed by 80 in-house engineers (25%), 73 investigators (23%), 135 designers (43%), and 26 contractors (8%). The number of in-house engineers was much larger than those of other occupations, a quarter of total respondents. A total of 43% of the respondents thought of themselves as structural engineers, and 35% of the respondents thought of themselves as geotechnical engineers. Judging from the organization of the Japanese construction industry, we believe that the respondents who worked in design consultancies or construction companies tended to think of themselves as structural engineers, while those who worked in ground investigation companies tended to think of themselves as geotechnical engineers.

Regarding the ages of the respondents, the percentages of respondents in the range of 36-40 years old and 41-45 years old were equal at 28%. The percentage of respondents over 46 years old was 22%, and the percentage of respondents in the range of 30-35 years old was 15%. The percentage of those younger than 29 years old was 7%.

Planning of geotechnical investigation

The results from all respondents to Q2 (Who currently plans geotechnical investigations?) indicate that in-house engineers, investigators, and designers were identified as planners of geotechnical investigations 41%, 32% and 25% of the time, respectively, as shown in Figure 2a. This result is understandable, because when considering the current Japanese procurement system, in-house engineers supervise ground investigations and design for structures. On the other hand, most (61%) of the respondents believed that, ideally, designers should be responsible for planning geotechnical investigations, whereas only 25% believed that the investigator should be responsible for planning geotechnical investigations.

The answers from the three types of respondents (i.e., in-house engineers, investigators, and designers) concerning the current and ideal situations are shown in Figure 2b. Regarding the current situation, their views were almost the same; namely, the person in charge was considered to be the in-house engineer, investigator, and designer, in this order. Regarding the ideal situation, however, few respondents proposed that in-house engineers should be in charge, and this included the replies from in-house engineers themselves. Both 70% of the in-house engineers and 70% of the designers proposed that the designer should be in charge of ground investigations, although most of the investigators were not in favor of this, as demonstrated by the fact that 56% of the investigators considered the planning of ground investigations to be their responsibility.

Current and ideal geotechnical investigation/testing methods

With regard to Q3 (What are the current and ideal investigation or testing methods?), the respondents replied that the Standard Penetration Test (SPT) was the most common method for determining both strength and deformation parameters, regardless of soil type, although it was not always the most suitable method.

In the case of spread foundations on sand, with respect to the determination of strength parameters, 67% of respondents identified the SPT as the most popular method. With regard to the ideal method, the percentage of respondents selecting the SPT was 33%, followed by the in situ plate loading test and the consolidated drained (CD) triaxial test at 21% and 20%, respectively.

For the case of pile foundations on clay, with respect to the determination of strength parameters, 41% of the respondents commonly used the SPT, with 26% using the unconfined axial compression test and 10% using the un-consolidated undrained (UU) triaxial test. In addition, 21% considered the unconfined axial compression test to be the ideal method, followed by the SPT and the UU test at 18% and 17%, respectively. As for the determination of deformation parameters, approximately 37% of the respondents commonly used the SPT or the in situ borehole loading test (BLT), which was identified as the ideal method by 43% of the respondents, followed by 16% for the SPT.

For the case of pile foundations on sand, with respect to the determination of strength parameters, 62% of the respondents identified the SPT as the most common method currently used. With regard to the ideal method, the SPT and the BLT were chosen by 32% and 25% of the respondents, respectively. As for the determination of deformation parameters, 45% and 39% of the respondents commonly used the SPT and the BLT, respectively. At 48%, the BLT was identified as the ideal method by the largest number of the respondents, followed by the SPT at 21%.

Who determines the soil parameter values for detailed design?

The replies from the respondents to Q4 (Who determines the parameter values for detailed design?) indicated that 43% reported that, at present, investigators determined the parameter values for detailed design, and 55% reported that designers determined the parameter values for detailed design, as shown in Figure 3a. This trend was more pronounced for the replies concerning an ideal situation, with 30% choosing investigators and 67% choosing designers. However, again, the responses varied with the occupations of the respondents.

Figure 3b shows the responses for the three types of respondents with respect to the current and ideal cases regarding who determines the parameter values. As for the current situation, many of the investigators thought that the investigators themselves determined the soil parameter values, while most of the designers thought that the designers themselves determined the soil parameter values. As for the ideal situation, over 80% of the designers considered that the designers themselves should be in charge of the determination of soil parameter values, and most of the in-house engineers agreed. In addition, 40% of the investigators also agreed, but 60% of the investigators thought that the investigators themselves should determine soil parameter values.

Determination of parameter values from measured values

Question 5 (How are the parameter values determined?) was divided into two categories, depending on whether several results were available. For the case in which several results were available, on average, the simple mean value from the derived values after excluding out-lying values was the most popular option for selecting parameter values (chosen by 63% of the respondents) followed by the Mean ± SD/2 (standard deviation/2) (chosen by 27%). A smaller number of respondents selected the lower bound of derived values after excluding out-lying values or experience/engineering judgment options. For the case in which few results were available, the lower bound (selected by 49%) and experience (selected by 22%) were the most popular options. In contrast, the simple mean of derived values after excluding out-lying values was chosen by few respondents. The answers of the investigators and designers to this question are shown in Figure 4. There was little difference in the average responses for all respondents for this question.

Views on the usefulness of statistics

With regard to Q6 (Usefulness of statistical approaches in geotechnical design), the differences among the results from different respondents are small. Over 50% of the respondents were in favor of a statistical approach, and approximately 30% were against a statistical approach. Many valuable comments on this matter were given in the questionnaires.

The respondents who are in favor of the use of statistics commented on objectiveness and transparency, as follows:

- Personal differences in determining the parameter value can be eliminated through the use of statistics. It is also possible to avoid judgments that are biased excessively on the favorable side or on the unfavorable side.
- It is an excellent tool in terms of accountability and objectivity to explain to a third-party the reason why particular parameter values are determined.

Conservative comments from the respondents in favor of the use of statistics were also identified:

- Statistics is available for eliminating out-lying values. The parameter values should be determined by considering not only the test results but also other information.
- Since measured values are affected by locality, such as regional characteristics and geological conditions, it is difficult to apply a statistical approach unless the test results can be grouped appropriately.

The respondents who answered that a statistical approach was not useful gave the followings reasons:

- Generally, obtaining a sufficient number of test results for applying a statistical approach is rare.
- The reliability of soil test results depends on the investigators or investigation companies concerned, and so there is a great need for improving the quality of investigation/testing methods.

Most respondents chose the simple mean excluding out-lying values or the mean ± SD/2, as shown in Fig. 5. This fact encourages the authors to introduce a quantitative definition of the characteristic value based on a statistical approach when introducing the LRFD in the next SHB.

Comments on the present situation regarding the procurement system

In Q7, the authors asked the respondents what should be done to improve the present situation regarding the procurement system, such as the contractual arrangement for ground investigation and design in Japan. A large number of comments could be summarized into the following three points:

- Inconveniences sometimes occur at the detailed design stage due to inadequacies in the result of ground investigation, e.g., the data has been obtained from locations not at or not near the construction point, and certain geotechnical information has not been investigated.
- Generally, it is rare to conduct additional investigations (necessary for design) at the detailed design stage because of the cost of additional investigation and the

time limitation of design. The system should be improved so that the designer can conduct additional investigations more easily.
- It is not feasible to hold satisfactory consultations among in-house engineers, investigators, and designers under the current procurement system, and hence formal meetings for communication among them should be required.

Regarding the first point described above, the following are examples of proposals suggested by the respondents:

(1) Design/build procurement in which the investigation and design are carried out together should be introduced to the extent possible because the investigation and design should have a close relationship at the detailed design stage.
(2) The designer who is in charge of the detailed design should propose a plan for the ground investigation, including the testing methods at the preliminary design stage. Furthermore, all of the geotechnical information necessary for design should be obtained before the detailed design is started.

IMPROVEMENT OF THE FLOW TO ESTIMATE CHARACTERISTIC VALUES

Based on the survey results, the PWRI has been studying the following three points for improving the flow of the estimation of soil parameters. The following items are similar to some features in the EPRI foundation design code study conducted by Kulhawy and Phoon (2002) and we have found their views to be very practical.

Definition of the characteristic value of soil parameters

Variability in soil parameter values is a significant source of uncertainty in foundation structural design. Based on the survey results, the respondents tend to estimate soil parameter values using a statistical approach. Mean values are preferred when several ground investigation data sets are available. Even when only a few data are available, only one out of three or four engineers tends to use engineering judgment. We inferred that even the respondents who favor engineering judgment do not adopt unrealistically small values. The respondents are likely to consider a possible distribution of mean values of similar sites and assume a reasonable value in an engineering sense based on their past experience.

Therefore, the survey results support the authors' belief that, for foundation design, the mean value for the soil volume that is mainly attributed to the foundation response should be taken into account as the characteristic value and be used in the calculation of soil resistances. This view is reflected in the commentary of the 2002 edition of the SHB, as follows:

> "Although ground materials have complex properties and vary widely, the geotechnical parameters for design should be estimated to predict the most probable performance of foundation behavior under the given ground conditions. Accordingly, the geotechnical parameters should principally take the average values of the ground concerned considering the accuracy and characteristic of the

equations used."

There are four reasons for this:

(1) Engineers need to focus on the structural aspects of highway bridge design. Statistical aspects should be considered by the code calibration.
(2) Engineers tend to prefer using values that capture physical behavior or experimental observations, as compared to hypothetical values, such as the 5% non-exceedance probability value, which inadvertently can lead to unrealistic foundation behavior.
(3) Because of the soil-foundation interaction, the underestimation of soil parameter values do not always result in design on the safe side, and there is the possibility that the underestimation of soil parameter values will inadvertently give a wrong failure mode of the foundation. For example, the bending moment at the top of piles can become either larger or smaller with the decrease in the horizontal soil resistance, because the degrees of contribution of the sway mode and the rocking mode to the total foundation deformation can change with the soil resistance value.
(4) Estimation of the mean value is expected to be a robust process. COVs of soil parameter values ranging from 30% to 100% are much higher than those for structural material parameter values, and it is difficult to obtain a lower-bound-like value for individual sites in a robust way with a limited number of ground investigation data sets at a site, such as the 5% non-exceedance probability value on the tail of a possible distribution function for the site.

Judgment is fine, but the target of the judgment should be to obtain a value that can explain the most likely behavior of the foundation.

Resistance factors with the categories of the quality of ground investigation

As shown by the results for typical ground investigation methods in terms of deformation parameters for clay, the respondents tended to use the standard penetration test, even though what they really wanted to use were the BLT or laboratory tests. This indicates that the respondents acknowledge that the status quo of SPT is not the best choice for clay, but there is little incentive to use the BLT or laboratory tests in addition to the SPT.

The values of resistance factors can reflect the degree of uncertainty in estimated soil parameter values that depend on ground investigation quality. Therefore, the resistance factors should be a function of ground investigation method. For example, the resistance factor of pile bending moment capacity should be different when using only SPT results and when using BLT or laboratory test results in addition to SPT results, so that the codes will be able to provide a motivation for improving the quality of ground investigation.

Clear guidance and education on the flow for ground investigation and the determination of characteristic values

In-house engineers, soil investigators and design consultants should be able to communicate smoothly with each other during a project. In addition, the code should estimate the uncertainty in the characteristic soil parameter values, provided a relevant quality of geotechnical investigation is accomplished.

Therefore, a new guideline for establishing satisfactory relationships between investigation and design and for educating the qualities of different types of ground investigation and testing should be published along with the new edition of the codes. The guideline should have the status between a design code of practice (mandatory document) and a standard for ground investigation and testing (non-mandatory document).

The target contents of the guideline should be as follows:

(1) The guideline should show a relevant flow from the ground investigation through to the estimation of characteristic soil parameter values to hold satisfactory interaction of in-house engineers, soil investigators, and design consultants during a project, including additional ground investigation, if necessary.
(2) The guideline should describe typical ground investigation methods that are assumed in typical design calculation models shown in the SHB.
(3) The guideline should ensure that the uncertainty in the estimation of soil parameter values has been incorporated into resistance factors and that there is no need to build additional conservatism into the soil parameter values used in the design calculation.
(4) The guideline should present the variation in typical transformation equations from a measured soil parameter to another derived soil parameter, such as a transformation equation from an SPT-*N* value (measured) to a deformation coefficient (derived) or an SPT-*N* value (measured) to an internal friction angle in terms of cohesionless soils (derived), so that engineers can obtain information on the quality of ground investigation.

CONCLUDING REMARKS

The authors conducted a questionnaire survey of geotechnical investigation methods, determination of soil parameter values, and the present situation concerning the procurement system in Japan in order to obtain information for the revision of the Specifications for Highway Bridges. The major findings of this study are summarized as follows:

1. The most popular method for determining parameter values from derived ground investigation results was based on the “mean” value, followed by the “mean value ± SD/2” when several data sets are available. When few data sets are available, the lower bound value was the most popular method.
2. Over 50% of the respondents accept the usefulness of statistical approaches. Some replied that statistics was an excellent tool in terms of accountability and objectivity.
3. Unsatisfactory consultations between investigators and designers were

achieved under the current procurement system.

Based on the survey results, we should incorporate the following concepts into the revised edition of the Specifications for Highway Bridges:

4. The characteristic soil parameter values in the design of foundation structures should be the mean or the average for the soil volume that is mainly attributed to the foundation response.
5. The quality of ground investigation should be built into the values of resistance factor.
6. A guideline filling the gap between design codes of practice and standards for the ground investigation/testing thereof should be published in order to realize a satisfactory relationship among design codes, investigation, and design calculation.

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Table 1 Inverse proportion approach

Options	Rank	Weighting
1) In-house engineer	5	0.20 (= 1/5)
2) Geotechnical engineer	1	1.00 (= 1/1)
3) Designer	2	0.50 (= 1/2)
4) Contractor	3	0.33 (= 1/3)
5) Others	4	0.25 (= 1/4)

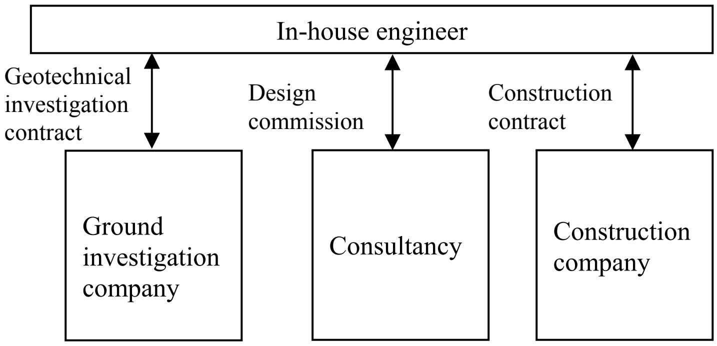

Figure 1 Typical procurement system in Japan

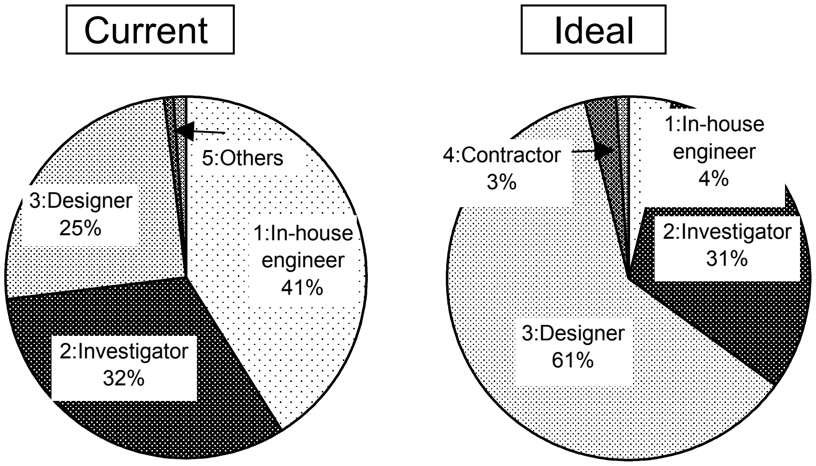

Figure 2a Who normally plans a geotechnical investigation?

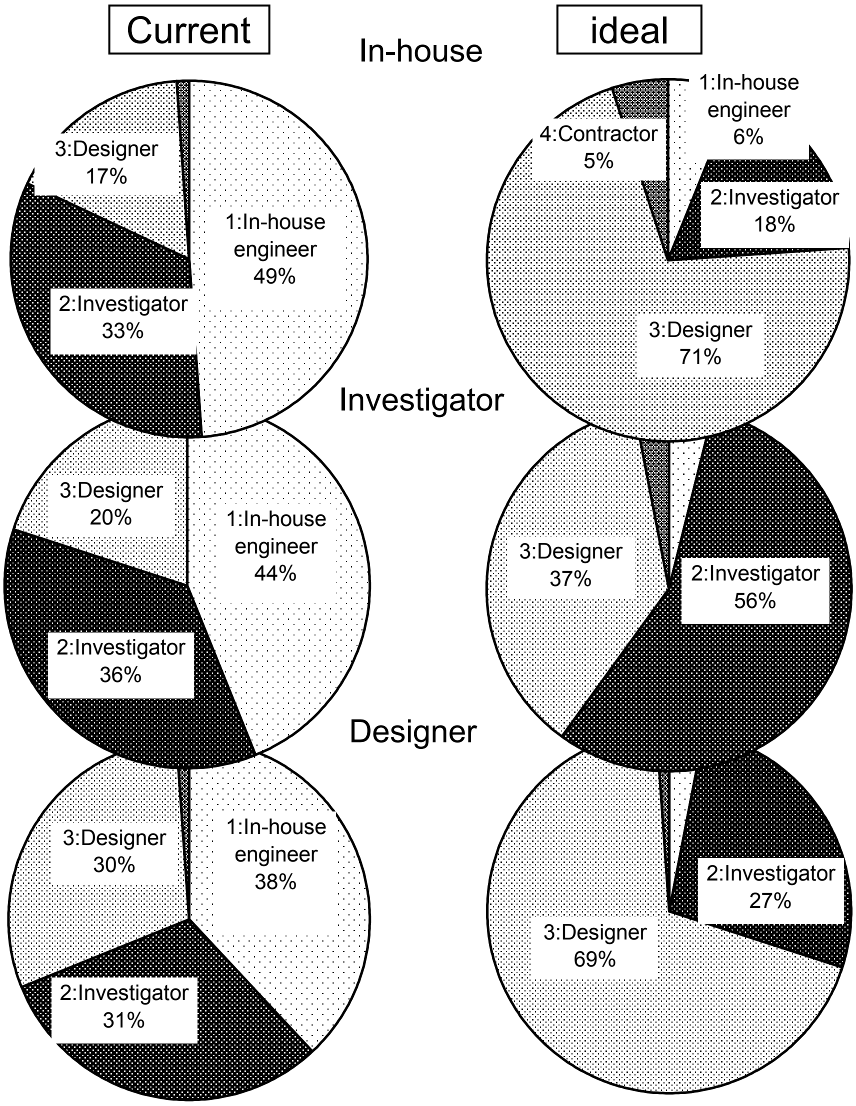

Figure 2b Who normally plans a geotechnical investigation?

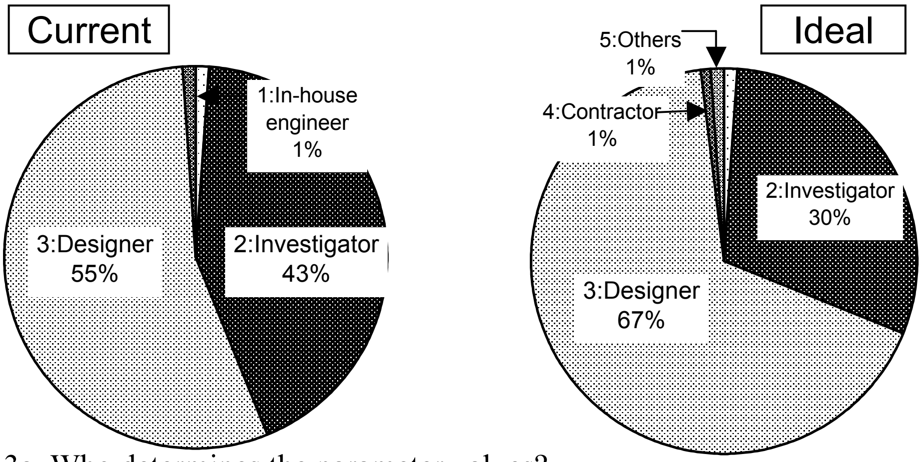

Figure 3a Who determines the parameter values?

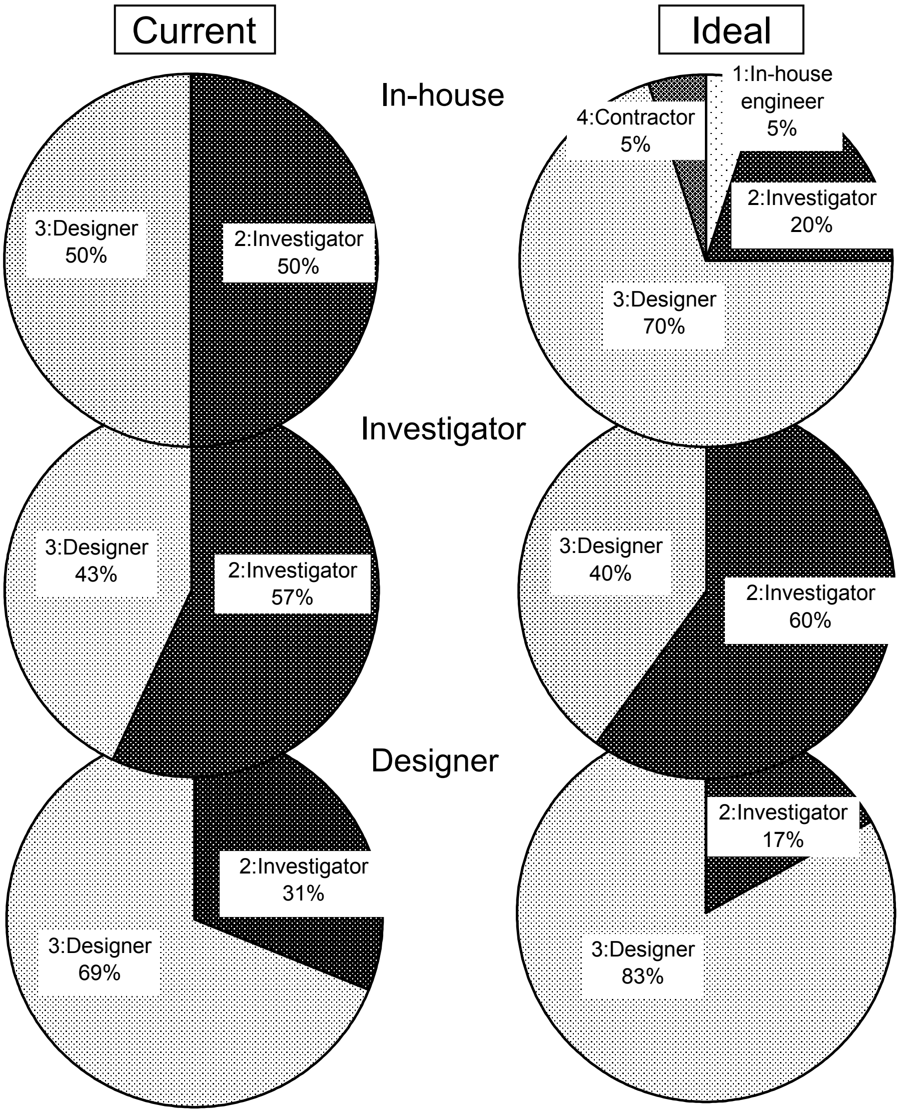

Figure 3b Who determines the parameter values?

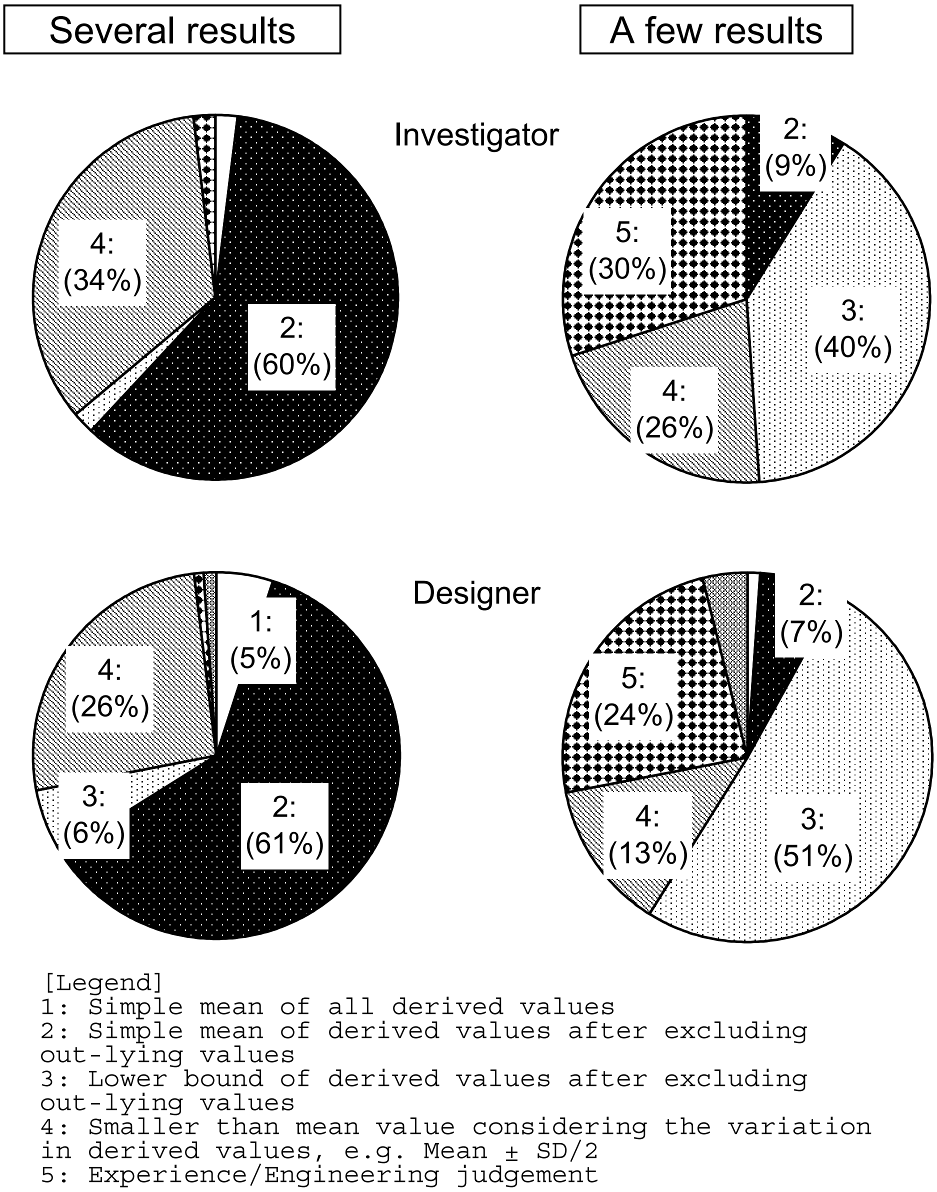

Figure 4 How do you determine the parameter values?