A study for enabling uncertainty evaluation of geological/geotechnical three-dimensional model in construction projects

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ABSTRACT

Applications of the BIM (Building Information Modeling) to civil engineering and construction industries have been started in Japan, under the initiative of Ministry of Land, Infrastructure and Transport of Japan. In the BIM for infrastructure, geological/geotechnical investigation results are transformed into a 3-D model and are consistently managed as public project information throughout the entire life cycle of an infrastructure to be shared and used among relevant parties. However, it should be noted that geological/geotechnical model is an inferred model with uncertainty, unlike product model for building structure that expresses a visible object based on a design drawing. In order to reduce such risks of improper designing that the accuracy of geological/geotechnical model is overestimated or misused in the downstream operations, it is important to maintain the records that specify the uncertainty of inferred model along with underlying actual data. We, members of a working group under the ISSMGE ATC10, are working on the following two issues currently; 1) identification of the factors that affect model uncertainty and 2) review of Japanese and international standards on the 3-D modeling. In first issue, based on some examples of construction projects, the factors that affect the model uncertainty and the information to be maintained for downstream processes have been identified. For example, modeling area and the validity for its setting, modeling process, type and position of input data, geologic stratigraphy applied to the model, and rationale for stratigraphic identification are recognized as such factors. In the standard review, a total of 51 Japanese and international standards related to geological/geotechnical survey have been reviewed and we recognize that there are descriptions of requirements for the reliability of the 3-D model. Some terms such as 'geological model' and 'geotechnical model' are found to have been used in different meanings and causes confusions among stakeholders, so we are defining and categorizing some important terms such as geological model, geotechnical model, geotechnical information, uncertainty and reliability. We continue to examine the actual description methods and formats that allow the information related to uncertainty is handed over to the downstream processes so that the uncertainty can be re-evaluated afterward. We plan to include the final outcomes of this study in "JAPANESE GEOTECHNICAL SOCIETY STANDARDS: Geotechnical and Geo-environmental Investigation Methods".

Keywords: geological 3-D model, geotechnical 3-D model, uncertainty, BIM

1 INTRODUCTION

Applications of BIM (Building Information Modeling) to civil engineering and construction industries have been started in Japan under the initiative of Ministry of Land, Infrastructure and Transport of Japan. In BIM for infrastructure, geological/geotechnical investigation results are transformed into a three-dimensional (3D) model and are consistently managed as public project information throughout the entire life-cycle of an infrastructure to be

shared and used among relevant parties.

On the other hand, some geological and ground survey standards were formulated before the implementation of BIM for infrastructure and have been in force in Japan. As a result of this, any expression methods and data formats with uncertainties of the survey results for 3D model are not included in those standards.

It should be noted that geological/geotechnical model is an inferred model with uncertainty, unlike the product model for building structure that expresses a visible object based on a design drawing. Furthermore, the geological structures and geotechnical conditions in

Japan are extremely complicated due to subducting tectonic plates underneath Japanese islands, and there are non-negligible amount of uncertainty being included in the created models.

In order to reduce such risks of improper designing that the reliability of geological/geotechnical model is overestimated or misused in the downstream operations, it is important to maintain the records that specify the uncertainty of inferred model along with underlying actual data. Therefore, we, members of a working group under the ISSMGE ATC10, have been working on the issues in realizing the evaluation of uncertainty (or quality) of the model.

In this paper, the findings and issues that have been clarified through our studies are reported.

2 ISSUES AND RESOLVING PROCESS

Goal of our committee is to propose a method by which the provider of a model can describe the information on its uncertainty and a way the user of the model can evaluate the uncertainty of the model. Since both the creator and user of models are expected as recipients of our results, diversified discussions to be conducted from the standpoint of both sides, the committee members are involved various positions such as owners, research firms, designers.

The investigation flow in the committee is shown in Fig1. Firstly, the subsurface models in a wide variety of the past construction projects have been researched. Then the factors that affected the accuracy and reliability of the models have been identified through cause-and-effect analysis. Case studies cover various business fields and subjects such as underground discharge control drain planning, airport construction, tunnel drilling, earthquake damage estimation and high-rise building construction. Concurrently, international and domestic standards about geological/geotechnical survey and design have been examined regarding descriptions about uncertainties, such as accuracy of the geological investigation results, reliability of the model, required

Fig.1 Investigation flow in this study.

performance of the model. Nextly, the factors that have found out to be affected to the model uncertainty have been categorized and systematized into common factors and specific ones from the viewpoint of business field and target. By analyzing each factor, we propose items and description methods to be handed over to the downstream process along with model data so that the users are able to evaluate the uncertainty of the model, in other words, users are able to trace the reliability of the model. We also propose a visualization method of the uncertainty in a 3D model on computer. The final outcomes of our committee will be included in "JAPANESE GEOTECHNICAL SOCIETY STANDARDS: Geotechnical and Geo-environmental Investigation Methods".

3 CASE STUDIES

For a wide range of considerations, a variety of cases have been selected regarding to the structure type, geological/ geotechnical condition, the purpose of modeling and what to be expressed in the model. Table.1 indicates the projects that we have been tackling. In older projects, it was common to have a 2D cross section and a plane as the final outcome instead of 3D model, so they have been also taken into account. In this chapter, two projects are introduced.

3.1 The kansai airport

The kansai international airport was built on a manmade island 5km off the coast of Osaka in 1994. Fig.2 shows the location map of the airport. In this construction project, the biggest challenge has been accurate subsidence prediction until now.

Fig.2 The location map of the airport.(1:1,000,000 INTERNATIONAL MAP, Geospatial Information Authority of Japan).

Fig.3 shows schematic diagram of geology below the airport islands (Kansai Airport, 2018). Under the soft alluvial clay layer with the thickness of about 20 m, several diluvial clay layers are deposited with a total thickness of 340 to 500m. The sand layers are sandwiched between the clay layers. This sedimental

Table1. The projects tackled in the committee

No.	Case	Stage	Purpose of modeling	Modeling area
1	Underground flood control drain	Investigation (early stage)	Identification of the load bearing layer for underground drain	H : 3.5km square V : elevation up to -100m
2	Offshore airport construction	Investigation	Subsidence prediction of the airport islands	H : 8km square V : elevation up to -200m
3	Mountain tunneling	Construction	Grasp of high-pressure aquifer	L = 22,251m
4	Mountain tunneling	Construction	Grasp of faults and fracture zone	L = 19,680m
5	Mountain tunneling	Construction	Grasp of distribution of altered rock including heavy metal	L = 26,455m
6	Subway construction	Investigation	Estimation of the position of active fault crossing the tunnel and displacement amount during faulting	L = 600m V : elevation up to -300m
7	Earthquake damage estimation (Chiba Prefecture)	—	Prediction of strong ground motion, slope collapse, liquefaction, etc.	H : 5,157.61km ² V : elevation up to -50m
8	Earthquake damage estimation (Osaka Prefecture)	—	Prediction of strong ground motion, slope collapse, liquefaction, etc.	H : 1,905.14km ² V : elevation up to -50m
9	High-rise building	Design	Estimation of the load bearing layer for piles	H : 300m square V : elevation up to -70m

structure is thought to be made during cyclic Glacial-interglacial period. Soft clay is laid thickly to a depth of about 400m, so the consolidation settlement by landfill load has been succeeding over a long period even in the deep part (Kansai Airport, 2018).

Fig.3 Schematic diagram of geology below the airport islands (Kansai Airport, 2018).

Table.2 shows the survey items in the construction project. Various investigations and analyses were conducted to obtain information about detailed geology and geotechnical characteristics under the airport islands, such as the lower limit of the diluvial clay layer that needs evaluation of consolidation settlement, and the distribution of sand as a drainage layer.

Fig.4 shows one of the investigation results. This model plan view indicates distribution of the diluvial sand layer based on borehole data and acoustic exploration data. As far as only the final results, information for quality evaluation of the model, such as the type and quantity of base data and the modeling procedure cannot be recognized. So, our committee has

identified the factors affecting model quality and the information to be attached to the model in order to confirm the traceability of the quality of model through cause-and-effect analysis among the base data, modeling process, completed models.

Table2. The survey items in the Kansai airport construction project

Period	Survey item
1st (1984)	Drilling survey ($L \leq 150m \times 63, L=400m \times 2$) Core sampling Microfossil analysis
2nd (1998-1999)	Drilling survey ($L=400m \times 4$) Acoustic Exploration(Single channel and multi-channel) Microfossil analysis Grain size analysis
3rd (2007-2008)	Full-length core drilling ($L=1400m$) Microfossil analysis Tephra analysis

Fig.4 The contour maps of the diluvial sand layers

Table3 shows example of the items identified by the committee. For example, regarding the modeling process, consistency between borehole data and

Table 3. Example of the items identified as affecting factors to the model quality

Regarding to base data
(Borehole log, Acoustic Exploration data)
Contractor
Drilling or exploration date
Location, the coordinate system, location acquisition method
Legend of geology, geological chronology
Regarding to modeling process
Quantity of borehole data and exploration data
Modeling area and data coverage
Coordinate system of the model and coordinate transformation method
Model calculation algorithms
Consistency between borehole data and acoustic exploration data
Identification accuracy of sand layer from base data
Regarding to the model
Possibility of different models with other interpretations
Construction risk on geotechnical condition
Model revision history

acoustic exploration data has been identified. The contour maps in Fig.4 were made out of a 3-D sand distribution model based on borehole data and acoustic exploration data.. In this case, consistency between the specified sand in the borehole and the reflection surface of the acoustic exploration should affect the model quality.

The total subsidence amount from the start of the landfill to 2017 is 13.25m in the 1st airport island and 15.85m in the 2nd island. These values are consistent with the simulation result obtained by using the subsurface model mentioned above.

3.2 An underground flood control drainage tunnel^a

The second case is the identification of load bearing layer for underground flood control drainage tunnel.

The Neyagawa River basin in the eastern area of the Osaka Plain is a low lying ground and surrounded by two large rivers called the Yodogawa River and the Yamatogawa River, so the area has been repeatedly devastated by rain-related flooding. In order to protect this hazard prone area from flood damage, a flood drainage tunnel is under construction. Fig.5 is topographic map on Osaka prefecture, which shows location of the Neyagawa River basin and the drainage tunnel. Fig.6 shows schematic representation of the underground drainage tunnel (River Improvement Division, Osaka pref, 2018). It can drain flood waters from sewer trunks to outside the basin. The drainage tunnel has an inner diameter of approximately 10 meters, and an overall length of 11.4kilometers. The range of 7.9 km on the east side was built at a depth of about 45m. However the 3.5km length on the west side is planned to be built at a depth of 70m, because road construction project on the underground tunnel route has not started, in addition land acquisition for construction at a shallower depth in this range is difficult.

Fig.5 The location of the Neyagawa River basin and the drainage tunnel (Digital Topographic Map 25000 published by Geospatial Information Authority of Japan).

Fig.6 Schematic representation of underground drainage tunnel (River Improvement Division, Osaka pref, 2018).

According to Japanese act on special measures concerning public use of deep underground, public underground facilities can be constructed without land acquisition in a place 10 meters deeper than the top of the load bearing layer for the foundation of the building without land acquisition. So, the challenge in this project was identification of the load bearing layer. The results of the survey were summarized in the geological cross section (Osaka Pref., 2018) along to the underground drainage tunnel route shown in Fig.7. In the figure, black

lines show the planned tunnel, and red line shows the top of load bearing layer. In this area, alluvial deposits are distributed in 20m thick and diluvial formations are underlying. Near the planned route, the strata formations are inclined from the west to the east, also from the north to the south. Since the objective of this project was to grasp the approximate depth of the load bearing layer, strict accuracy was not required.

Fig.7 The geological cross section along the underground drain route (revised Fig.-3.26 of (Osaka Pref., 2018)).

Unless information on accuracy is attached to the outcome, there is a risk that the designer misunderstands that it has enough accuracy for detailed design. Table4 shows the survey items in this project. This survey was characterized by using past borehole data accumulated in the public DB because of the following two reasons; 1) difficulty in drilling new borehole in the private land on the planned route, 2) difficulty in large amount of expense in the early stages of the investigation.

Table4. The survey items in the underground flood control drainage tunnel construction project

Survey items	Purpose
Literature review	Understanding the outline of topography and geology
Drilling survey(25)	Confirmation of the depth and strength of load bearing layer around the project area.
Collection and analysis of existing borehole data(15)	※the past borehole data accumulated in the public DB were also taking into account.

Table5 shows proposed items to be handed over to the downstream process along with model data. In this case, information on the quality of the borehole data referred from the public DB is thought to be important, because the public DB contains data drilled in various eras for various purposes targeting various structures, that is, data having various reliabilities and resolutions. For example, the drilling era is one of important information because the newer data might be having higher the reliability due to improving drilling technology and location acquisition technology. Another important item in this case is notifiable information that the geological model is a schematic drawing inferred from only few data at the early stages of the survey, so it

has insufficient reliability that can be used for detailed design and construction.

Table5. Example of the items identified as affecting factors to the model quality

Regarding to past borehole log
Purpose and object of investigation
Client and Contractor
Drilling time of investigation
Data source(DB)
Regarding to modeling process
Position of basis data
Contour drawing method (=by hand on a 2D plane)
Regarding to the model
Position and scale
Point to note for using the outcome
= Those created to grasp the rough distribution of the strata at the early investigation stage (not applicable to detailed design and construction)

4 RESEARCH ON EXISTING STANDARDS

If there have been existed any standards that mention terminology, required performance, and uncertainty of the geological/geotechnical model, our study must be consistent with them. Fifty-one international and national standards on geology / geotechnical survey and design have been collected and are currently being studied. Some standards have been found that regulate the survey density or provide a measure of survey density (Japan Institute of Construction Engineering, 2012) (BS EN 1997-2:2007). They must give constraints on the accuracy and resolution of the geological /geotechnical model. It has been also found the standard regulating the representation of uncertainty in geological map. For example, in the Japanese industrial standard "JIS A 0204" (JIS A 0206, 2013), accuracy and reliability of geological boundaries represented in a geological map are classified based on two items of the existence certainty and position accuracy. Because this standard is for paper - based 2 - D models, uncertainty is represented by the dotted line and the mark "?". There are some issues in applying the standard to a 3-D model expressed in the computer, such as how to express the dashed line in electronic data, however, it is thought to be useful from the viewpoint of visualizing the uncertainty of a model.

5 CONSIDERATIONS

In this section, two issues clarified by our committee are discussed.

The first is terms and definitions. For example, the terms of geological model and the geotechnical model are found to be confused in projects, standards and other literature. Since the confusion of terms cause a

Table6. The factors affecting the uncertainty of subsurface model

Survey item/model	Raw data	Interpretation data	Dimension	Uncertainty	
				Items regarding the precision	Items regarding the accuracy
Drilling survey	○	○	1	Positioning method Drilling method	Complexity of the geological structure Engineer's skill
Sampling, Soil test	○		0	Positioning method Sampling method Specimen Manufacturing method Test method	Same as above
Geophysical exploration	○	○	2	Positioning method Traverse line interval Exploration method	Complexity of the physical properties distribution and geological structure Engineer's skill
2D model		○	2	In addition to above, the density of data	Same as above
3D model		○	3	In addition to above, modeling method, grid size, interpolation method	Same as above

risk of information sharing and communication between stakeholders, our committee is defining the terms and semantics for computers to understand the terms.

The second is a systematization of affecting factors. Table6 shows factors affecting the uncertainty of subsurface model. The uncertainty is thought to be consisted of precision and accuracy. The precision is considered as a deviation from an average in accordance with the definition the field of measurement technology. And the accuracy is considered as a deviation from the true or absolute value. In this table, factors affecting the precision and the accuracy of each survey item or model are described. For example, geophysical exploration results consist of raw data and interpretation results, and the outputs is usually expressed in 2-D. The accuracy is influenced by the positioning method, traverse line interval, the exploration method, and so on. On the other hand, the accuracy is affected by the complexity of the distribution of physical properties and geological structure at the research site, and the level of engineering skill. As the dimension of the survey data improves, influencing factors increase, resulting in large uncertainty in the 3-D model output.

The time axis is not shown in this table, but time dependent factors must also be taken into account. For an understanding of quantity of uncertainty, it must be important to systematize factors of uncertainty and showing how they are accumulated.

6 CONCLUSIONS

A working group under the Japanese chapter of ISSMGE ATC10 has been working on propose a method by which the provider of the model can describe the information on its uncertainty and also a way user of the model can evaluate the uncertainty of the model.

As a result of the case studies, items to be

attached to the model data such as location and its coordinate system, investigation date, quantity and distribution of base data, modeling method and point to note for using the model have been clarified.

As a result of the discussion at the committee, it has been turned out that the confusion in the terminology and definition of geological/geotechnical model has to be solved, and also the influence factors on the model uncertainty have to be systematized by taking into consideration the dimension of the survey, measurement and model output.

We are now tackling those issues, and also proposing information forms and formats attaching to the model and visualizing of the uncertainty of 3D models.

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