Promotion of ground investigation for avoidance of geo-risk and better construction management

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ABSTRACT: This study is an activity of Professional Image Committee of ISSMGE in collaboration with several engineering institutions. Despite recent developments of ground investigation, uncertainties still remain in soil data for design. Projects encounter unexpected troublesome soils and suffer from extra cost. This situation is called georisk. The most important way to mitigate georisk is elaborate investigation to capture ground conditions precisely. Georisk Society collected many case histories from projects in which extra cost on soil investigation helped avoid risk and reduce the total construction cost. Other case histories show that insufficient investigation resulted in financial loss. Those knowledge is summarized and interpreted in this paper. It is further important that engineers have an opportunity to anticipate the subsoil uncertainty. This is made possible not only through personal experience but also by knowledge transfer from past projects to future. Another importance is with "open-access" database of bore hole data.

Keywords: georisk, ground investigation, cost saving, geotechnical knowledge

1. Introduction

Technology for subsurface investigation has achieved amazing developments in the recent decades. As shown by the successful use of cone penetrometer, pressuremeter and geophysical technologies among others, subsoil condition can be captured nowadays more elaborately and even in a three-dimensional manner. Accordingly, many design parameters can be determined from the obtained data. One of the still-remaining difficulties comes from the fact that ground was made by nature without taking care of homogeneity and engineering quality requirements. Thus, ongoing projects sometimes encounter unexpected poor soil condition and suffer from increased cost and elongated construction period. Delay in foundation construction puts super-structure construction under strict time limitation. The present study calls these problems "georisk."

Because the underground condition is not directly visible, there is always uncertainty in underground information. Probabilistic approach may be one of the ways to cope with uncertainty but the authors are working on more complicated heterogeneity and uncertainty that cannot be handled by a probabilistic approach alone. Thus, it is the objective of the authors' activity that clients and contractors acknowledge the importance of subsoil investigation and carry out a greater number of investigations than has been conventionally the case. This point was made in 1994 [1, 2] to show that the construction cost can avoid increase due to georisk by allocating more budget on subsurface investigation. It is important to educate people about georisk by using accumulated relevant information from real projects [3]. These practice-oriented attitudes are very important because most researchers are interested in probabilistic approach to undergrond uncertainty possibly because case history data is hardly available to them. The authors suppose that the real uncertainty is more complicated than what probabilistic approach can handle as suggested by caverns, faults, local backfilling etc.

Since 2009, the importance of subsurface investigation has been pointed out for achievement of good construction project [4]. In line with this, since 2010, Georisk Society in Japan has been organizing periodical events to collect and discuss case histories with emphasis on the value of subsurface investigation in successful management of georisk. This activity will be discussed in detail in Chapter 3 of this paper. It is a pity, however, that the reality nowadays is even opposite from the goal and clients tend to allocate less and less budget to subsoil investigation under the name of "cost cutting" and are later annoyed by a significant soil trouble.

Geotechnical Baseline Report (*GBR*) is another practice to manage unforesseen underground risk [5]. However, even *GBR* would allow more uncertainty and increase the construction cost if the underground information is insufficient. In this respect, the importance of subsurface investigation is obvious.

2. *Examples of georisk*

This chapter addresses several examples of incidence that were induced by insufficient knowledge of subsurface conditions. It may be said that this insufficiency could have been avoided if more detailed subsurface investigation had been carried out. Hence, those examples show the essential point of georisk problem.

Unexpected tilting of an expensive building is a typical example of georisk. Tilting during construction causes additional cost for correction of the tilting or demolition, in the worst case, of the tilted building. This additional work may cause delay of construction as well. If tilting happens after completion of a building, the value of the real estate decreases and/or the safety/stability of the building is suspected. Figs. 1 and 2 illustratestwo examples of tilted buildings. The one in Fig. 1 resulted in reduced value of the property, while the other in Fig. 2 resulted in the total demolition and re-construction of 5 buildings in a condominium complex despite that only one of them tilted slightly. For the latter case, residents suspected the insufficient length of pile foundation and the project leader and the contractor were forced to demolish 5 buildings, although only one of them was subject to tilting of merely 0.04% (2cm versus 50 m length). Because tilting is induced by the heterogeneous subsoil condition, subsurface investigation should have been carried out at a sufficiently big number of points to capture the heterogeneity. Another issue is that those investigation had to be able to obtain the modulus of soil in addition to strength of soil, because the encountered problem is not the bearing capacity but deformation. Question is whether or not the current investigation practice is able to provide such a sensitive information as predicts a few cm deformation of soft soil.

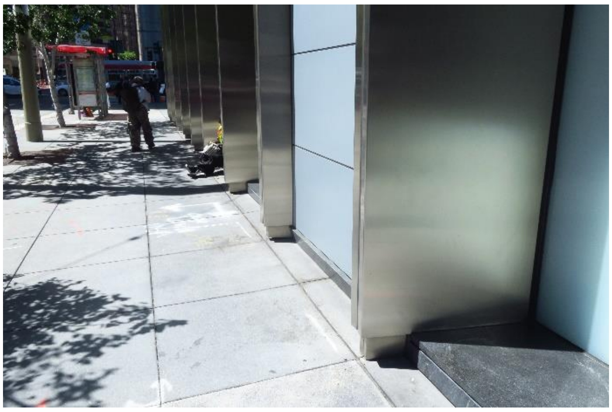

Figure 1.Distorion at ground surface around tilting high-rise expensive condominium building.

Depression, which is otherwise called surface settlement, is the second type of georisk. In urban environment, depression is often related with underground excavation/tunneling. In 2016, Fukuoka City, Japan, experienced a substantial depression of 6200 m^3 in size during construction of a new metro tunnel. The official investigation committee [6] studied the causative mechanism of this depression in the street surface and concluded that the metro construction by the New Austrian Tunneling Method did not take into account the varying thickness of an impervious layer above the tunnel's crown. At a place where the thickness of this layer was as small as 2 m, the overlying pore water pressure could not be sustained by this layer when tunneling reached there, leading to the overall collapse and depression. The committee stated the importance of subsurface investigation. Noteworthy is that this incident site had been recognized by a previous project as a site of heterogeneity. Unfortunately, this lesson had not been transferred to future projects.

Fig. 3 schematically illustrates the mechanism of collapse in a tunneling project [7] that took place in a mountainous site with significant tectonic compression. Due to horizontal compression, the geological layers are folded to be vertical. When tunneling hit a layer of soft sandstone, the pore water with high water head in the layer flooded into the tunnel (volume of water being 30,000 m^3) together with sand and gravel [8]. This incident stopped the tunneling project for 2 years. The problem was that this layer was as thin as a few meters and had not been recognized in advance.

Figure 2. Condominium building of 0.04 % tilting among 5 buildings in a residential complex.

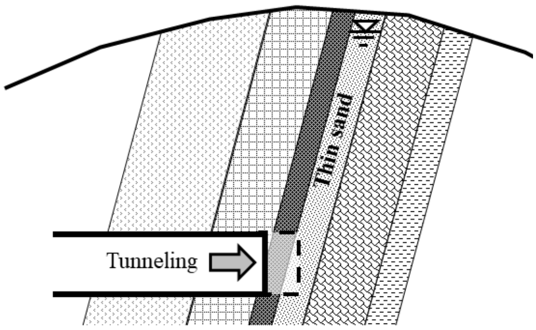

Figure 3. Schematic illustration of collapse mechanism of Iiyama Tunnel Project.

Urayasu City in Japan is situated on a young man-made island in Tokyo Bay and was affected by significant seismic liquefaction during the 2011 Tohoku earthquake (Fig. 4). The induced damage was comprised of tilting of residential houses and breakage of buried lifelines. In order to mitigate future liquefaction disasters, a governmental project was resumed in which the liquefaction vulnerability was mitigated by installing grid-type rigid walls under residential areas. The grid wall was expected to constrain cyclic shear deformation during earthquakes, thereby reducing the possibility of liquefaction.

Figure 4. Liquefaction damage in Urayasu City during the 2011 Tohoku earthquake, Japan.

The use of this method was decided because existing houses at the surface did not allow most liquefaction mitigation technologies such as compaction, and another risk of consolidation settlement in the underlying 40-meter soft clay did not allow ground water lowering. When grid wall construction started by jet grouting, the operation of machine was significantly disturbed by plastic drains that had been buried since the land reclamation in 1970s (Fig. 5). Obviously, the drains were installed to accelerate consolidation procedure in the reclaimed island. The problem was that the existence of drains had not been recognized by the liquefaction mitigation project. This problem was finally solved in a technical sense by increasing the jetting energy but the cost and the construction period increased substantially. Although the cost problem was solved by additional financial support from the national government, the elongated construction period was not accepted by most local people [9]. Finally, the size of the project had to be drastically reduced. The lesson was that those drains were not detected by boring investigation and cone penetration tests as well as that the record of plastic drain installation was not available in the recent times.

Figure 5. Detected plastic drain that made jet grouting difficult and costly.

A positive example is taken here by which the value of detailed subsurface investigation is validated. This example addresses the construction of pile foundations of a connecting long-span bridge between the Kita-Kyushu Airport Island and the mainland [10]. Fig. 6 illustrates the situation therein where the depth of bearing layer for end-bearing piles is quite variable. In the earliest stage of design, end-bearing piles were designed on the basis of *SPT*-N data (Standard Penetration Test N value). However, the length of piles was too deep to be accepted by a public project. Hence, the type of piles was changed to shorter frictional piles. Among two types of design methodology, practice of more detailed field investigations, including undisturbed soil sampling and laboratory tests, was considered more appropriate than *SPT*, although it is more expensive. Accordingly, the initial budget of US one million $ for subsurface investigation was increased to 3 million $ (increment = 2 million $) and the pile length was significantly reduced (Fig. 7). The shorter pile length successfully reduced the total construction cost by 100 million $; the ratio of the saved budget over the increased investigation cost was 100:2 which was marvelous.

Georisk Society has been collecting case history information and has organized annual conventions since 2010. In this series of convention, many case histories have been presented in order to verify the importance of subsurface investigation in avoiding georisk and reducing damage. This activity is a break-through because publication of "negative" georisk case history had been difficult before [3]. The present paper interprets 143 case histories that were presented from 2010 to 2018. Fig. 8 shows the studied types of structure. Note that majority is the slope problem in which unexpected instability was encountered.

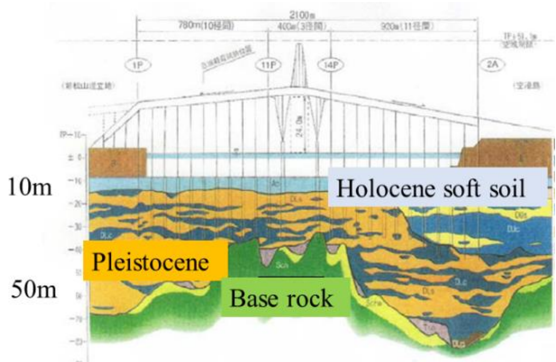

Figure 6. Complex subsoil condition under the Kita-Kyushu Airport Bridge [10].

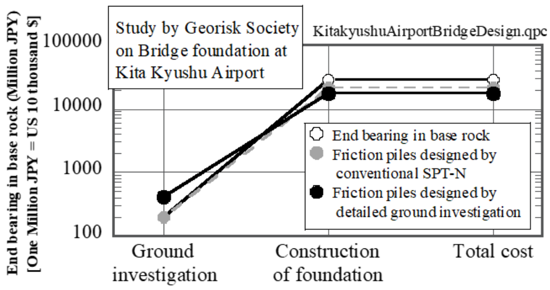

Figure 7. Cost reduction by detailed subsurface investigation [10].

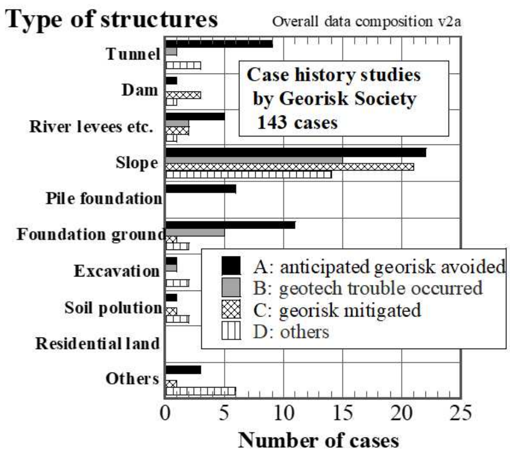

Figure 8. Composition of Georisk Society's case history study.

3. *Case history studies by Georisk Society*

Georisk Society classified the studied cases into 4 groups;

- Group A: Original design was over-conservative and additional ground investigation helped reduce the cost, or georisk was anticipated after the initial design and additional ground investigation helped avoid disaster (59 cases),
- Group B: Risk (trouble) occurred during project and countermeasures increased the total cost (24 cases),
- Group C: Risk was anticipated during early stage of project and mitigation helped avoid the catastrophe (29 cases), and
- Group D: Detail is not clear (31 cases).

The following discussion addresses Groups A-C because somewhat detailed information is available for them.

3.1. *Group A with successful risk management*

This is the group in which georisk was anticipated well in advance or more cost-effective method of construction was proposed by running subsurface investigation. Its typical example is the bridge foundation in Fig. 6.

Fig. 9 compares the total costs, consisting of those for investigation, design and construction, when georisk was (○) or was not (●) managed by relevant (additional) subsurface investigation. In the present paper, the cost control from the viewpoint of georisk is called "georisk management" where capturing the subsurface ground condition plays a major role. The costs are plotted against the original construction budget that was planned before finding the risk. It is clear that the cost was reduced by the georisk management. Then, the ratio of profit by management is defined by

Profit ratio = [(Total cost without additional investigation, including damage by georisk) – (Total cost after relevant management)] / (Costs for additional subsurface investigation, changing design etc.) (1)

in which the numerator of this formula designates the profit. Fig. 10 plots this profit ratio against the original construction budget. Although there is not clear correlation between the plotted data, it may be said that the profit ratio of as high as 10 or more is possible. Note that the ratio <1 still means that smooth progress of projects without trouble was appreciated by site engineers although monetary profit was small as verified by 4 cases with numbers in the figure.

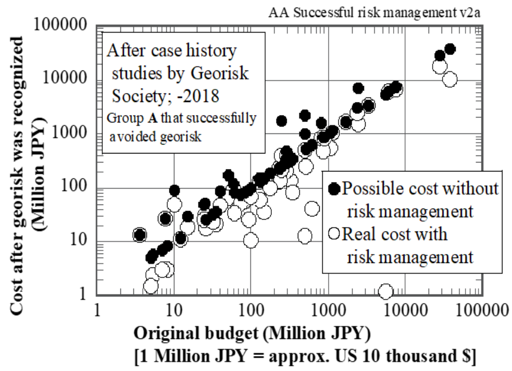

Figure 9. Comparison of cost with and without successful risk management (Group A).

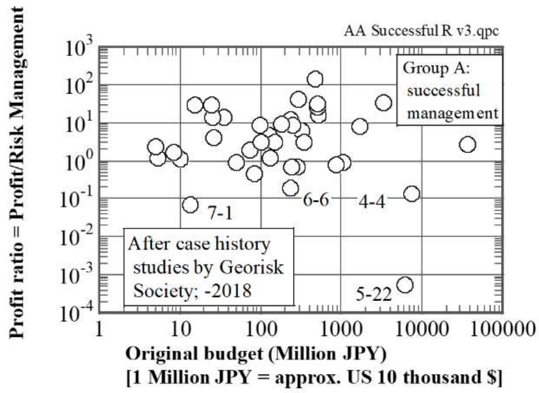

Figure 10. Profit ratio versus original construction budget (Group A).

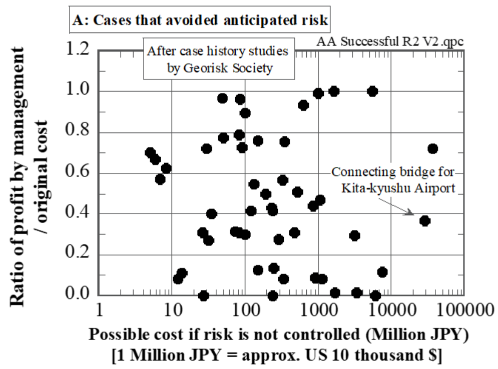

Figure 11. Ratio of profit and original project budget plotted against total cost after possible risk manifestation (Group A).

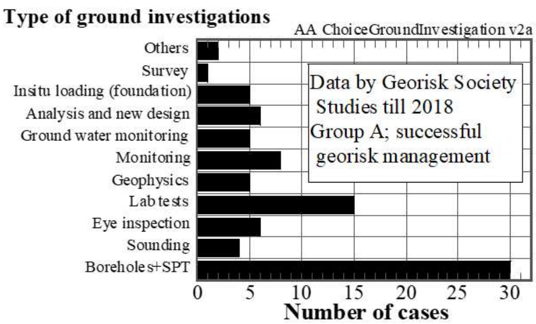

Figure 12. Types of investigation employed for georisk management (Group A).

The worst-scenario cost is a hypothetical idea of cost that would have been spent if georisk had not been managed. This worst-scenario cost is plotted in Fig. 11 against the profit divided by the original cost. The size of the worst disaster (worst cost) does not have a correlation with the profit ratio. This means that good profit ratio exceeding 0.5 is possible, irrespective of the project size. Note that the ratio = 1 means that the entire project was canceled to avoid the risk. Thus, cancellation is one of the choices to manage risk.

Fig. 12 presents the types of additional subsurface investigation that was employed after finding the possibility of georisk. The majority is borehole drilling and standard penetration tests partly because of the tradition of the engineering community (*SPT* is the must in practice) but also because the number of boreholes is considered important in heterogeneous subsoil. Moreover, laboratory soil testing is important because, if conducted on samples of good quality, the soil properties can be more directly determined than assessing by means of sounding data (*SPT*-N etc.).

3.2. *Group B in which georisk was not avoided and cost increased*

The cases in Group B were unsuccessful in georisk management. During construction, some incident happened and the existence of georisk was understood. After the incident, additional subsurface investigation was carried out and restoration works were conducted. Thus, the total budget as well as the construction period increased. A typical example of this group is the tunnel collapse in Fig. 3.

For this group, an attempt was made to assess the hypothetically reduced cost if georisk management had been performed. Fig. 13 compares the real cost increased by georisk and the hypothetically reduced cost. It is shown in this figure that difference between these costs decreases as the original budget (project size) increases. This probably implies that the influence of one georisk decreases as the project becomes greater and more complicated.

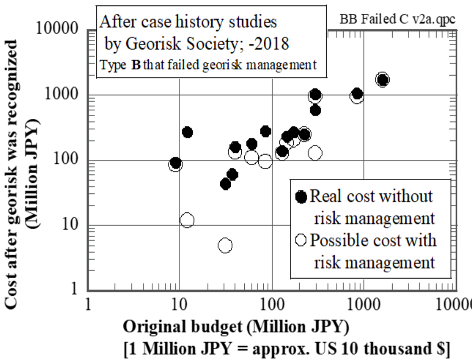

Figure 13. Comparison of real cost increased by georisk and possible cost reduced hypothetically by missed risk management (Group B).

Fig. 14 indicates that the ratio of profit / original budget may take a maximal at the intermediate size of the project and decrease afterwards. This again implies that the influence of single georisk is not very large and becomes less important in very big projects. Fig. 15 examines the ratio of the missed profit either over the total cost increase (real cost – original budget) or the possibly reduced cost if georisk had been reasonably managed. Although there is no clear trend, there is always a possibility to achieve the high ratio of 0.5 or greater.

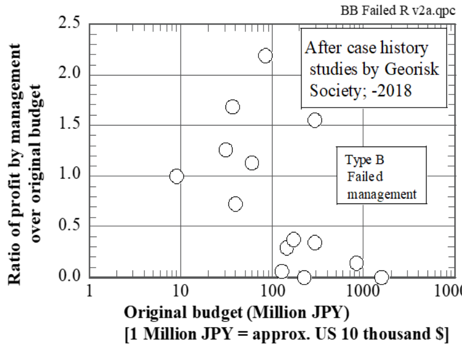

Figure 14. Relative profit and size of project (Group B).

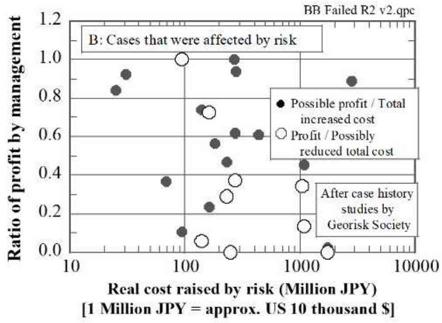

Figure 15. Ratio of profit over two types of costs versus real cost increased by georisk (Group B).

3.3. *Group C in which georisk was found in the intermediate stage of construction and was partially avoided*

In the projects of Group C, georisk was detected at an intermediate stage after the construction has started. Because of this early detection, it was possible to carry out additional subsurface investigation, change the design and/or construction methods, and mitigate the risk. Thus, the worst scenario was avoided. In other words, risk was not fully mitigated but appropriate georisk management reduced the total expenditure to an acceptable level. In this regard, Group C is called partial success. In addition to the actual total cost, another hypothetical cost was assessed. This is the worst-scenario cost that would have been the reality if no mitigative action had been taken.

Fig. 16 compares these two types of cost; the hypothetical cost without risk mitigation and the actual cost that was the consequence of georisk management. This figure exhibits three cases in which the actual cost was less than even the original budget and is considered good success of georisk management. Certainly, other cases are successful as well because the actual cost therein is less than the worst-scenario cost. Fig. 17 examines the ratio of the profit (difference between the worst-scenario cost without management – real cost) over the original budget. It is possible thus to achieve a very good ratio of profit. Fig. 18 illustrates that the profit ratio over the hypothetical worst-scenario budget is not related with the real cost after georisk management. Note that significant cost saving is possible even if georisk occurs during ongoing project.

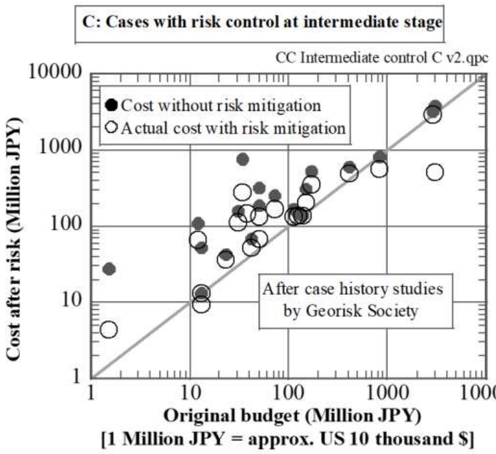

Figure 16. Relationship between costs with and without georisk management and the original construction budget (Group C).

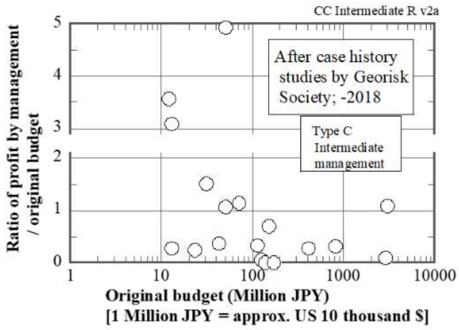

Figure 17. Ratio of profit in Group C changing with the original budget.

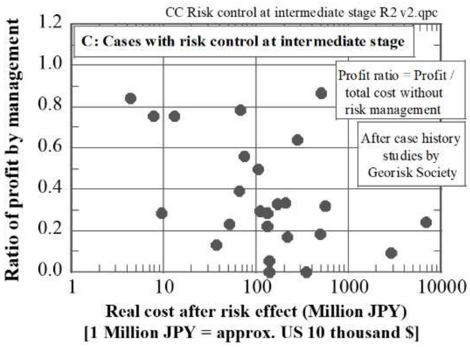

Figure 18. Ratio management profit over total cost without management.

3.4. *Overall view*

The overall summary of case history studies is presented in this section. First, Fig. 19 plots the profit as calculated above for all groups against the additional investigation budget. In most cases, the profit data lies above the 1:1 line, which means that the obtained profit was greater than the spent budget. When the profit is less than the investigation cost, engineers may be still happy with smooth progress of the projects, thus calling those projects "successful". Thus, detailed subsurface investigation deserves. Second, as shown in Fig. 8, many cases were reported from slope (cutting) projects. By reading the report in details, it was found that many troubles happened in cutting of natural slopes in which layers were normal to the surface (opposite dip). Presumably such a slope was supposed stable during design because sliding along a geological stratum was unlikely. Due to seepage of rain water along joints, weathering and deterioration chemically deteriorated deep portions and the slope material was weaker. After finding this, necessary stabilization measures were taken.

Third, it is noteworthy that most case history reports did not mention the change in construction period. Fig. 20 plots only available data for Groups A (successful georisk management) and B (failed management). The negative value in the vertical coordinate means elongated construction period. It is therefore understandable that Group B is associated with negative values. On the other hand, many cases in Group A report shortening of merely a few months. This, together with those cases without report of period change, suggests that the original construction plan was very conservative and prepared sufficient time for georisk management. In case of tunnel incident in Fig. 3, the entire railway construction was allocated with 10 years and the most difficult part, which was tunneling, was executed in the earliest time slot. Hence, delay of a few years in tunneling did not affect the progress of the entire project. The engineers were satisfied to complete the project within the time as the contract specified.

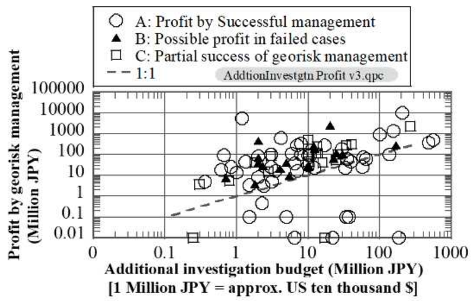

Figure 19. Overall summary on profit of georisk management changing with cost for additional subsurface investigation (Groups A-C).

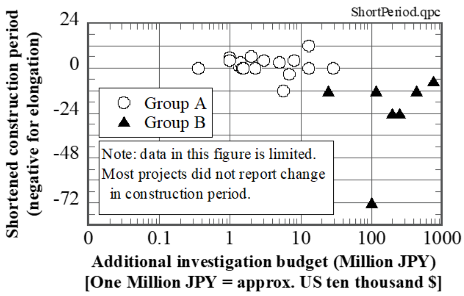

Figure 20. Change in construction period after georisk management (Groups A and B).

4. *Social mechanism of unreasonable reduction of subsurface investigation budget*

There are several social issues that try to reduce the subsurface investigation budget in the early stage of construction projects. The first is the insufficient budget on the client's side. Most public sectors are under high pressure from the people to reduce the budget and not to spend "unnecessary" expenses. Because the ground appears stable and not likely to collapse or cause troubles soon (normalcy bias), officers in charge have to reduce the investigation budget. Most probably, the officers intend to reduce the construction budget in the later stage of projects as well. However, georisk occurs and prevents this additional money saving. Against expectation, georisk may increase the total cost. To date, the ratio of georisk occurrence out of the total number of construction projects is unknown, although many projects encounter georisk. This makes it difficult to make pre-project negotiation with the officers.

The problem behind this situation is that most officers in charge of construction "budget" are not necessarily familiar with practice and tend to be affected by heavy pressure from the public and the media who are always insisting on budget saving.

General perception of "stationary" ground is another problem. People often consider that the ground is a stationary media without displacement/deformation and do not think of possible collapse or shear failure. They do not change this idea although they often see landslides in TV news. This attitude is related with the above-mentioned normalcy bias. As a consequence, the subsurface investigation budget is reduced first in planning of a construction project and it is still believed that good design is possible at reduced cost. They do not imagine the importance of quality (including number of investigations in a heterogeneous media) and misunderstand that good construction is possible once some subsurface investigation is conducted, irrespective of the quality and the quantity. For them, investigation is nothing more than a formality and detail is out of concern. Success of construction project is taken for granted.

5. What to do

5.1. *Quality improvement in subsurface investigation practic***e**

The aim of this paper lies in promotion of geotechnical subsurface investigation in construction projects on the condition that the greater efforts in this direction make it possible to achieve the less construction cost or avoid troubles during construction (georisk). To convince clients of these points, the quality of investigation has to be secured. It is unfortunate that some consulting firms do not pay much attention to the quality of laboratory soil tests or maintenance of laboratory/field equipment. To convince the clients of the value of investigation, it is essential for them to maintain all devices maintained in good condition.

The role model of good geotechnical investigators is found in the working style of medical doctors. It is possible to compare different stages of their activities as shown in Table 1. Both experts plan and conduct treatment/operation based on preliminary investigation. The difference is the significance of cost reduction. As a public activity, geotechnical project is under higher pressure to avoid money wasting. Clients, who are mostly public officers, have to make a great effort to reduce the cost. They start efforts with reducing investigation cost, followed by saving construction costs. As stated above, the insufficient budget for investigation leads to insufficient subsurface information and may trigger georisk. Although similar situation is found in medical examples, patients tend to allow more budget to be spent on preliminary investigation because insufficient data may result in failure of operation and loss of life. Although georisk may result in loss of life as well in geotechnical incidents, much less consideration is made. Some clients state that geotechnical engineer as a professional has to be able to make a correct judgement based on a limited number of data. This idea is wrong. Medical doctors do not want to start surgery without sufficient data. At this moment, the authors simply insist that more public concern is needed for avoidance of georisk. Note that individual medical doctors are authorized to choose expensive measures to cure patients.

Table 1. Similarity in played roles between geotechnical investigation and medical checks prior to surgery.

Geotechnical	**Medical**
Local geology & geomorphology	Health/medical history
Structures to be constructed	Current illness/surgery
Ground monitoring from outside	Health monitoring from outside
Sounding & boring	Camera, X-ray etc.
Undisturbed soil sampling	Sample incubation
Design	Treatment planning
Construction	Surgery
High pressure to save cost	Low pressure; accuracy is respected
Trouble and georisk	Unsatisfactory treatment

5.2. *Georisk knowledge transfer over generations*

Many construction projects encounter troublesome ground conditions. Most of them are treated successfully and do not cause serious troubles. Therefore, those valuable experiences are forgotten, although possibly recorded in construction diaries. Decades later when the next project takes place at the same site, georisk may occur. This was the case in the ground depression in Fukuoka City. Then, the question is how to transfer the experience (knowledge of adverse ground condition) over decades or over generations. Everybody thinks about electronic database and it is absolutely an important idea. A question concerns durability of electronic data; in other words, possible decay of electronic memory media. The first author proposes to embed a stone plate at a site of georisk and describe therein briefly what happened and how the problem was solved. The idea is certainly primitive but the information is durable for decades or more.

5.3. *Open-access data base of bore-hole and sounding information*

Bore-hole investigation and sounding exploration are essential parts of geotechnical subsurface investigation.

Many projects carry out those investigations and use the results for reasonable design. The problem is that the valuable data is not always open to the public and future projects in the vicinity cannot refer to the existing but hidden data. Even though the final design should be based on the project's own investigation, the preliminary planning and design can get advantage if data from past projects is available. Nowadays, governmental sectors tend to release the data for public use but private sectors do not.

Problems lying behind the current situation are as what follows.

(P1) Data is considered personal properties and protected by copy right regulations.

(P2) Adverse subsoil condition under factories and properties may affect the stock value of a company.

(P3) Quality of data is variable and cannot be fully trusted.

In response to them, the following ideas deserve attention.

(A1) Ground is a public property and open-access to subsurface information helps promote safer design of structures. Conflicts between public and private views occur in many situations. One should know that information on disaster-prone sites has been opened to the public for the people's safety.

(A2) Private sectors are promoted to make their facilities safer and achieve better business continuity. Construction of safe facilities at less cost meets this demand.

(A3) Users of open-access data base should bear in mind the quality issue. Although the *SPT*-N value or Atterberg limits may be subject to variation, the depth of bearing layer for pile foundation can be captured by any data base without much error.

The availability of bore-hole information to the public is variable from country to country. The first author found high availability in Iran in 2016, while there are countries that strictly control the access to subsurface information. In Japan, National Geo-information Center that was established in 2018 is expected to promote the availability of data that are owned by national and local public sectors. One problem is that the format of the bore-hole database is different among sectors. Some sectors release bore-hole profile by image only (hard copy or pdf file). Most electronically-released data uses different formats. Thus, the unified access to data is difficult.

It is still impossible to use the private bore-hole data. Thus, there is still a long way to achieve fully-open access data base. The concerned institutes and agancies will first work on data from pubic sectors and demonstrate people the great value of the open-access data base. It is hoped that people will then support the idea and the private sectors will join it.

6. Conclusions

This paper addressed mitigation of troubles related with geotechnical construction. The addressed troubles are called georisk and induced frequently by inaccurate or insufficient information on subsurface conditions. The major conclusions of this study are summarized in what follows.

(1) Georisk is often induced by insufficient soil data,

(2) The current trend towards cost saving results in insufficient budget for subsurface investigation and georisk management requires additional expenditures.

(3) Case histories show that the chance of cost saving increases with increased budget on subsurface investigation

(4) On the other hand, possibility of shortening the construction period is not clear.

(5) To promote subsurface investigation, the quality of investigation has to be improved.

(6) Open-access data base of investigation data as well as knowledge transfer over generations are additional measures to avoid georisk.

Acknowledgement

The present study was conducted as a collaborative activity among the Japanese Geotechnical Society, Georisk Society of which the second author is the Founder President, and the Japan Geotechnical Consultants Association to which the third author contributes as the managing director. The entire work is intended to contribute to the activity of the Professional Image Committee of ISSMGE that is chaired by the first author. The assistance and contributions made for the present study and, in particular, the collection of case history data are deeply appreciated.

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