Portfolio structuring and social implementation in the development of complex technology

— Case study of the development of GERAS and its evolution —

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A portfolio analysis of composing elements using a synthesiological method has been carried out for complex technology development, which involves fusion of various technology systems and elemental technologies. To assess the method's effectiveness, a case study was conducted on GERAS (Geo-environmental Risk Assessment System), a system for soil contamination diagnosis. The analysis spanned the entire development phase, from the generation of research ideas to the dissemination of results to society. The benefit of using this method was greater ease in system design and social implementation, through the analysis of critical components in the developmental process. I also discuss applying this method to novel areas, such as the development of technology for reconstruction after The Great East Japan Earthquake disaster.

Keywords **:** Environmental risk, risk assessment, soil contamination, synthesiology, portfolio structure

1 Introduction

Various reactions have been received since the publication of the paper on the Geo-environmental Risk Assessment System (GERAS) published in *Synthesiology* Volume 1 Number 4 (2008)[1] four years ago. There are direct requests from companies and local governments for the use of GERAS in environmental measures, and the paper has played a major role in its social diffusion. The paper has also been cited in many researches on risk assessment. However, more essentially, there were many comments on the methodology for establishing and diffusing the process and on the synthetic thinking that led to the development of GERAS. In another series of comments, constructive proposals and new viewpoints were provided, such as the optimal scenario as well as ways to fuse the elemental technologies in order to promote such complex technological development.

Most of the environmental technologies are clusters of diverse technological elements, and they realize products or social systems through analyses and processing of vast amounts of information. Although there are numerous R&Ds for technological elements, the technique to combine them is lacking. Ultimately it is necessary to integrate them and to fix them into society by maintaining the socioeconomic perspective. After the Great East Japan Earthquake of March 2011, there were high expectations for new developments for helping disaster restoration efforts by diffusing environmental technologies quickly in society.

In this paper, I shall discuss the scientific and sociological methods for developing GERAS further and for diffusing it in the industrial field. Also, since the combination and fusion of the complex technological elements are important, the discussion will be from new viewpoints including the drafting of whole scenarios in R&D, improvement of vulnerability of the system, and the construction of a portfolio and social implementation. Also, the author currently belongs to the environmental science department of a university, and would like to state the basic concept on the role and collaboration of industry, government, and academia in a technological development, mainly from the academic stance.

2 Current situation and future of technological development

In the development of GERAS, various types of analysis models were created in the past 10 years, and were applied to the actual environmental pollution problems. It is now employed in over 1,500 Japanese companies and organizations, and it has been established as a standard risk management tool. The users suggest various future developments, such as making it usable for economic risk evaluation in addition to environmental risks, or incorporating risk evaluations to social systems for soil environment and possibly to legal systems. As the next step, we are developing the economic model to quantify the cost-effectiveness of the remediation measures. We are also developing a submodel for the impact of soil pollution measures on the living environment and the ecosystem. In the new development, risk based decision-making and investigations of environmental economy are necessary, and the introduction of a methodology to fuse the humanities and

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sciences is mandatory. The efforts of industry, government, and academia are extremely important to actively employ human resources from social sciences. Specifically, AIST is working on difficult socioeconomic problems by conducting several joint researches with the environment divisions of local governments and public research institutions. Since universities harbor abundant human resources in social and environmental sciences, the amalgamation of academic fields that specializes in risk assessment is important. By conducting researches on soil contamination risk assessment through collaborative lectures and joint researches with universities as well as innovation school systems of companies, we obtained composite results unseen before. Joint researches on risk assessments of radioactive materials and new mathematical statistics methods are being conducted with universities. Also, through questionnaire surveys on the use and diffusion of GERAS, much know-how was accumulated such as functions that are truly needed in the assessment system, methods to feedback various data, and ways of securing reliability of the assessment results.

3 Development scenario and portfolio analysis

3.1 Composition of the portfolio

In order to achieve research goals in a short time, to realize products, and to implement the results in society in efficient ways, the most important point is the management of the processes including the composition of portfolios for individual elements as well as designing R&D scenarios. Indeed, it is extremely rare to be able to realize a product with only a single technology or a single technological system. The overwhelming majority of the cases are achieved by combining and fusing multiple technological elements. In such scenarios, the key to success is to perform preliminary portfolio analysis for what are the elemental technologies essential for technological development, what is the optimal combination of the technologies, and which elements are lacking within the team.

Figure 1 shows the portfolio of the technological elements (research topics) that were considered necessary for the development of GERAS. This figure shows the qualitative relationship in terms of the maturity of R&D and society (market). While the goal of the technological development for both is to show the upward vector, appropriate fusion is important in addition to the improvement of various technological elements such as of soil surveys, chemical analyses, environmental restorations, risk assessments, information analyses, physical explorations, and others. For example, although soil contamination information is deeply related to all elements, the possibility of fusion is determined by how such elements can be linked organically from the perspective of "risks." In addition, it was necessary to respond to the social demands for assessment of tsunami deposits and radioactive materials. That is, not only basic research and product realization research shown in the legend of the figure, but also the combination of the integration and demand-response researches based on social demand become important. In fact, there were no clear images from the beginning of the development, and only some technological elements were clearly positioned and defined. However, in the course of the development, methods were devised to accelerate the development when we hit the stage of the "valley of death." As discussed here, the construction of the portfolio provides important implications for the fusion and integration of technologies by clarifying the goals to be achieved. In addition to the advancement of the core technological elements, the dynamics of the technologies that must be newly deployed and those that must be accelerated become clear.

3.2 Weakness of elemental technologies and its reinforcement

The great mistake one tends to fall into in R&D is to focus on technological elements with high priority and lose sight of the peripheral technologies. This may be the disadvantage of the R&D in Japan, and there are many cases

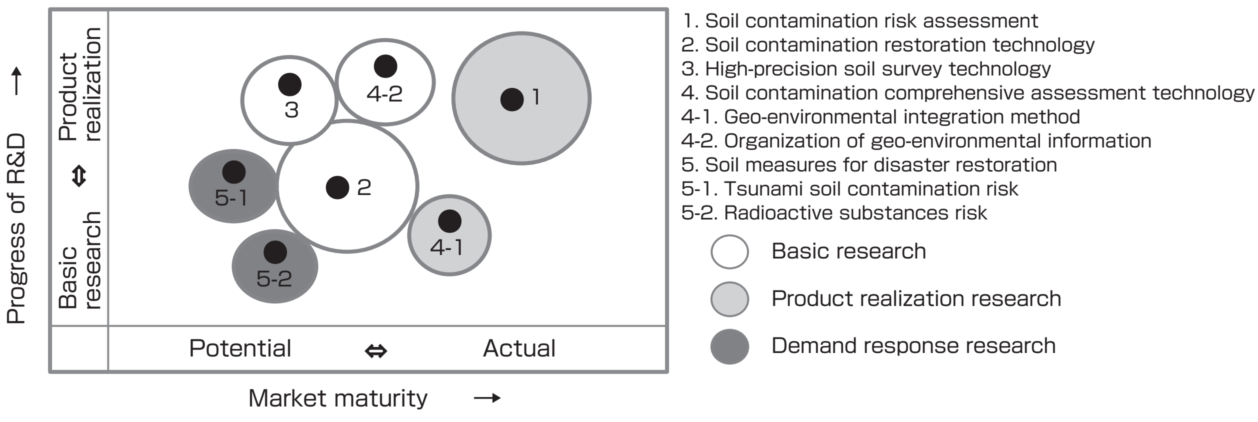

Fig. 1 Portfolio analysis in the development of GERAS

Shown in the diagram are the positioning of individual elements from the perspectives of the progress of R&D and maturity of market for soil contamination countermeasures, for the various technological elements that comprise GERAS.

in which the overview analysis of the technological system to be developed is lacking. It is important to discern the weakest technological element in a system, in addition to concentrating on the technological development that must be nurtured, after carefully analyzing the property of the whole system. Even if an excellent technology is completed, if the related peripheral technologies and the relationships are not maintained, the system may be unusable. In the development of GERAS, the initial researches on which we concentrated were soil surveys, soil contamination restorations, and mathematical statistics methods, and these were mainly handled by the researchers in the engineering field. Later, exposure assessment methods and system development were strengthened, as they were considered weak, and the researchers of different fields such as physical exploration and geochemistry joined the project. About ten years were spent to complete GERAS. The research development that involved field fusion and leadership in R&D were important.

Another important point was the construction of a database and analysis parameters that were essential for GERAS. To enable interactive risk assessment by the model creators and the users, the actual measurements of the contamination on site and the measurements of geology and groundwater were necessary. Since it was impossible for AIST alone to compile these data, the valuable on-site data and geological information were collected through joint researches with universities, local governments, and private companies. In such industry-government-academia collaborations, the Soil Contamination Working Group (the author was the chairman) of the Industrial Technology Cooperative Promotion Committee played a major role. For example, the studies included: survey and analysis of naturally-derived heavy metals conducted jointly with the Geological Survey of Hokkaido; risk assessment of organic compounds performed jointly with the Tokyo Metropolitan Research Institute for Environmental Protection; clarification of groundwater contamination by volatile organic compounds (VOC) done jointly with the Environmental Science Research Center of Yamagata Prefecture; and development of a geo-environmental informatics system conducted jointly with the Graduate School of Environmental Studies, Tohoku University.

3.3 Fusion of the technological development and its continuous development

The methods that were used to construct multiple components or elements and to fuse the elements in the development stage of GERAS are shown using several composition diagrams (Fig.2). First, with the conventional fields of environmental geology or geological contamination only, practical risk assessments could not be provided by these fields alone. Therefore, in the next stage (II), the fields of geochemistry and environmental sciences (biology, ecology, etc.) were introduced to fuse the fields and to enable scientific interpretation of the assessment results. Since it also became clear that the developments of exposure analysis and numerical simulation methods were bottlenecks (or weak elements) in the entire system, the technological fusion was attempted using the exposure and risk as integration scale, by incorporating the findings of risk science. Fortunately, these elements were highly compatible, and in stage (III), they served as the glue to hold the elements together, and played an important role in creating a new method of information processing based on information sciences and statistics. Also, for the social implementation of technology, sociology and the efforts in industry-academia collaboration were essential. In addition to the synthesis phase of technological

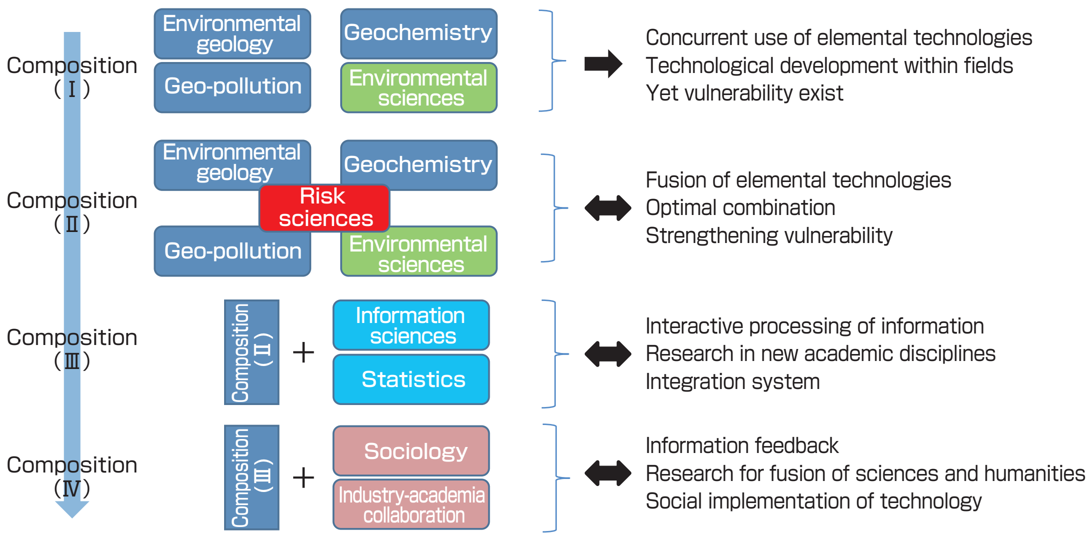

Fig. 2 Changes in the composition in the GERAS development
The characteristics of the composition in the four phases from beginning, during, and to maturity are shown, according to the research fields necessary for the development of GERAS and their composition. In addition to technical development, the final phase of social implementation is important.

development, it was most important to incorporate the final stage (IV) for social implementation. We believe that the optimal system design would not have been possible if any of the elements were lacking. One of the factors of success was the smooth linkage of the elements using risks as a scale (rate of occurrence of a phenomenon), and the by-product included the establishment of sociogeology (the author is the chairman of the Japanese Society of Geo-Pollution Science, Medical Geology and Urban Geology) that links geology to medicine (health).

4 Diffusion of the developed technology and realization of social implementation

4.1 Collaboration with society and industry and the feedback

The mechanism to diffuse the various types of GERAS developed in industry and society is also an important element. The aforementioned activities of the Soil Contamination WG, efforts in the academic activities for geo-pollution and urban geology, committee activities such as in councils and research groups in local governments, and involvement in businesses for soil surveys and environmental restorations with private companies were good opportunities to attract attention to GERAS. The activity on which we spent the most effort was the feedback of the assessment data from users that actually used the system. Normally, GERAS risk assessment is a forward analysis based on input data, but it is also possible to simultaneously conduct backward analysis from real contamination data. By repeating the two-way operation, not only did the reliability of the assessment results increase, but also the system efficiency increased. Moreover, good results were obtained in the communication with interested parties. By conducting risk assessments in realistic conditions rather than in a virtual environment, the risk awareness increased and the assessment results could be better understood. Therefore, researches in new academic disciplines are being done on optimizing prior and posterior distributions of risks using the sparse Bayesian modeling.[Term 1]

4.2 Public utilization of technology and its standardization

As a mechanism to diffuse a technology, utilization of public institutions of the government and local governments is effective. Since the release in 2008, the GERAS-1, 2 versions have been used in over 200 government and local government institutions. Using this name recognition, we made appeals to the persons in charge of the soil contamination measures at major government agencies whenever we had opportunities. It was officially employed as follows. GERAS-1, 2 were employed as risk assessment methods for the Site Assesser, which is a certification system to diagnose land use, in the Ministry of Economy, Trade and Industry. The improved new versions of GERAS-1, 2 were deployed as risk assessment tools for soil and sand from construction work at the Ministry of Land, Infrastructure, Transport and Tourism. Also, the thinking of GERAS was introduced into the risk assessment methodology at the Ministry of Environment and Tokyo Metropolitan Government. Recently, through joint research with the Environment Bureau of Tokyo, the new version of GERAS is being developed with added life cycle assessment (LCA). In the risk assessment of remediation measures, it is important to establish a comprehensive assessment method for individual life cycles from the perspective of environmental energy as well as environmental burden. Therefore, as shown in Fig. 3, the general assessment is done for total environmental impact, including those on the surrounding environment and ecosystem as well as the external environmental burden (CO_2 emission). To evaluate

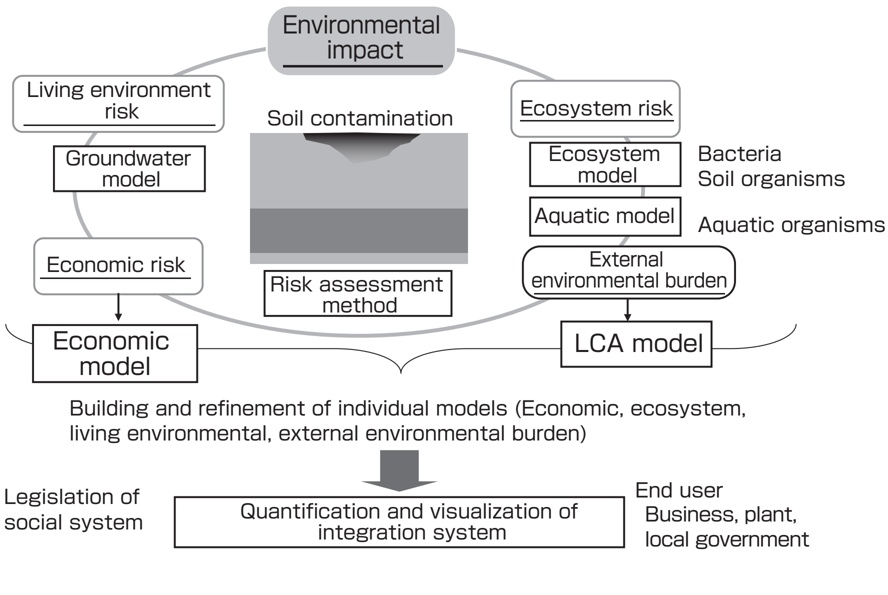

Fig. 3 Composition of the integration system in the development of GERAS
In addition to the assessments of soil contamination risk and environmental load, the integration system including economic model, groundwater model, ecosystem model, LCA model, etc. is developed.

risks on the living environment and ecosystem in addition to conventional soil contamination risks, the development of specific groundwater models, ecosystem models, and aquatic modes are in progress.

Moreover, there are moves toward international standardization of risk assessment methods for soil contamination. GERAS is widely used in advanced nations as well as in Asian countries, and there are efforts to standardize the methodology for exposure and risk assessment incorporated in GERAS, by creating a new framework in the International Standard Organization (ISO). Also, the standardization of the domestic risk assessment technology looking at international standardization is important, and there are efforts across the agencies and ministries toward JIS standardization. In the future, the research results will be opened to the world, and international efforts to diffuse and expand risk assessment technologies will be done, mainly for the Asian countries.

4.3 Social implementation and contribution to earthquake disaster restoration

Since the Great East Japan Earthquake and Tsunami of March 2011, the ways of R&D have been questioned. There emerged an attitude that the results obtained by research must be recognized by society as usable products and systems, and must be applicable to immediate issues that society faces. The environmental pollution that is the subject of GERAS was mainly geared for heavy metals and organic compounds that are regulated by the Soil Contamination Countermeasures Act, but after the earthquake, the R&D was accelerated for applications to tsunami deposits, debris of the earthquake and tsunami, and also for radioactive substances. This was done to enable social implementations by establishing risk assessment methods for diverse environmental pollution problems, and also in hopes of helping the disaster restoration.

Due to the giant tsunami that hit the coasts of East Japan, voluminous amount of tsunami deposits and debris were generated. Since some of the deposits and debris contained harmful chemical substances such as arsenic and lead, risk control was necessary. The author and co-researchers spent about a year from 2011 surveying the physicochemical properties of the tsunami deposits, and conducted environmental risk assessment using GERAS. As a result, it was found that there were some regions with high risk of arsenic in the coastal area from Miyagi to Iwate Prefectures, and there was a need for risk management of groundwater.[2] Also, it was found that the environment risk of heavy metals was small for about 95 % of the region, and the deposited sand and gravel could be reused as building materials for reconstruction efforts. This research received an award of the Japan Society of Civil Engineers in 2013, as an important research for social implementation.

The issue of soil contamination by radioactive substances such as caesium 137 is another extremely important issue from a social standpoint. Currently, new researches are being done to incorporate radioactive substances in GERAS, and we are now collecting observations on the behavior of radioactive caesium and other substances in the environment. Since the physicochemical properties of radioactive substances are known, it is possible to introduce them into GERAS at this point, but to improve the accuracy of risk assessment, it is necessary to clarify the interactions with soil particles and the migration properties according to their existence form. We are now organizing the parameters necessary for the GERAS analysis, such as building the database for soil properties in the East Japan region and monitoring the soil, water, and river sediments in Fukushima Prefecture.

5 Summary

In the development of the geo-environmental risk assessment system (GERAS), we went through valuable experiences from escaping the valley of death of R&D to the diffusion of results to society. As mentioned in this paper, new versions of GERAS have been developed with new viewpoints, and the results are being transmitted widely to society. Blessed with the efforts and good luck (serendipity) of the research team, the research seemed to progress smoothly. However, immediately after the earthquake, it felt as if we had entered the second valley of death, with added responsibility of supporting the reconstruction. Although still in the research stage, the course has been laid down for the completion of the assessment system that can handle assessment of tsunami deposits, earthquake debris, and radioactive substances. To overcome the difficulties and to fix the technology in society, sufficient understanding of the elemental technologies that comprise the system and the ability to fuse them are necessary.

Finally, I have learned that the following commitments are necessary for the research leader.

- Have many possessions in the attaché case (or drawer), meaning, accumulate various kinds of knowledge.
- Optimize the combinations of the things inside the drawer, meaning, optimize the combinations of knowledge.
- Clarify what are weak (and what are strong).
- Take on society and industry and navigate the great sea or venture out.
- Finally, show strong leadership.

Terminology

Term 1. Sparse modeling is one of the information analysis methods using the Bayes' theorem. Recently in geosciences, it has been utilized for the extraction of main information in big data and for the restoration of images. In the field of risk assessment, it is gaining attention as a new numerical method for estimating the preliminary risk from posterior occurrence rates, and it has been applied to few complex systems such as the ecosystem. The author and co-researchers are engaging in the research to apply the Bayesian statistics to the geochemical identification of the surface horizon and tsunami deposits.

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Author

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Has been in charge of research management from the planning, production, and diffusion of GERAS, and has spent effort in the diffusion of GERAS to industry and society at the Research Institute for Geo-Resources and Environment, AIST. Innovation Coordinator from April 2010; and Director, Research Institute for Geo-Resources and Environment, AIST from April 2012. Specialties are environmental engineering and environmental geology. Has worked on the solutions of various issues that lie between resources and environment, and on the diffusion of environmental technologies to industry. To diffuse the research results, served as member of the Tokyo Environment Council, member of the Chiba Prefecture Pollution Committee, specialist member of the Ibaraki Prefecture Environment Council, and others. Retired from AIST in March 2013. Currently in charge of the lectures for Geo-resources and Energy Science as professor, Graduate School of Environmental Studies, Tohoku University.

Discussions with Reviewers

1 Overall

Comment (Chikao Kurimoto, Evaluation Department, AIST; and Hiroaki Tao, Research Institute for Environmental Management Technology, AIST)

This article shows the synthesiological process of GERAS, a risk diagnosis system for soil and groundwater contamination, from its conceptualization to the diffusion into society. Based on the research paper [*Synthesiology*, 1(4), 276-286 (2008)] that discussed the process from its development to social provision, this article discusses the scientific and social measures for further technological development and diffusion into industry, as well as the role and collaboration of industry, academia, and government. Particularly, focus was placed on the overall scenario and portfolio to combine and fuse the technological elements, to clarify the elements that should be emphasized and those that are weak, and to outline the importance of utilizing them in system design and social implementation. The content of the article is synthesiological, and we think that it is appropriate for publication in *Synthesiology*.

2 Portfolio analysis

Comment (Chikao Kurimoto)

In this paper, you discuss the technologies for soil surveys, chemical analyses, environmental restorations, risk assessments, information analyses, and geophysical explorations, but in Fig. 1, you present the technologies and measures that integrate multiple technologies such as “1. Soil contamination risk assessment, 2. Soil contamination remediation technology, etc.” Please organize the terminologies such as the elemental technologies in the legend of Fig. 1 and the technological elements (research topics). Please explain the fusion and integration of the technologies in this article.

Answer (Takeshi Komai)

The legend of Fig. 1 and the terminologies in this paper were organized, and the details of the method of fusion and integration and the process composition were added to the article. I consider the portfolio shown in Fig. 1 as one expression of using the maturity of technology and society as an index. The three categories in the legend were revised to basic research, product realization research, and demand-response research, and the terminologies were organized to enable better understanding of the overall image. Throughout the paper, instead of an explanatory content, revisions and additions were made to present theoretical discussions that indicate synthesiological thinking.

3 Composition of the GERAS development

Comment (Chikao Kurimoto)

The three-phase composition of GERAS development and their characteristics are well organized and easy to understand in Fig. 2. In chapter 4, the activities for collaboration with industries and for social implementation are explained. I think the understanding will be enhanced if you can clearly show the flow from industrial collaboration to social implementation in Fig. 2. How about setting sociology and industry-academia collaboration of Fig. 2 as the composition stage IV and position it as the next phase?

Answer (Takeshi Komai)

I think the composition where the objective is the diffusion to society is the next step of these R&Ds or the final stage of the loop. I realized it was very important to add the process for social implementation, not just the technological development, in the synthesiological process. Therefore, based on the changes in the three phases in Fig. 2, I added a new process through social activities such as sociology and industry-government-academia collaboration as stage IV. Figure 2 was revised to show the four stages to make it understandable.

4 Sparse Bayesian modeling

Comment (Hiroaki Tao)

I think the “sparse Bayesian modeling” in risk assessment is a very important analysis method. I think it will help the readers’ understanding if you provide a brief explanation in the terminology section.

Answer (Takeshi Komai)

Sparse modeling is one of the information analysis methods using the Bayes’ theorem. Recently in geosciences, it is utilized for the extraction of main information in big data and for the restoration of images. In the field of risk assessment, it is gaining attention as a new numerical method for estimating prior risks from posterior occurrence rates, and it has been applied to some complex systems such as the ecosystem. The author and co-researchers are engaging in research to apply the Bayesian statistics to geochemical identification of tsunami deposits. I added a terminology section.

5 Public utilization of the technology and its standardization

Comment (Hiroaki Tao)

In “subchapter 4.2 Public utilization of the technology and its standardization,” you write, “Recently, through the joint research with the Environment Bureau of Tokyo, the new version of GERAS is being developed with added LCA.” I think you can indicate the potential of the new development if you describe the significance of adding LCA to the components. Perhaps LCA is included partially in the statistics and information science in Fig. 2, but can you add LCA to the components?

Answer (Takeshi Komai)

In the risk assessment up to now, the chronological analysis of the frequency or probability of phenomena or events was not done. However, in soil contamination measures, it is necessary to conduct chronological and spatial analysis for environmental load and energy balance of the various processes from survey to decontamination. Therefore, we developed a method to comprehensively evaluate the life cycles of countermeasures, from the perspective of environmental energy, and not just the environmental burden. The objective is to conduct general assessment of the environmental impact as a whole, including the effects on the surrounding environment, ecosystem, and earth environment (CO_2 emission). Figure 3 was newly added to explain these points.

Comment (Hiroaki Tao)

In “subchapter 4.2 Public utilization of the technology and its standardization,” you write about international standardization. Please describe if there are any actions toward JIS standardization.

Answer (Takeshi Komai)

For the international framework, we are already proposing the risk assessment model to ISO. In Japan, the introduction of the risk assessment method is considered within the legal system of individual agencies and ministries, and some have already employed it as the official framework. The next step is the standardization of the domestic risk assessment technology, with international standardization in mind. I think it is about time we begin the efforts across various ministries and agencies for standardization including JIS.

6 Integration system for GEARS development

Comment (Chikao Kurimoto)

For the synthesis of academia and research in Fig. 2, I think it is appropriate that you added Fig. 3 that presents integration and provides comprehensive discussion of the geo-environment. It shows the course for conducting assessments of the environmental risks that exist in the geo-environment, and for integrating the groundwater model, aquatic model, and the economic and LCA model that lie ahead. Please check the uniformity of the terminologies such as the economic model, ecosystem model, LCA model, and others in the figures, captions, and text of the article.

Answer (Takeshi Komai)

Figure 3 shows the scenario where the groundwater and aquatic models are developed in addition to the soil contamination, the economic and LCA models are developed in relation to the individual models, and the entire integrated system that links with the individual models is delivered to the end user. The terminologies were organized and revised so they would be uniform in the text and in the figure caption.