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Geoenvironmental Challenges – Beyond the 2011 East Japan Earthquake and Tsunami

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ABSTRACT: *Among the several geoenvironmental issues caused by the 2011 earthquake off the Pacific coast of Tohoku, this paper summarizes two issues, namely (1) treatment of disaster debris and utilization in geotechnical applications and (2) countermeasures against nuclide contamination. Utilization of the treated disaster debris for the recovery works have been conducted at the disaster affected areas, in particular at the areas subsided by this disaster. Characterization, standardization, and strategic utilization of the recovered soils obtained from the disaster debris have been discussed. Countermeasures against soils and wastes contaminated with nuclides require the approach from several geoenvironmental viewpoints, such as the design and performance evaluation of containment system for contaminated materials.*

INTRODUCTION

A massive earthquake of magnitude 9.03 (Mw), referred to as the 2011 earthquake off the Pacific coast of Tohoku, occurred at 14:46 on March 11, 2011, as the most powerful known earthquake ever to have hit in Japan, as well as one of the five most powerful earthquakes in the world since modern record-keeping started. The earthquake triggered tsunami that reached heights of up to 40.5 m at maximum in Miyako city, Iwate Prefecture and travelled up to 10 km inland in the Sendai plane in Miyagi Prefecture. “Totally” and “half” collapsed buildings counted more than 129,000 and 254,000 respectively. The recovery from this catastrophic disaster has been a crucial issue not only for the affected areas but for all over Japan.

This earthquake and subsequent tsunami caused several serious geoenvironmental problems mainly in the coastal area of the Tohoku and North-Kanto Regions in Japan. These geoenvironmental problems may include (1) generation of disaster debris and tsunami deposits, (2) contamination with salt, (3) land subsidence, and (4) geoenvironmental contamination with nuclides caused by the Fukushima Daiichi Nuclear Power Plant. Among these geoenvironmental issues, this paper focuses on the management of disaster debris and tsunami deposits, as well as the countermeasures against nuclide contamination.

Treatment of the disaster debris in the affected areas has been conducted to be completed by March 2014. Since the disaster debris and tsunami deposits include a significant amount of soil fractions, proper treatment to recover these soils and utilization of these recovered soils in geotechnical applications in re-construction works are strongly expected. The second chapter of this paper presents the results of characterization and potential utilization of such soils recovered from the disaster debris.

As for the nuclide contamination related to geoenvironmental engineering, radioactive Cesium exists (1) wastes and incinerator ashes, (2) sewage sludges, (3) soils and wastes generated from nuclide decontamination works, and (4) excavated soils and wastes from construction works, etc. Countermeasures against such soils and wastes contaminated with nuclides require the approach from several geoenvironmental viewpoints, including the design and performance evaluation of containment system for contaminated materials, which are summarized in the third chapter of this paper.

DISASTER DEBRIS

Generation and treatment of disaster debris

Immediately after the 2011 earthquake off the Pacific coast of Tohoku and subsequent tsunami,

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the government estimated that approximately 20,000 Gg (20,000,000 ton) of disaster debris had been generated through this disaster mostly in Iwate, Miyagi, and Fukushima Prefectures. Locations of these prefectures are shown in Figure 1. In addition, the government has also decided that about 10 million tons of tsunami deposits transported by the tsunami require proper treatment as well. These numbers are comparable to those generated at the previous catastrophic disasters such as 2010 Haiti earthquake, 2008 Si-chuan earthquake in China, etc [1]. Since it is geographically and economically unrealistic to construct new waste disposal facilities having a sufficient capacity to accept these wastes, which corresponds to several times of the annual generation of municipal solid waste in each local municipalities, utilization of these materials is required. Since the national government decided that treatment of debris and tsunami deposits should be completed by 2014 March, proper treatment and utilization of the materials treated from these disaster wastes have strongly been expected.

Treatment of the disaster wastes generated by this earthquake has been a big challenge, since such a large amount of such mixed wastes had never been generated in Japan before. A significant fraction of these wastes corresponds to the soils which are the tsunami deposits. Figure 2 shows the fractions of generated waste materials in Iwate and Miyagi prefectures estimated in March 2012 [2, 3, 4].

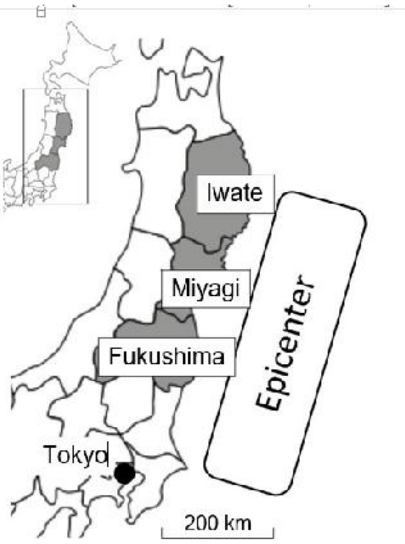


Fig. 1 Location of Iwate, Miyagi, and Fukushima Prefectures

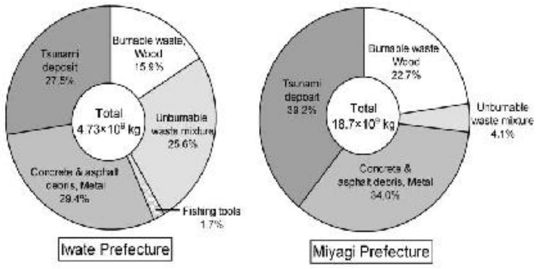


Fig. 2 Composition of disaster debris in Iwate and Miyagi Prefectures [2, 3, 4]

Primarily in Japan, local municipal governments are responsible for disaster debris treatment. As for the 2011 East Japan earthquake and tsunami, the national government decided to complete disaster waste treatment within 3 years by national subsidy. While the detailed processes of disaster debris treatment vary by the municipality, common system can be illustrated as shown in Figure 3. First, the debris was cleared at the affected sites, collected, and transported to the primary storage sites, which counted more than 300 sites at maximum. At the primary storage sites, wastes were stockpiled depending on the separation upon collection, such as waste mixtures dominant with burnable materials such as collapsed wooden houses, concrete-dominant stockpiles, tatami mat dominant stockpiles, soil-dominant stockpiles, etc. Only rough separation, such as separation using operation vehicles and manual separation, is conducted. After the rough separation, “advanced treatment,” or mechanical treatment, is conducted at the secondary storage and treatment sites, which were set 1 or 2 sites per one municipality (approximately 30 sites in Miyagi and Iwate prefectures). This “advanced treatment” can also be called “mechanical treatment” because various mechanical equipments/machineries have been installed, and also be called “advanced separation” because most of the systems installed in each municipality result in the separation. “Separation” systems mostly consist of “crushing” and “separating” processes. The basic idea of the separation system is to separate mixed wastes into fractions based on the substances, such as burnable materials, unburnable materials, metals, etc, as shown in Figure 4 (a) illustrating the general flow of disaster waste treatment. As a result, significant amount of soils and other fine fractions can be obtained. As for the soil-dominant stockpiles which are mainly the collections of tsunami deposits, only sieving (separation using sieve) is conducted to separate soils from the wastes.

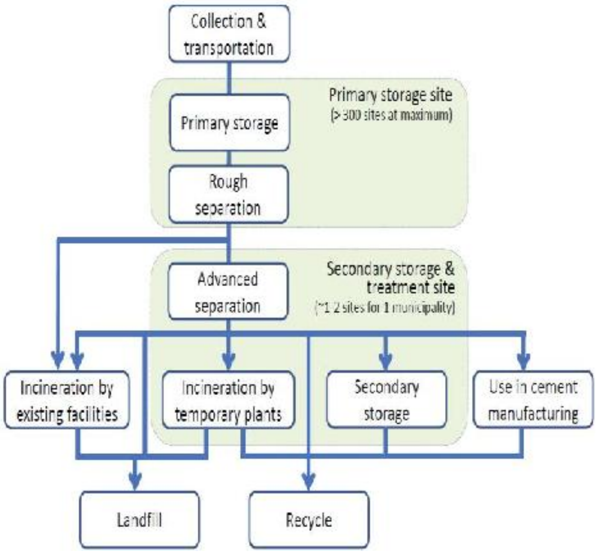
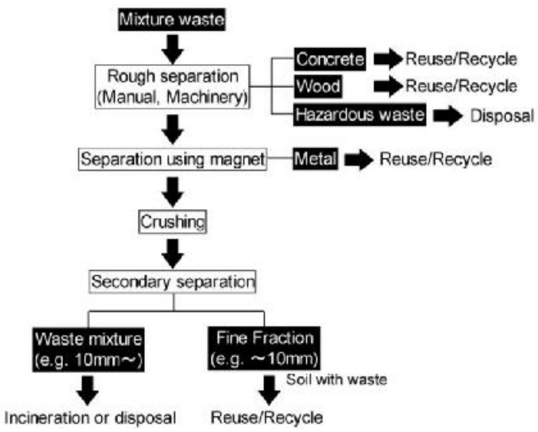
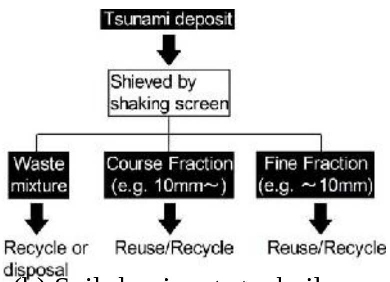


Fig. 3 Basic flow of disaster waste management



(a) Waste-dominant stockpiles



(b) Soil-dominant stockpiles

Fig. 4 Typical flow chart for the treatment of waste-dominant disaster debris and tsunami deposits or soil-dominant disaster debris [4]

The question is where the materials obtained from the advanced separation process can be accepted. As shown in Figure 3, the materials generated from the advanced separation may be subjected to the incineration treatment in the existing incineration plants, incineration using temporally plants, secondary storage, utilization, landfill, and use for cement manufacturing. Capacity of the existing incineration plants in the local areas was limited. Treatment site of each municipality therefore installed temporally incineration plant. Discussion has been made on the utilization, in geotechnical application, of incinerator ashes discharged from these temporally plants. In Iwate prefecture, disaster wastes after advanced separation have been decided to be used for cement manufacturing, because one cement factory exists in the coastal area. This cement factory has also been damaged by tsunami, but recovered in several months, and started to produce cements using disaster debris treated materials in 2011 November after the trial production. As for the separated soils, or recovered soils, some of them have been utilized in re-construction works, while some have been stored in the secondary storage sites to wait for the utilization. As mentioned the following sub-sections, utilization of such separated soils has been an important geoenvironmental challenges.

The system of "advanced treatment" varies from sites to sites, depending on the different given conditions of materials to be treated (amount of disaster debris generation, primary separation and storage, type of original soil, etc.), site environments (area limitation, air pollution risks, number of primary storage sites, etc.), and local resources (waste incinerators, cement plants, etc.). At the most municipalities, construction companies have been engaged in the advanced treatment business of such mixed wastes based on their own proposals. One example of the systems is illustrated in Figure 5, in which three "separation" processes using sieving machines (Vibrating screen, 35-mm-opening rotating screen, 15-mm-opening rotating screen), one "crushing" process, and three "separation" processes using manual separation, and two "separation" processes using special machine to separate burnable fractions from waste mixtures. Evaluation of these treatment systems from the viewpoint of treatment efficiency and applicability to construction materials is a next inevitable consideration.

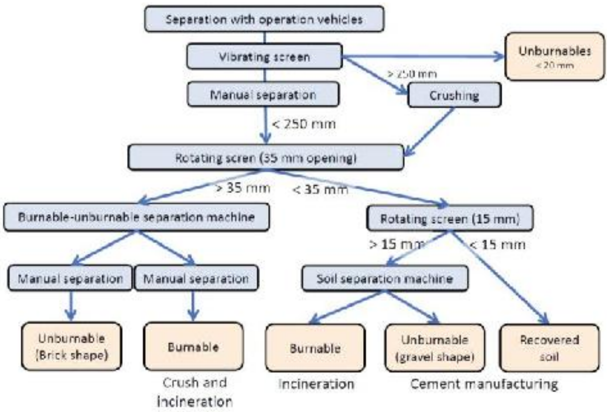


Fig. 5 Example of disaster waste treatment system

Utilization policy and limitations

At the affected areas, ground subsidence has occurred due to the earthquake. For example, maximum lateral and vertical movements were recorded 5.3 m and -1.2 m respectively at Oshika Peninsula in Miyagi Prefecture. Many other places along the Pacific coast from Iwate to Fukushima Prefectures suffered more than 0.5 m ground subsidence [5]. These ground subsidence are considered mostly permanent, and caused secondary problems such as difficulty in recovery and resettlement and sanitary problems because the stored water was not able to go out from the area in early months. Therefore, embankment is necessary for the recovery both for residential, commercial, and green areas. Utilization of the materials treated from the disaster wastes and tsunami deposits have been strongly expected. In particular, the geotechnical utilization of the soil fraction in disaster debris and tsunami deposits has become a big challenge for geotechnical engineers since temporal and spatial variations in the geotechnical properties of waste-mixed soils or recovered soils should be considered if a large amount of these soils are used for constructing embankments and levees against tsunami in reconstruction projects.

To promote the utilization of disaster debris in recovery works, the Japanese Ministry of Land, Infrastructure, Transports and Tourism (MLIT) has established two technical guidelines to construct

(1) parks and green spaces as a redundancy zone against huge tsunamis in which embankments be constructed using disaster wastes as shown in Figure 6 and (2) fill embankments at the areas where ground subsidence occurred significantly due to the earthquake [6, 7]. Green areas had a positive effect on reducing the energy of tsunami and trapping the flowing obstacles such as cars, while some trees did not have sufficient root depth, which resulted in insufficient resistance against tsunami. Therefore, embankment construction for green areas is considered advantageous to provide a sufficient distance from groundwater table to the ground surface.

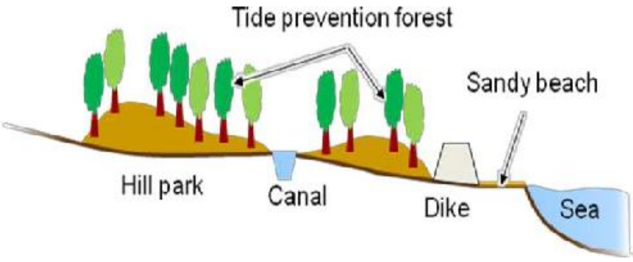


Fig. 6 Green park construction for disaster recovery using waste materials [8]

Table 1 Criteria for the materials treated from disaster wastes used for embankment [7]

Item	Criteria
Maximum grain size	< 300 mm
Cone index	> 400 kN/m^2
Salt content	< 1 mg/g (in principle)
Electrical conductivity	< 200 mS/m
pH	6.0 – 9.0
Swelling (at CBR soaking)	> 3%

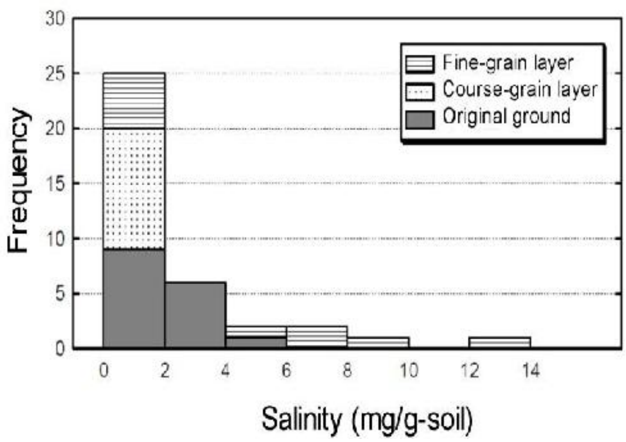


Fig. 7 Salinity of the tsunami deposits collected at farmlands in Fukushima Prefecture [9]

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The material criteria proposed by the above guideline are shown in Table 1. There have been several discussions about these criteria. As for the salt content, to prevent the corrosion of underground steel materials such as steel piles and adverse impacts on vegetations, a salt content lower than 1 mg/g is generally required. However, this technical guideline might consider the situation to construct embankments at the tsunami affected areas, in which the salt concentration is already high because they are located close to the ocean, although significant portion of the materials such as tsunami deposits may exceed this criteria of salt content as shown in Figure 7 indicating the results of salt content of tsunami deposits [9]. It was anticipated that the strict application of this criteria might limit the utilization of materials. Therefore, this technical guideline also covers the utilization of the materials having a salt content higher than 1 mg/g.

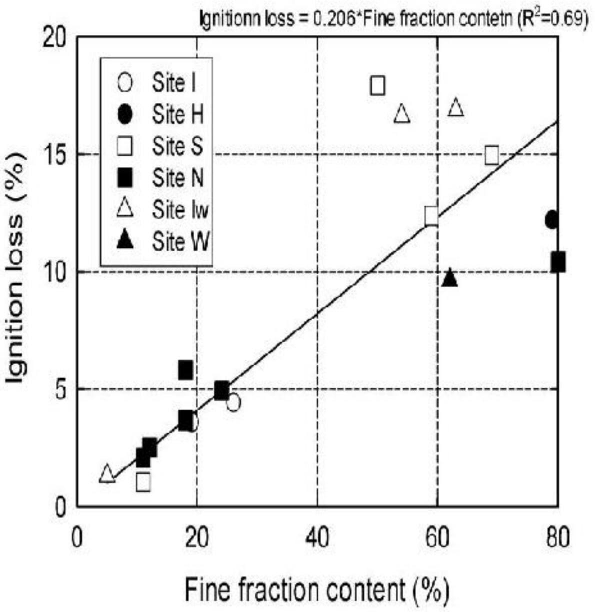

Fig. 8 Relationship between the fine fraction content and ignition loss of tsunami deposits [4]

Another concern of such materials is the potential of degradability which may cause the generation of gas and leachate and ground settlement. In the field of waste management, ignition loss has been used to evaluate the degradability. However, the ignition loss is not only reflected by the materials which will be degradated but also other components such as hydration products and organic components naturally contained in the original soil, while standardized test for ignition loss only uses the samples smaller 2 mm in particle size. For example, if the materials (soils) are rich in fine fraction, they will exhibit higher ignition loss as shown in Figure

Therefore, it is required to establish the criteria to evaluate the intactness of materials.

Characterization of the soils recovered from disaster debris

Evaluating the engineering properties of tsunami deposits and soils separated and/or obtained from disaster waste mixture is an important issue to ensure the performance such as stability of the earthen structures if they are used in geotechnical applications in recovery works. However, no experience or knowledge on the treatment and geotechnical properties of such waste mixed soils has been accumulated before. Evaluation of the engineering properties of such soils obtained from the disaster debris have therefore conducted to be carried out by the researchers and engineers including the JGS (Japanese Geotechnical Society) Geoenvironmnetal Technical Committee on the 2011 East Japan Earthquake and Tsunami chaired by the first author.

As mentioned in the previous sub-section, wastes with large sizes are removed from the mixture at a first temporary storage site (rough separation), and further separation is conducted using trommels, vibrating screens, or other machineries/equipments at a secondary storage site (secondary separation). Morita et al. (2012) sampled the soil-waste mixtures and separated soils from several temporary storage sites, and conducted the experiments to evaluate their basic properties such as particle density, particle size distribution, ignition loss, waste composition, compaction, and cone index [8, 10]. Non-separated soil (sample A-1, A-3) and roughly separated soil (A-2) were taken at a first temporary storage site in Town A, and non-separated soil (B-1, B-2) were collected at a storage site in Town B. Secondary separated soil (C-1) was taken at a secondary storage site in Town C. Roughly separated soil (D-1), which was passed through a 20-mm opening screen, was taken at a temporally storage site in Town D. The samples used in Morita et al. (2012) are indicated in Figure 9 in terms of the treatment system [10].

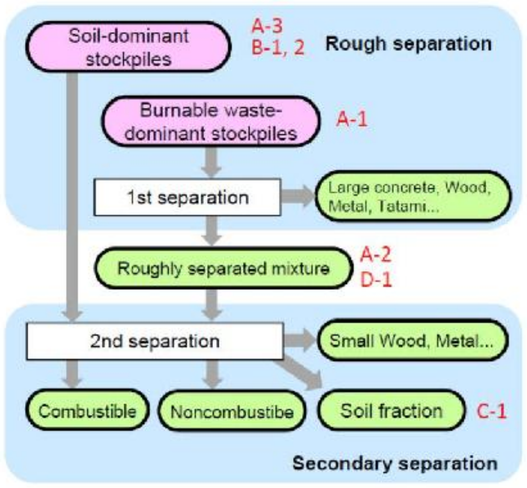

Fig. 9 Typical treatment procedure of waste mixed soil [8, 10]

One of the important considerations is the effect of combustible substances on the engineering properties, since these combustibles may be deteriorated, resulting in the emission of gas and leachate and ground settlement. Ignition loss test conducted on the sample sieved by a 2 mm opening screen accord-ing to JIS A 1226 does not consider all the organic matters in the soil-waste mixture mainly consisting of combustible wastes such as wood chips, paper scraps or plastic, etc. Because most of these combustible materials exhibit the particle sizes larger than 2 mm. Therefore, manual separation test in which the fraction over 2 mm was separated into combustible, noncombustible, and soil particles was conducted [10].

Compaction characteristics of each sample are shown in Figure 10 [10]. The numbers listed in left side of each compaction curve mean the combustible content larger than 2 mm of each sample, obtained according to the aforementioned method. From this result, the samples of high combustible content such as A-1 and D-1 exhibited a high optimum water content for obtaining the maximum dry density. Besides, the maximum dry density values of such samples are low (1.1 to 1.4 g/cm^3) compared to other samples (1.7 to 2.0 g/cm^3). This is because the samples which contain large amounts of combustible substances cannot be properly compacted, and the densities of combustible substances are low. The samples which contain smaller volumes of combustible substances exhibited lower optimum water contents and higher maximum dry densities, and have clear peaks of compaction curves. Therefore, it is expected that such samples can be used as geo-materials with sufficient compaction. Further investigation should evaluate how the waste and combustible matters will affect the engineering properties for a long term by their decomposition if the waste mixed soils or separated soils be used in geotechnical applications.

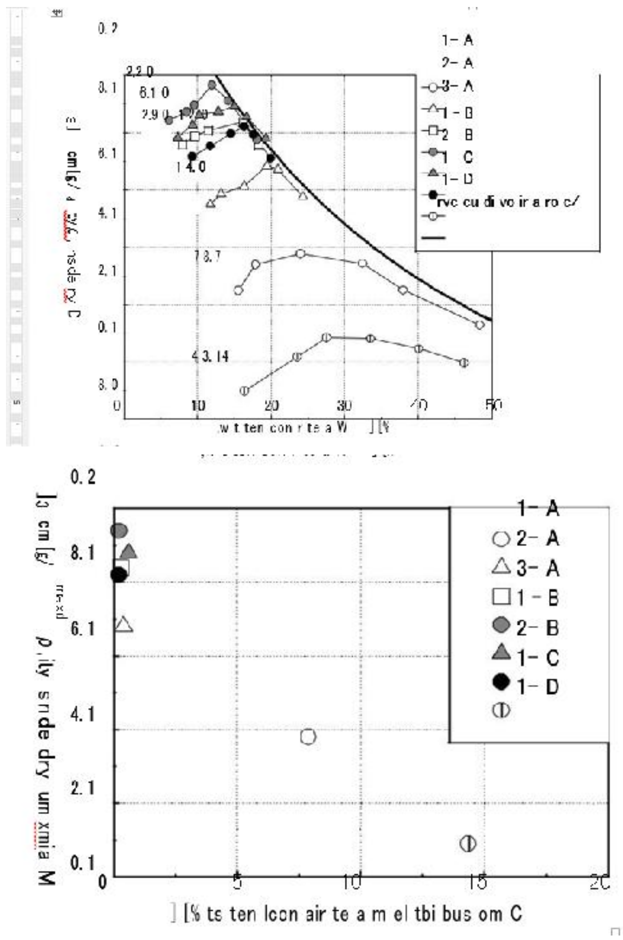

Fig. 10 Compaction curves of the soils recovered from disaster debris (upper, Numbers are the content of combustible substances in percentage) and maximum dry density versus combustible contents (lower) [10]

Recovered soils in civil engineering applications

There are several types of soils recovered from the disaster debris, depending on the original soil, the collection manner and stockpiles, the treatment system, etc. as shown in the previous sub-chapter.

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Based on the results presented as well as the results conducted by the JGS Geoenvironmental Technical Committee on the 2011 East Japan Earthquake and Tsunami [11, 12], "Guideline for Utilization of Treated Wastes for the Recovery Works" has been published by Iwate Prefecture (2013) [13], in which "recovered soils" are categorized into three classes, namely "Recovered Soil Class A," "Recovered Soil Class B," and "Recovered Soil Class C," depending on their origins and natures. "Recovered Soil Class A" is the soils separated from the soil-dominant stockpiles, mostly tsunami deposits, while "Class B" and "Class C" are the finer fractions (mostly soils) obtained from waste-dominant stockpiles, after rough and secondary separations respectively. This categorization intends the strategic utilization of the recovered soil materials. Class A recovered soils have started to be used in the applications for recovery of seaside forests in Iwate Prefecture.

Table 2 Classification of recovered soils designated by Iwate prefecture [13]

Classes	Contents
Recovered Soil Class A	Soils separated from soil-dominant stockpiles
Recovered Soil Class B	Soils separated from waste-mixed stockpiles, and satisfying the criteria for utilization
Separated fine fractions (Recovered Soil Class C)	Fine fractions obtained through the treatment process of disaster waste

There have been hesitations to promote the utilization of the soils recovered from the disaster debris, in particular from the waste-dominant stockpiles. Construction sectors of the local governments are rather conservative against the utilization of the soils obtained from the disaster wastes, because long-term properties are not well known as mentioned in the previous chapter. Since the sectors to manage the construction works are different from the sectors to proceed the disaster waste management, utilization will not occur automatically even for the manual. The incentive to use these soils is important.

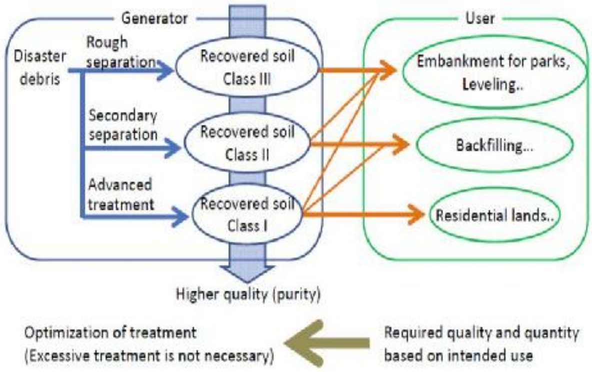

Fig. 11 Ideal basic concept of optimization of disaster debris treatment based on the utilization of recovered soils in geotechnical applications

The recovered soils with higher quality may be obtained depending on the manner of treatment. In general, more expensive treatment system might result in the higher quality of the recovered soils. However, such high quality soils may not be required for some applications, while other applications do. Therefore, if we have the information about what types of applications are expected, what qualities and quantities of soils are required for these applications, and when these soils are needed, constructing the optimum system of disaster waste treatment might have been possible, as shown in Figure 11 for the future disaster. Integration of treatment system and application of treated materials has started to be discussed by the related institutions including the local governments. The recovery and re-construction works have been done by national, prefectural, and municipal governments, of sections of either environmental, construction, or forestry, as well as the private sectors including railway companies. Necessity of management of the soil materials beyond these sections has started to be aware in the related institutions.

NUCLIDE CONTAMINATION

Management of the radioactive contamination of surface soils caused by the accident at Fukushima Daiichi Nuclear Power Plant, which includes fall-out radioactive materials such as ^{134}Cs and ^{137}Cs, has been a serious geoenvironmental issue. The tsunami generated by the earthquake caused great damage to widespread coastal areas in the Tohoku Region including Fukushima prefecture where the

Fukushima Daiichi Nuclear Power Plant is located. On March 14, 2011, hydrogen explosions occurred in both the No.3 and No.1 reactors. As a result of the explosions, large amounts of radioactive materials including ^{131}I, ^{134}Cs, and ^{137}Cs were released into the atmosphere. Radioactive Cesium exists (1) wastes and incinerator ashes, (2) sewage sludges, (3) soils and wastes generated from nuclide decontamination works, and (4) excavated soils and wastes from construction works, etc. Countermeasures against such soils and wastes contaminated with nuclides require the approach from several geoenvironmental viewpoints.

Sewage and waste materials may contain radioactive substances concentrated through natural and artificial processes in some areas in the Tohoku and Kanto regions in Japan. The wastes which contain radioactive materials lower than 8,000 Bq/kg are allowed to be disposed of at existing MSW (municipal solid waste) landfill sites, according to regulations. However, these regulations only consider the exposure of radioactive substances to workers, but not the fate and transport of these substances in the subsurface, including landfill sites. For example, the leaching ratios are very different between MSW bottom ash and fly ash, as shown in Figure 12, even though they may contain the same level of concentration of radioactive cesium. While radioactive cesium in MSW bottom ash may be stable in terms of the leaching (only 1.6% leaching ratio), 79.8% cesium from fly ash, and 62.5% from granulated fly ash, will leach out [14].

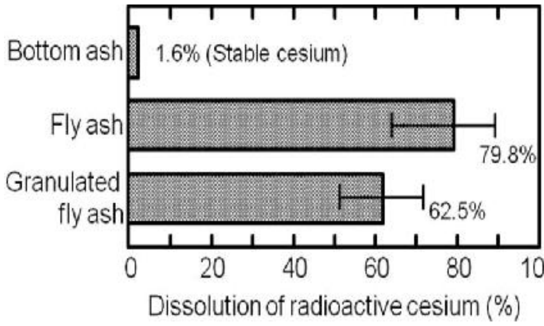

Fig. 12 Leaching ratio of radioactive cesium from MSW in-cinerator ashes [14]

In addition, it should be noted that the basic concept of Japanese MSW landfills is to allow the infiltration of rainfall into the waste layer, and to accelerate the biodegradation under semi-aerobic condition, as well as to wash out the contaminants that may be dissolved. At the landfill sites designed following such basic concept, if the leaching ratio of radioactive cesium in the disposed wastes is high, it will be important to evaluate its fate and transport, because the existing landfill leachate treatment facilities will not be able to treat the radioactive cesium. Installing soil layers to act as a sorption layer against radioactive cesium is required for MSW bottom ash as shown in Figure 13, while soil layers both for hydraulic barrier and for sorption are required for MSW fly ash which exhibits higher leaching potential as shown in Figure 14. Since these sorption layers may be constructed over the existing waste layer, differential settlement and chemical compatibility should be taken into account. Geosynthetic reinforcement such as geogrids and/or geosynthetic barriers such as GCLs may be considered for the safe disposal of such waste materials. Researches on the applications of such geosynthetics against differential settlement and chemical compatibility are expected [15].

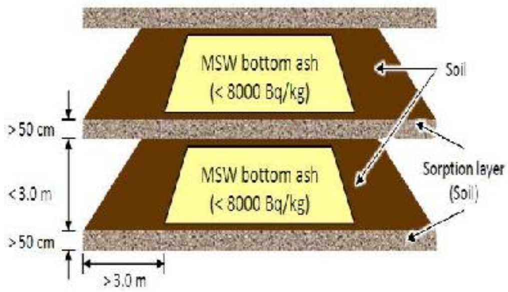

Fig. 13 Landfill of MSW bottom ash lower than 8000 Bq/kg with lower dissolution (edited from NIES 2012 [14])

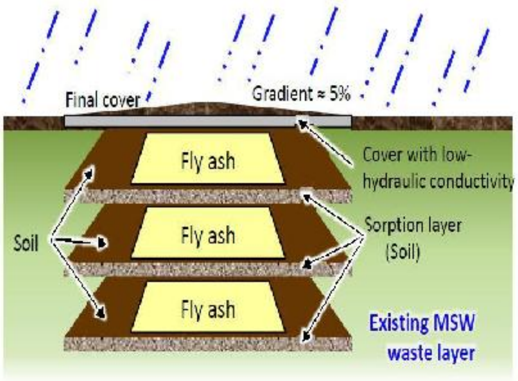

Fig. 14 Landfill of MSW fly ash lower than 8000 Bq/kg with higher dissolution (edited from NIES 2012 [14])

For the wastes higher than 100,000 Bq/kg and waste soils and plants discharged through decontamination works, the scenario consisting of storage at a temporary yard, then at an interim storage facility, and finally at a permanent disposal site, has been de-cided by the national government (Figure 15). At some temporary yards, GCLs are used as a containment barrier. At the interim storage facilities, as well as at the permanent disposal sites, establishment of design method including the use of geosynthetics for reinforcement, hydraulic, and chemical barrier, filtration, and other functions, is strongly anticipated.

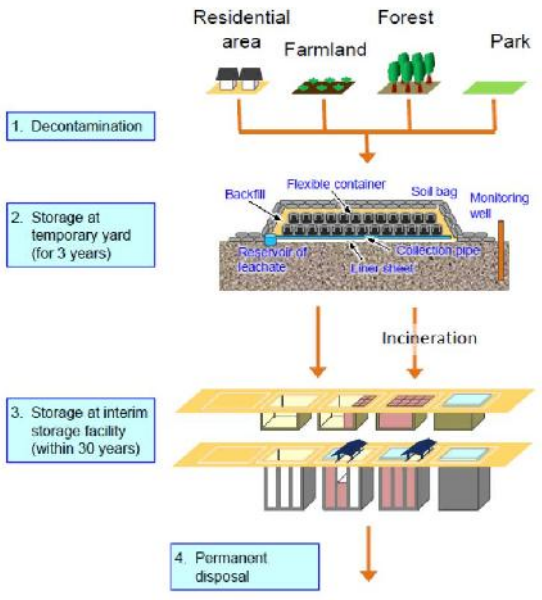

Fig. 15 Disposal scenario of radioactive contaminated soils and wastes [16]

CONCLUDING REMARKS

Among the geoenvironmental issues caused by the 2011 East Japan earthquake and tsunami, the generation of disaster wastes and tsunami deposits and the geotechnical investigations on the soils recovered from the disaster debris, as well as the countermeasures against nuclide contamination of soils and wastes, are presented in this paper. Utilization of disaster debris for the recovery works after proper treatment has been proposed at the disaster affected areas, in particular at the areas that suffer from subsidence. Characterization of waste mixed soils obtained from the disaster debris that has been conducted to evaluate the applicability to construction materials for disaster recovery requires further research in understanding the physical, chemical, and biochemical effects. As for the nuclide contamination due to nuclear power plant accident, concerns should be addressed to (1) wastes and incinerator ashes, (2) sewage sludges, soils and wastes generated from nuclide decontamination works, and (4) excavated soils and wastes from construction works, etc. Fate and transport of radioactive cesium including leaching from MSW bottom and fly ashes is an important consideration. Performance of sorption and barrier layers applied in the existing MSW landfill sites should be discussed from the viewpoints not only of chemical phenomenon but also physical and mechanical phenomenon.

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