1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake, off the eastern coast of Japan, with Mw = 9.0 occurred at 14:46 JST (05:46 UTC) on 11 March 2011. It is the most powerful earthquake to have struck in Japan. Moreover, an extremely destructive Tsunami followed the earthquake. Following the Tohoku earthquake and Tsunami, the Fukushima Dai-ichi nuclear power plant (37.4250°N, 141.0300°E; Fig. 1), which is located in the towns of Futaba and Okuma of Fukushima Prefecture, was damaged. The drywell vent and the explosion of the nuclear power plant released radioactive materials including $^{134}\text{Cs}$ (2.1 year half-life) and $^{137}\text{Cs}$ (30.2 year half-life). Through the air, these radioactive materials contaminated soil, river, sea, and so on. The total amount of $1.3 \times 10^{16}$ Bq of $^{137}\text{Cs}$ released into the environment by the Fukushima Dai-ichi nuclear power plant from March 11 to April 15, 2011.$^{1}$

Many examinations of radioactive materials derived from the Fukushima Dai-ichi nuclear power plant have been reported since the accident outbreak. For example, several kinds of radio-
Radioactive materials (\(^{131}\)I, \(^{132}\)Te, \(^{134}\)Cs, \(^{136}\)Cs, and \(^{137}\)Cs) were found in Chiba Prefecture, located about 220 km south from the Fukushima Dai-ichi nuclear power plant\(^2\). Radioactive \(^{131}\)I, \(^{134}\)Cs, and \(^{137}\)Cs were detected at Fukuoka Prefecture, located about 1000 km southwest of the Fukushima Dai-ichi nuclear power plant, within 3 days after the explosion at No. 2 reactor\(^3\). The total \(^{137}\)Cs contamination investigated by integrating daily records and the model simulation showed that \(^{137}\)Cs contaminated soils in large areas of eastern and northeastern Japan whereas western Japan was sheltered by mountain ranges\(^4\).

Shizuoka city, the central part of Shizuoka Prefecture, is located ~370 km southwest from the Fukushima Dai-ichi nuclear power plant (Fig. 1). Shizuoka city is surrounded by hills or mountains on three sides (Fig. 2). Around 400 m and 300 m height hills are located at west and east sides of Shizuoka city, respectively. On the other hand, there are lots of mountains, including the Mt. Takayama (717 m height), at northern part of Shizuoka city. The Abe River flows western part of the Shizuoka urban area from north to south. The Warashina River, biggest tributary of the Abe River, flows toward the urban area from northwest to southeast and meets with the main stream, the Abe River.

A previous study calculated that up to 500 Bq/m\(^2\) of \(^{137}\)Cs was deposited in Shizuoka city using model simulation\(^4\). The System for Prediction of Environmental Emergency Dose Information (SPEEDI) simulation calculated that few thousands Bq/m\(^2\) of \(^{137}\)Cs was deposited in Shizuoka city before end of March\(^5\). This and other simulations show that radioactive materials derived from the Fukushima Dai-ichi nuclear power plant arrived in Shizuoka city around noon on March 15, 2011\(^5,6\).

Incidentally, maximum 679 Bq/kg of Cs radioactivity was detected in tea leaves processed at the Warashina area of Shizuoka city on June 2011 (Fig. 2).

In the present study, we measured the radioactivity of \(^{134}\)Cs and \(^{137}\)Cs of surface soil samples in the urban and vicinity area of Shizuoka city including Warashina area in order to clarify the distribution of \(^{134}\)Cs and \(^{137}\)Cs radioactivity in surface soil. Then, we discussed the cause of radioactivity distribution pattern to topography and weather condition.

---

**Fig. 2. Distribution of \(^{137}\)Cs radioactivity in soil at Shizuoka city.**

Sampling stations are shown in Stn. 01 to 43. Monitoring post of radiation dose rate is located at the Kita-Ando monitoring site. The roof rain-water catchment system is installed at the Mabase site. The topographic map used is publishing by Geospatial Information Authority of Japan.
2. Materials and Methods

2.1. Surface soil sampling

Surface soil sampling was carried out four days (November 11, 2011; December 4, 2011; March 20, 2012; March 30, 2012) in Shizuoka city. Sampling sites were selected soil surface such as city parks and open air of public places without covered by tree branches. Surface soil samples were collected at 43 stations (total 60 samples) (Fig. 2). To measure $^{134}$Cs and $^{137}$Cs radioactivity, circular surface soil samples were collected using a stainless thin guide pipe with $\sim$11 cm in diameter (93.3 cm$^2$, approximately 1 cm depth).

2.2. Depositional pit sample

At the Mabase site of northern part of the Udo Hills (Fig. 2; 35.0042°N, 138.4612°E), mud samples were collected in a depositional pit and final water tank of the roof rain-water catchment system. All rain-water fallen on the house roof (90 m$^2$) were completely channeled to a depositional pit and overflowed into the final water tank (1000 L). The depositional pit has been filled with ca. 5 kg charcoal since $\sim$18 years ago. From the depositional pit, dead plant fragments, charcoal, and mud of the pit bottom were separately collected. From the final water tank, a mud including small amount of sand grains up to a few mm in diameter was collected.

2.3. Measurement of radioactivity

Each sample was dried and put into a plastic container called U-8 container (inner diameter $= 47$ mm; height $= 59$ mm). The activity was measured using high purity Ge detectors. The spectra were analyzed with the Gamma Studio software (SEIKO EG&G Co., Ltd.). In the analysis, counting efficiency curves prepared using a set of gamma standard U-8 sources with different heights, certified by the Japan Radioisotope Association, were used.

We report the $^{134}$Cs and $^{137}$Cs radioactivity of surface soil using both Bq/kg and Bq/m$^2$ units. The Bq/m$^2$ value obtained was converted the calculated Bq value of surface soil sampling area (93.3 cm$^2$) into 1 m$^2$ using the measured Bq/kg value, because Cs atoms are mainly adhered to the soil surface. Radioactivity data in this paper were corrected decay to March 15, 2011 (the day many radioactive materials were released). The measurement for each sample was continued until at least statistical error to be less than 10 %.

3. Results and discussion

3.1. Distribution of $^{134}$Cs and $^{137}$Cs radioactivity in Shizuoka city

The radioactivity of $^{134}$Cs and $^{137}$Cs in surface soil sample is summarized in Table 1. In Shizuoka city, 37 to 2435 Bq/m$^2$ (1 to 95 Bq/kg) of $^{134}$Cs and 57 to 2242 Bq/m$^2$ (2 to 98 Bq/kg) of $^{137}$Cs were observed. The production ratio of $^{134}$Cs and $^{137}$Cs radioactivity in origin was roughly 1:1 (Fig. 3). According to previous study, it was estimated that up to few thousand Bq/m$^2$ of $^{137}$Cs deposit in Shizuoka city using model simulation \cite{4,5}. Our data accorded with the scale of $^{137}$Cs radioactivity estimated using model simulation program.

Distribution map of $^{137}$Cs radioactivity is shown in Fig. 2. Because of the ratio of $^{134}$Cs and $^{137}$Cs was roughly 1:1, the distribution of $^{134}$Cs radioactivity was nearly equal to that of $^{137}$Cs.

3.2. Reasons for the Cs radioactivity distribution pattern

To explain this distribution pattern of $^{137}$Cs radioactivity in this study area, we would like to estimate plausible pollution processes by wind transportation and deposition of precipitation.

The atmospheric mass included and transported radioactive Cs released from the Fukushima Dai-ichi nuclear power plant in the morning on March 15, 2011. In Shizuoka city, radiation dose rate is continuously measured in full-time at the Kita-Ando monitoring site by Shizuoka Prefecture Government \cite{7}. This site is located near sampling stations of Stn. 08 and 33 (Fig. 2). At this monitoring site, an apparent increase of radiation dose rate was observed from 11 a.m. to noon on March 15, 2011 as shown in Fig. 4. After the pulse of radiation spike, the next secondary broad spike of radioactivity was observed on March 21 and 22, 2011. On the other hand, $^{137}$Cs radioactivity of air dust collected by air sampler was observed on March 15, 2011 in Shizuoka University, Japan (sampling station of Stn. 01), whereas $^{137}$Cs...
Radiation dose rate increase on March 15, 2011 is associated with wind transportation. According to the Japan Meteorological Agency (JMA), the local wind direction of in and around Shizuoka city was northeast wind in the morning and followed the southeast wind in afternoon on March 15, 2011\(^\text{11}\). According to the simulation model of SPEE DI, Shizuoka city was completely covered by pollutant atmosphere on March 15, 2011, and completely diminished in the morning on March 16, 2011\(^\text{11}\).

With all information, it is plausible that radioactive materials primarily reached to Shizuoka city including the sea of the Suruga Bay (the Pacific Ocean) with northeast wind in the

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Station No.</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Sampling Date</th>
<th>(^{134}\text{Cs}) (Bq/kg)</th>
<th>(^{137}\text{Cs}) (Bq/kg)</th>
<th>(^{134}\text{Cs}) (Bq/m(^2))</th>
<th>(^{137}\text{Cs}) (Bq/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZK-001</td>
<td>Stn. 01</td>
<td>34.9641°N 138.4314°E</td>
<td>November 18, 2011</td>
<td>17.9 ± 0.9</td>
<td>19.1 ± 0.8</td>
<td>491.8 ± 25.0</td>
<td>526.0 ± 22.9</td>
<td></td>
</tr>
<tr>
<td>SZK-002</td>
<td>Stn. 01</td>
<td>34.9635°N 138.4329°E</td>
<td>November 18, 2011</td>
<td>16.3 ± 1.2</td>
<td>22.5 ± 1.2</td>
<td>432.5 ± 31.1</td>
<td>595.8 ± 31.2</td>
<td></td>
</tr>
<tr>
<td>SZK-003</td>
<td>Stn. 01</td>
<td>34.9619°N 138.4352°E</td>
<td>November 18, 2011</td>
<td>11.9 ± 0.9</td>
<td>11.6 ± 0.8</td>
<td>451.0 ± 33.1</td>
<td>441.3 ± 30.1</td>
<td></td>
</tr>
<tr>
<td>SZK-004</td>
<td>Stn. 01</td>
<td>34.9620°N 138.4358°E</td>
<td>November 18, 2011</td>
<td>10.6 ± 1.0</td>
<td>12.3 ± 1.0</td>
<td>367.1 ± 33.4</td>
<td>591.3 ± 30.6</td>
<td></td>
</tr>
<tr>
<td>SZK-005</td>
<td>Stn. 01</td>
<td>34.9622°N 138.4359°E</td>
<td>November 18, 2011</td>
<td>39.9 ± 1.7</td>
<td>40.9 ± 1.6</td>
<td>1059.6 ± 42.6</td>
<td>1084.7 ± 41.4</td>
<td></td>
</tr>
<tr>
<td>SZK-006</td>
<td>Stn. 02</td>
<td>34.9736°N 138.4145°E</td>
<td>December 14, 2011</td>
<td>120. ± 0.8</td>
<td>15.4 ± 0.8</td>
<td>406.2 ± 28.0</td>
<td>518.0 ± 27.6</td>
<td></td>
</tr>
<tr>
<td>SZK-007</td>
<td>Stn. 03</td>
<td>34.9692°N 138.4016°E</td>
<td>December 14, 2011</td>
<td>11.3 ± 0.9</td>
<td>12.4 ± 0.8</td>
<td>337.3 ± 27.6</td>
<td>370.9 ± 25.4</td>
<td></td>
</tr>
<tr>
<td>SZK-008</td>
<td>Stn. 04</td>
<td>34.9685°N 138.3733°E</td>
<td>December 14, 2011</td>
<td>7.4 ± 0.4</td>
<td>9.3 ± 0.4</td>
<td>253.4 ± 24.3</td>
<td>270.4 ± 24.3</td>
<td></td>
</tr>
<tr>
<td>SZK-009</td>
<td>Stn. 05</td>
<td>34.9784°N 138.3560°E</td>
<td>December 14, 2011</td>
<td>45.8 ± 1.9</td>
<td>43.4 ± 1.6</td>
<td>1468.0 ± 59.5</td>
<td>1389.6 ± 52.8</td>
<td></td>
</tr>
<tr>
<td>SZK-010</td>
<td>Stn. 06</td>
<td>34.9777°N 138.3407°E</td>
<td>December 14, 2011</td>
<td>1.4 ± 0.4</td>
<td>2.3 ± 0.3</td>
<td>36.9 ± 10.4</td>
<td>56.7 ± 9.0</td>
<td></td>
</tr>
<tr>
<td>SZK-011</td>
<td>Stn. 07</td>
<td>34.9777°N 138.3379°E</td>
<td>December 14, 2011</td>
<td>42.4 ± 1.9</td>
<td>41.0 ± 1.8</td>
<td>1186.0 ± 65.2</td>
<td>1148.8 ± 49.5</td>
<td></td>
</tr>
</tbody>
</table>

### Table 1: Sampling data of surface soil and radioactivity concentrations of \(^{134}\text{Cs}\) and \(^{137}\text{Cs}\).

radioactivity was observed (only \(^{131}\text{I}\) was observed) from March 20 to March 22\(^\text{10}\).
morning on March 15, 2011. Then, radioactive materials were transported by the southeast wind in the afternoon on March 15, 2011. However, an increase of radiation dose rate was not observed at the Kita-Ando monitoring site in the afternoon on March 15, 2011, because the movement of radioactive materials toward the urban area was severely shielded by the Udo Hills and hillsides (Fig. 5). The ascending wet air current faced to southward of the Udo Hills would be controlled by adiabatic ascent process and produce cloud, because the wind direction changed from northeast to southwest in afternoon on March 15, 2011.

As a result, $^{137}$Cs radioactivity at northward of the Udo Hills is lower than that of southward, and $^{137}$Cs radioactivity in the urban area is the lowest in Shizuoka city. On the other hand, radioactive $^{137}$Cs was transported in the Warashina area through the Abe and Warashina Rivers because there are no hill sides which block the wind in the south of this area (Fig. 5). In this report, it is also important information that pollutant fine particles of air mass, introduced by the southeast wind in the afternoon on March 15, 2011, was relatively not homogenous in the scale of 10 km width.

3.2.2. Radiation dose rate increase on March 21 to March 22, 2011

Radiation dose rate increase on March 21 to March 22, 2011 is accompanied with precipitation of between March 20 and 22, 2011 (Fig. 4). Generally, because of the wet deposition, radiation dose rate increase when it rains. Wet deposition caused the increase of radiation dose rate at the Kita-Ando monitoring site between afternoon of March 21 and 22, 2011. However, the radioactive Cs could be hardly included in the second plume and the increase of radiation dose rate in this period would be caused by mainly $^{131}$I. Moreover, the meteorological data shows northeast wind blew from the evening of March 21 to the evening of March 22. With all these factors, pollutant fine particles with radioactive Cs was fall down by precipitation near the Fukushima Dai-ichi nuclear power plant and only $^{131}$I in the gaseous form arrived in Shizuoka city due to the northwest wind transportation.

This study shows that it is difficult to observe radiation dose

---

Fig. 3. Original production ratio of $^{134}$Cs and $^{137}$Cs radioactivity.

Fig. 4. The radiation dose rate and the precipitation in Shizuoka city on March 2011.
The radiation dose rate was measured by Shizuoka Prefecture Government. The precipitation was measured by Japan Meteorological Agency.
using only one monitoring post in urban area of Shizuoka city, which has complex and variable topography. This retains the potential to make a mistake for judgment of observation.

3.3. Hot spot formation of the roof rain-water catchment system

For the roof rain-water catchment system at the Mabase site, the radioactivity of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ in mud, charcoal, and plant fragments samples is shown in Table 2 which shown in the same manner of the soil results in Table 1. The radioactivity of radioactive Cs per square-meter (Bq/m² unit) was calculated with the total radioactivity and roof area.

The radioactivity of radioactive Cs per kg (Bq/kg unit) was very high level relative to the highest values of surface soil sam-

Fig. 5. Cross-section view and pattern of expected Cs movement.
While the radiation dose rate was not so high in the afternoon, 11 a.m. to noon on March 15, 2011, increase of radiation dose rate was observed from 11 a.m. to noon on March 15, 2011, that is the Warashina area and southern slope of the Udo hills, that is the Warashina area and southern slope of the Udo hills. The reason of the shielded air dust by the Udo hills, the decrease of radiation dose rate in the afternoon on March 15, 2011 is the reason of the shielded air dust by the Udo Hills and hillsides.

To research the distribution of the 134Cs and 137Cs radioactivity were observed. Generally, high 137Cs activity was mainly observed along the southern slope of mountains and hills, that is the Warashina area and southern slope of the Udo Hills. The local wind direction of in and around Shizuoka city was northeast wind in the morning and followed the southeast wind in afternoon on March 15, 2011. Thus, pollutant fine particles with radioactive Cs were arrived at Shizuoka city by northwest wind transportation in the morning and were arrived by southwest wind transportation in the afternoon on March 15, 2011.

The decrease of radiation dose rate in the afternoon on March 15, 2011 is the reason of the shielded air dust by the Udo Hills and hillsides.

The Bq/m² value of mud sample was relatively lower than that of surface soil in Shizuoka city. It is probably due to loss of the total amounts of radioactive Cs during overflow of rain water suspended fine particles and adsorption to the roof of Cs of some quantity. Moreover, the 137Cs radioactivity of charcoal was one digit lower than mud samples. This lower value indicates that the surface of charcoal was covered by old sediment before the Fukushima Dai-ichi nuclear power plant accident (the mud sample in the depositional pit contained an accumulation of total dust for ~18 years long).

4. Conclusions

To research the distribution of the 134Cs and 137Cs radioactivity in surface soil in Shizuoka city and relate the cause of distribution pattern to topography and weather condition, soil samples were collected at 43 stations (total 60 samples) and measured the 134Cs and 137Cs radioactivity.

In Shizuoka city, 37 to 2435 Bq/m² (1 to 95 Bq/kg) of 134Cs radioactivity and 57 to 2242 Bq/m² (2 to 98 Bq/kg) of 137Cs radioactivity were observed. Generally, high 137Cs activity was mainly observed along the southern slope of mountains and hills, that is the Warashina area and southern slope of the Udo Hills.

At the Kita-Ando monitoring site, increase of radiation dose rate was observed from 11 a.m. to noon on March 15, 2011, while the radiation dose rate was not so high in the afternoon.

Acknowledgements

We appreciate the financial support from Shizuoka University, Japan. We are grateful to Drs. Hiromitsu Haba and Yoshitomo Uwamino (RIKEN) and Dr. Akio Noto (Tokyo Medical and Dental University) for use of the gamma standard U-8 sources. We thank undergraduate students, Messrs. Masato Okada, Kazuki Okochi, Keisuke Kunita, Syo Otake, and Kouta Shimizu (Shizuoka University) for their help in soil sampling and sample preparations for measurements. We thank Dr. Atsuo Suzuki and Mr. Akihiro Suzuki (Shizuoka Prefecture Government) to provide the radiation dose rate data. We would like to thank two anonymous reviewers.

References


6) Institute de Radioprotection et de Sûreté Nucléaire <http://www.irsn.fr/FR/popup/Pages/animation_dispersions_rejets_19mars.aspx>

