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Impact on Absorbed Dose Rate in Air from Asphalt Pavement Associated with Transport Infrastructure Developments on Phu Quoc Island, Vietnam

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The absorbed dose rate in air was measured using the car-borne survey technique on Phu Quoc Island, Vietnam in December 2015. The average absorbed dose rate in air measured on asphalt pavement was 61 ± 15 nGy h^{-1} and higher dose rates in air were observed along asphalt roads, whereas the average value measured on unpaved roads was 29 ± 6 nGy h^{-1}, meaning the former average dose rate was 2.0 times higher. The average dose rate for the entire island was 44 ± 20 nGy h^{-1}. The estimated annual external effective dose was 0.29 mSv y^{-1}, which is 60% of the worldwide average.

Key words: absorbed dose rate in air, car-borne survey, asphalt pavement, Phu Quoc Island, dose rate distribution map, annual effective dose

1. Introduction

Environmental radioactivity and the associated external exposure due to gamma radiation depend primarily on the geological and geographical conditions, and they appear at different level in the soils of each region in the world[1]. It has been estimated that the dose contribution in the environment from natural radionuclides is 85% while the remaining 15% is from cosmic rays and nuclear processes[2]. It is critical to assess the effects of radiation exposure as well as to determine the distribution of natural radionuclides in the environment. Currently, many researchers worldwide have been measuring the absorbed dose rates in air as well as in artificial structures such as buildings and the materials they are made of. Especially, large amounts of natural radionuclides such as ^{40}K and the ^{238}U series and ^{232}Th series are contained in artificial structures, resulting in effects on the absorbed dose rate in air and external exposure[3, 4].

Phu Quoc Island, the largest island in Vietnam, is located in Kien Giang Province, in the westernmost area of Vietnam (Fig. 1). The island has a total area of 589 km^2 and its population was approximately 91,200 in 2014. In recent years, transportation infrastructure developments such as roads, bridges, elevated bridges, and the construction of high-rise buildings and resorts have proceeded on this island in association with economic developments in Vietnam. Thus, there is a possibility that the absorbed dose rate in air and external exposure in this island have changed. Some studies have been performed to determine the environmental radioactivity in Vietnamese soil samples[6-8] and the average absorbed dose rate in air (range) and annual effective dose for all of Vietnam were estimated to be 72 ± 25 nGy h^{-1} (18 − 149 nGy h^{-1}) and 0.540 mSv, respectively. However, Phu Quoc

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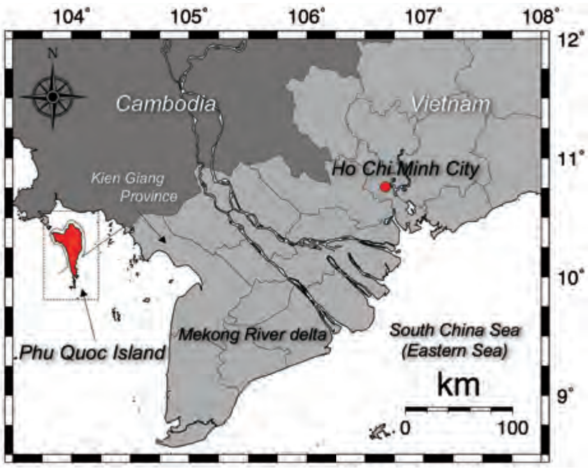

Fig. 1. Map showing location of Phu Quoc Island, Vietnam drawn using the Generic Mapping Tools (GMT) of Wessel and Smith[5].

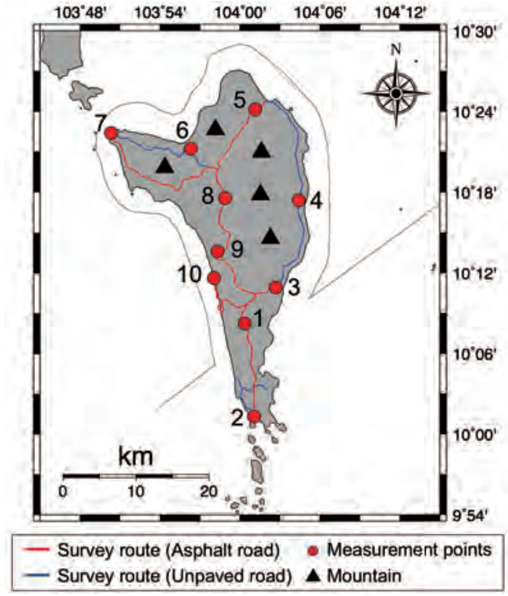

Fig. 2. December 2015 survey route measuring the ambient dose rate on Phu Quoc Island drawn using the Generic Mapping Tools (GMT) of Wessel and Smith[5].

Island was not included among the research areas in these studies.

In this study, a car-borne survey was carried out on Phu Quoc Island in December 2015 to draw a detailed dose distribution map using the obtained data and the annual external dose was estimated. The effect from extension of asphalt pavements associated with transportation infrastructure developments on the absorbed dose rate in air was also estimated. Finally, activity concentrations of natural radionuclides in soil samples from the island were measured.

2. Materials and methods

2.1. Survey route

The absorbed dose rates in air (nGy h^{-1}) from the natural radionuclides such as ^{40}K and ^{238}U series and ^{232}Th series were measured on 17 December 2015 on Phu Quoc Island, Vietnam. The weather was sunny throughout the measurement day. Roads which could be accessed by car were chosen for this survey (Fig. 2) and the route was approximately 150 km long. The route map was drawn using the Generic Mapping Tools (GMT) created by Wessel and Smith[5].

2.2. Car-borne survey

A car-borne survey technique is a very useful way to make a fast assessment of dose rate in a large area[9]. In this study, a car-borne survey was carried out using a 3-in × 3-in NaI (Tl) scintillation spectrometer with a global positioning system (EMF-211, EMF Japan Co., Osaka, Japan). The NaI (Tl) scintillation spectrometer was positioned at the center of the car (Inventory, Toyota, Vietnam) at a height of 1 m above the ground surface. At the time of the survey measurements, there were three researchers and a driver in the car. Latitude and longitude at each measurement point were measured at the same time as the count rates at gamma-ray energies of 50 keV – 3.2 MeV were recorded[10]. Measurement of the counts inside the car was performed every 30 s while the vehicle was moving. The car speed was around 40 km h^{-1}. The photon peak of ^{40}K (E_γ = 1.464 MeV) was used for calibration from the channel number and gamma-ray energy before measuring counts[10]. The peak position was determined accurately by smoothing the gamma-ray pulse height distribution. Because count rates were measured inside the moving car, then shielding by the car body was also estimated by making measurements inside and outside the car at 30-s intervals during 2 min at 10 locations (Fig. 2; red circles). A shielding factor was calculated from the correlation between count rates inside and outside the car. The count rates inside the car were then multiplied with this shielding factor. The gamma-ray pulse height distributions were also measured outside the car for 10 min at 10 locations (Fig. 2; measurements at #3 and #7 were the unpaved roads) for estimating the dose rate conversion factor (nGy h^{-1}/cps)[10]. The NaI (Tl) scintillation spectrometer was positioned 1 m above the ground surface. The measured gamma-ray pulse height distribution (i.e., total counts with gamma-ray energies of 50 keV - 3.2 MeV) was then unfolded using the 22 × 22 response matrix method[11] and dose rates were calculated. These calculated dose rates were used to estimate the dose conversion factor from the correlation between dose rates and count rates outside the car. Because detection of the photon peak of each gamma-ray is impossible in the 30-s measurement of the car-borne survey, absorbed dose rates in air outside the car were estimated using a dose conversion factor[10, 12-15]. The obtained factor was multiplied by the corrected count rates outside the car, and the calculated ambient dose rates were obtained. All data obtained from the car-borne survey were plotted on the distribution map of the absorbed dose rate in air on Phu Quoc Island using GMT[5]. In addition, the annual external effective dose was calculated based on the measured dose rates.

2.3. Evaluation of the effect of asphalt pavement on measurement

One-third of the survey route was not paved with asphalt (unpaved roads; Fig. 2, blue lines). The measurements of gamma-ray pulse height distributions were carried out for 10 min at 1 m above the asphalt surfaces and bare (earth) surfaces at locations #8, #9 and #10 for evaluating the effect of asphalt pavement on the absorbed dose rates in air. For a more detailed discussion, a correction factor for asphalt was calculated from the correlation between count rates measured on the bare surfaces and on the asphalt surfaces, and the corrected count rates outside the car were by multiplying with this factor. A dose distribution map was also drawn using the corrected dose rates. In addition, the activity concentrations (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th were calculated using the 22 × 22 response matrix method. The energy bins were set to 1.39–1.54 for ^{40}K, 1.69–1.84 MeV and 2.10–2.31 MeV for ^{214}Bi (^{238}U series) and 2.51 – 2.72 MeV for ^{208}Tl (^{232}Th series) to unfold the gamma-ray pulse height distribution. Detailed information on the procedure was presented in previous reports[11, 15].

2.4. Sample collection and preparation

Soil samples were collected from the 10 locations on the survey route shown in Fig. 2. At each location, about 500 g of soil was collected from a layer to 10 cm below the ground surface. All soil samples were dried for 24 h in an oven with temperature controlled at 100℃ to ensure that the moisture was completely released. Dried samples were then sieved and < 2 mm size particles were retained for this measurement. These samples were placed in cylindrical polypropylene containers (48 mm diameter × 55 mm height) and sealed with araldite. The sealed samples were left for one month to ensure the equilibrium of ^{228}Ra and ^{226}Ra with their decay products in the thorium and uranium series.

2.5. Measurement of Radioactivity by Gamma Spectroscopy

The activity concentrations (Bq kg^{-1}) in the soil samples were measured using a high-purity germanium semiconductor (HPGe, GMX10P, ORTEC, USA). This detector has a relative efficiency of 22.5% and an energy resolution of 1.80 keV at the gamma-ray energy of 1.33 MeV (i.e., ^{60}Co). The measurement time was set to 30,000 s. The activity concentration of ^{226}Ra was calculated using a weighted average of the activity concentrations of ^{214}Pb (E_γ = 0.352 MeV) and ^{214}Bi (E_γ = 0.609 MeV)[16]. For ^{228}Ra, the calculation was based on the activity concentration of ^{228}Ac (E_γ = 0.911 MeV) and the activity concentration of ^{40}K was calculated directly from the gamma-ray energy of 1.461 MeV.

3. Results and discussion

3.1. Shielding and dose conversion factors

The correlation between count rates inside and outside the car obtained at the 10 survey locations is shown in Fig. 3a. The shielding factor and standard uncertainty were found to be 1.45 and 0.08, respectively. Shielding factor is influenced by several items such as the type of car used in the survey, the number of passengers and the dosimeter position inside the car[10]. Previous reports[10, 12-14, 17] have given shielding factors of 1.3 to 1.9; then the present value was within this range.

The correlation between absorbed dose rate in air (nGy h^{-1}) and count rate outside the car is shown in Fig. 3b. The dose conversion factor and standard uncertainty were found to be 0.160 nGy h^{-1}/cps and 0.05, respectively. Both shielding factor and dose rate conversion factor were used with Eq. (1) to calculate the absorbed dose rate in air (nGy h^{-1}) outside the car at 1 m above the ground surface (D_{out}):

$$D_{out} = C_{in} \times SF \times DCF \qquad (1)$$

where C_{in} is count rate (cps) inside the car obtained by the measurements for every 30-s interval, SF is shielding factor and DCF is dose conversion factor (nGy h^{-1}/cps). It should be noted that the standard uncertainties for SF and DCF will be included in the results obtained from Eq. 1.

3.2. Evaluation of the effect of asphalt pavement on measurement

A correction factor for asphalt pavement was calculated from the correlation between count rates measured on bare surfaces and the asphalt surfaces (Fig. 3c), and it was found to be 0.49. Thus, the absorbed dose rate in air measured on asphalt was 2.0 times higher than that of bare surfaces.

No research on evaluating the effect of asphalt pavements has been carried out in Vietnam because the absorbed dose rate in air has never been measured for the country. The effect of asphalt pavements in Japan on absorbed dose rate in air has been reported[18, 20]; and there was some dependence on the production area of the crushed stone utilized for the asphalt pavement

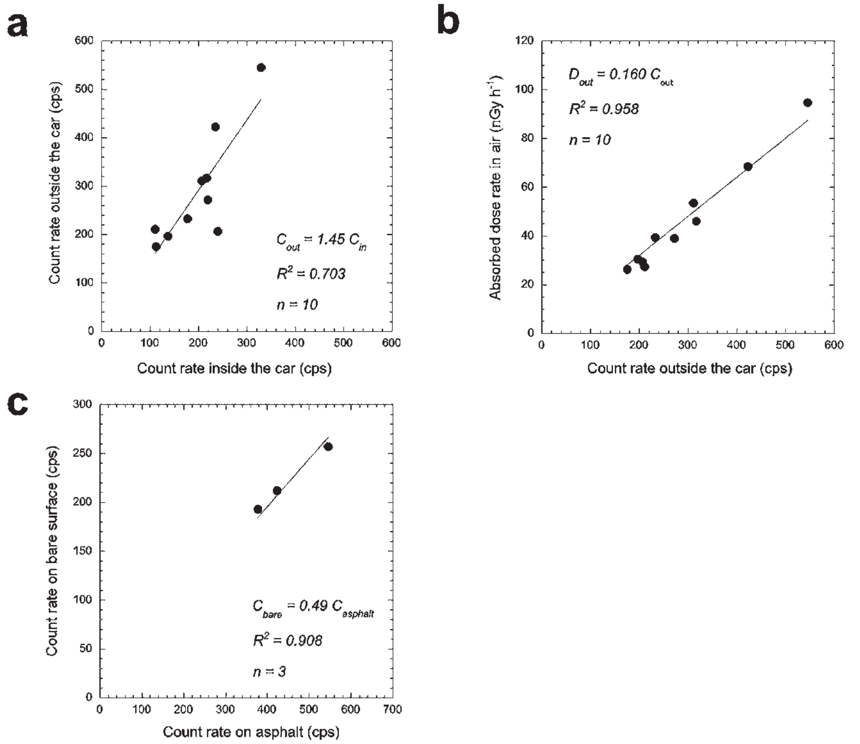

Fig. 3. Correlations between: (a) count rates inside and outside the car; (b) dose rates in air and count rates outside the car; and (c) count rates on the bare surfaces and count rates on asphalt surfaces.

Table 1. Activity concentrations on asphalt and bare areas

Location	Activity concentrations (Bq kg^{-1})		
	^{40}K	^{238}U	^{232}Th
Asphalt	720 ± 133	49 ± 15	36 ± 17
Bare	155 ± 22	19 ± 4	17 ± 5

(i.e., stone containing activities of ^{40}K, ^{238}U and ^{232}Th) and on the basement geology (i.e., primary terrestrial gamma radiation dose rate). For example, paved roads in Katsushika Ward in northeastern Tokyo have been constructed using stone materials quarried from nearby prefectures which have different activities than found for the natural loamy layer of the ward. The loam soil of Katsushika Ward was reported to have a low absorbed dose rate in air of 40 - 50 nGy h^{-1} [18, 19], and the ambient dose rate in air on asphalt was 1.5 times higher than that of bare areas[20]. On the other hand, similar absorbed dose rates in air on asphalt and bare areas (i.e., correction factor = 0.97) have been observed for the Tokai district (Aichi, Gifu and Mie Prefectures)[4]. This district is formed extensively from granite, resulting in about 2-3 times higher dose rates compared to that of the Kanto district which includes Tokyo[19, 21]. In addition, stone quarried from one prefecture has been utilized to construct paved roads for that prefecture, resulting in the prefecture having similar absorbed dose rates in air on asphalt pavement and on bare areas.

Table 1 summarizes average activity concentrations measured on asphalt and bare (earth) areas at #8, #9 and #10 in Fig. 2. Those values of ^{40}K, ^{238}U and ^{232}Th measured on asphalt pavement were respectively 4.6, 2.6 and 2.1 times higher than values measured on bare areas. It was confirmed on-site that stone quarried from outside Phu Quoc Island had been used in the road construction. On the other hand, absorbed dose rate in air based on the basement geology was low on Phu Quoc Island. Therefore, the differences in activity concentrations were seen on asphalt pavements and bare areas. In this study, the correction factor for asphalt (i.e., 0.49) was used for dose rates measured on asphalt to estimate the effect of asphalt pavement on absorbed dose rate in air.

3.3. Distribution of ambient dose rate on Phu Quoc Island

The average absorbed dose rate in air was 44 ± 20 nGy h^{-1} (11 – 99 nGy h^{-1}). This dose rate was lower compared to the value (75 ± 20 nGy h^{-1}, 27–115 nGy h^{-1}) for the Mekong River delta (Fig. 1) calculated on the basis of activities of soil samples[8]. Fig. 4a shows the distribution map of absorbed dose rate in air on Phu Quoc Island. This map was drawn using 774 data. A heterogeneous distribution of absorbed dose rates in air was seen. Especially, higher absorbed dose rates in air of over 60

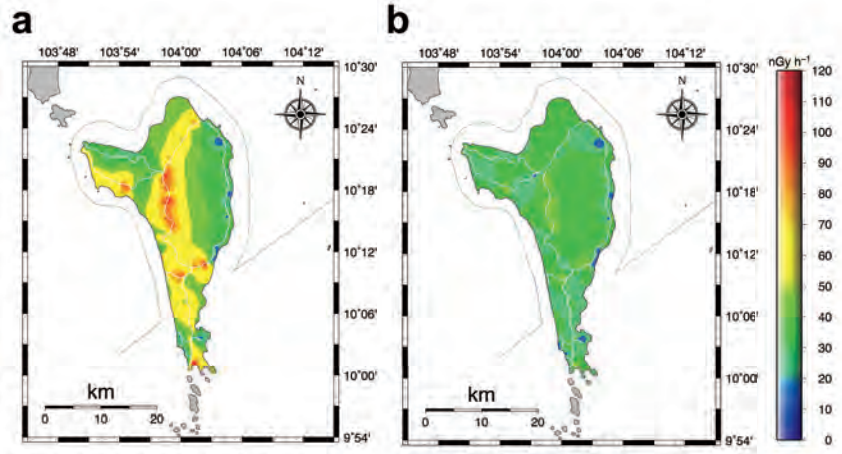

Fig. 4. Distribution maps of absorbed dose rate in air based on the dose rates measured from the car-borne survey (a) before and (b) after using the correction factor for asphalt (n = 774).

Fig. 5. Granite stone (diameter, about 10 - 15 cm) utilized as roadbed under the asphalt pavement.

nGy h^{-1} were observed along the asphalt roads (red lines in Fig. 2). On the other hand, dose rates of less than 50 nGy h^{-1} were observed on unpaved roads (blue lines). The average absorbed dose rates in air on asphalt and unpaved roads were 61 nGy h^{-1} (23 – 99 nGy h^{-1}) and 29 nGy h^{-1} (11–45 nGy h^{-1}), respectively.

Fig. 4b shows the distribution map of absorbed dose rate in air calculated using a correction factor for asphalt pavement (i.e., 0.49, shown in Fig. 3c). The dose distribution map was changed to a homogeneous dose distribution and average absorbed dose rate in air was also changed to 30 ± 7 nGy h^{-1} (11–49 nGy h^{-1}). In Vietnam, crushed granitic stones with diameters of about 10–15 cm (Fig. 5) have been used under the asphalt cover as a roadbed. According to Minato[21], the dose rate of granite stone is high (79 ± 25 nGy h^{-1}) compared to other rocks such as basalt (20 ± 12 nGy h^{-1}) and andesite (37 ± 10 nGy^{-1}). Thus, the height difference of the dose distribution as shown in Fig. 4a might be caused by the presence of such crashed stones under the asphalt cover. On the other hand, Fig. 4b represents the original dose rates (i.e., homogeneous dose distribution) because the whole area of Phu Quoc Island was formed by the same continental sedimentary rock[22].

On Phu Quoc Island, transportation infrastructure developments such as roads and bridges and the construction of high-rise buildings have been associated with resort development. Thus, it is expected that the absorbed dose rate in air on Phu Quoc Island would be changed depending on those developments.

3.4. Annual external effective dose estimation

The annual external effective dose for Phu Quoc Island was estimated using the following equation:

$$E = D_{out} \times DCF \times T \times (Q_{in} \times R + Q_{out}) \times 10^{-6} \qquad (2)$$

where E is the annual external effective dose (mSv y^{-1}), D_{out} is the average absorbed dose rate in air (nGy h^{-1}), DCF is dose conversion factor from the dose rate to the external effective dose for adults (0.748 ± 0.007 Sv Gy^{-1})[23], T is 8,760 h (24 h × 365 d), and Q_{in} and Q_{out} are indoor (0.8) and outdoor (0.2) occupancy factors, respectively. Because there are not enough statistical studies on the time spent in houses in Vietnam, the average world values were used for the occupancy factors[7]. R is the ratio of indoor dose rate to outdoor dose rate. Since no study has been performed to determine R in Vietnam, 1.0 was used for this factor. This means that the absorbed dose rate in air indoors was assumed to be equivalent to that outdoors. Here, the annual external effective dose (mSv y^{-1}) for Phu Quoc was calculated to be 0.29 mSv. This value for Phu Quoc Island is 54% of the Vietnam average excluding Phu Quoc Island (0.54 mSv y^{-1})[7] and 60% of the worldwide average (0.48 mSv y^{-1})[1].

3.5. Activity concentrations of soil samples

The average activity concentrations (range) of ^{40}K, ^{228}Ra and ^{226}Ra of 10 soil samples were found to be 40 ± 54 Bq kg^{-1} (15–180 Bq kg^{-1}), 7 ± 8 Bq kg^{-1} (11–32 Bq kg^{-1}) and 5 ± 7 Bq kg^{-1} (0–20 Bq kg^{-1}), respectively. These activity concentrations were lower than the average values of Vietnam excluding Phu Quoc Island (411 Bq kg^{-1} for ^{40}K, 60 Bq kg^{-1} for ^{228}Ra and 43 Bq kg^{-1} for ^{226}Ra)[7].

4. Conclusion

The car-borne survey using a NaI(Tl) scintillation spectrometer was done on Phu Quoc Island, Vietnam, in December 2015. The average absorbed dose rate in air was found to be 44 ± 20 nGy h^{-1} (range: 11–99 nGy h^{-1}). Higher dose rates in air of over 60 nGy h^{-1} were observed along asphalt pavement roads. The count rates on asphalt road were 2.0 times higher than the rates on unpaved roads. When the effect from asphalt pavement was removed using a correction factor, the average absorbed dose rate in air was decreased to 30 ± 7 nGy h^{-1}, and the homogeneous dose distribution was obtained for the entire island. Based on the average dose rate before the correction for the asphalt pavement, the annual effective dose was estimated to be 0.29 mSv. This value was 60% of the worldwide average. The activity concentrations of 10 soil samples for ^{40}K, ^{228}Ra and ^{226}Ra were found to be 40 ± 54, 7 ± 8 and 5 ± 7 Bq kg^{-1}, respectively.

Acknowledgments

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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