EVALUATION OF THE RADIATION EFFECT ON BUILDING HIGHWAY SUBGRADE USING ^{137}Cs SLIGHTLY POLLUTED SOIL AFTER NUCLEAR POWER PLANT ACCIDENTS

by

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After the accident at the Fukushima nuclear power plant in Japan, a large amount of radioactive contaminated soil was generated, which brought great challenges for treating and disposing of the soil. The recycling of slightly polluted soil can reduce the amount of contaminated soil. This paper analyzes the main exposed scenes of ^{137}Cs polluted soil used in the construction of highway subgrade, soil bag handling and paving. The Monte Carlo algorithm (MCNP) and RESRAD-ONSITE program are used to simulate the two scenes respectively, and the concentration of ^{137}Cs is derived in the soil at the effective dose of 1 mSv per year. It is concluded that: the annual effective doses of porter and paver are 0.41 mSv per year and 0.23 mSv per year respectively caused by 1 Bqg^{-1} ^{137}Cs contaminated soil; the activity of ^{137}Cs are 2.44 Bqg^{-1} and 4.26 Bqg^{-1} respectively in the soil at 1 mSv per year for porter and paver; the calculated results are consistent with those reported by the Japan Atomic Research Agency. Also, they are lower than the activity concentration corresponding to the effective dose control level of 1 mSv per year under low-probability events in IAEA No. RS-G-1.7 slightly.

Key words: recycling, ^{137}Cs, soil

INTRODUCTION

The resources available to humans are limited, and the radioactive contaminated soil generated after nuclear power plant accidents is a resource worth reusing. On the one hand, recycling can reduce the amount of contaminated soil. On the other hand, it makes full use of the available resources and realizes the circular economy. But, radioactive substances lead to external and internal radiation entering through various sources and paths in soil [1, 2]. After the Fukushima nuclear power plant accident in Japan [3-6], the Japanese government conducted a recycling test verification work for contaminated soil in the long mud area of Izomura and Minamisoma. The results indicated that the activity concentration of ^{137}Cs was less than 5 Bqg^{-1} in the soil in the long mud area of Izomura, and the average activity concentration of ^{137}Cs was 0.77 Bqg^{-1} in the soil in Minamisoma. By the end of 2021, the radiation environment around the test area has not changed. It is also specified that the annual effective dose control for workers in the contaminated soil recovery process is less than 1 mSv. There have been no nuclear power plant accidents in China, but nuclear accidents and nuclear pollution are inevitable. We should take precautions to do a good job in the treatment of radioactive contaminated soil in the late stage of the nuclear accident, and reduce the amount of radioactive contaminated soil that needs to be treated and disposed of. It not only protects the environment, but also produces good social and economic benefits.

The radiation dose assessment method for the recycling of materials and equipment was given in PNL-8724 UC-610 [7]. The considered recycling exposure scenarios include loading/unloading workers, transport workers, processing workers, primary processing workers, final processing workers, users and so on. Li *et al*. [8] calculated the radiation doses of different populations caused by the recycling of radioactive contaminated metals. It can be seen that the time and distance are the main factors.

This paper analyzes the radiation effects of reusing ^{137}Cs polluted soil. The exposure scenarios include lightly contaminated soil loading/unloading, transportation, subgrade construction workers, the public driving on the highway, and residents living on both sides of the highway. Residents on both sides of the expressway have the longest exposure time, but the distance is relatively long. Secondly, for the porters and roadbed construction workers. Porters and road-

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bed builders are closest to the radioactive soil, followed by transport workers.

The scope of highway construction control area is not less than 30 m from the outer edge of highway land in China [9]. The highway subgrade under the impervious cushion layer, with the mud base and surface layer, can effectively prevent the infiltration of ^{137}Cs and radiation external irradiation. Shiwei *et al*. [10] and Yong *et al*. [11] pointed out that the migration rate of ^{137}Cs was very slow in groundwater and soil. Its activity concentration decreased by 10~100 times when migrating 30 m away. Therefore, the use of slightly contaminated soil with radioactive ^{137}Cs has little radiation influence on the nearby public for highway subgrade construction. So, this paper analyzes the radiation effects of ^{137}Cs polluted soil recycling, including porters and roadbed builders.

SOIL BAG HANDING

Model assumptions

The size of the radioactive contaminated soil package refers to the bag-shaped container given in Japan's Flexible intermediate bulk containers (JIS Z1651-2002) [12], and one (cross-type) of the dimensions is 800 mm and the height is 800 mm, the other (convenient type) with a side length of 800 mm is used for the simulation study. Figure 1 shows the radioactive contaminated soil storage container bags after the Fukushima nuclear power plant accidents in Japan.

The main pollution nuclide in radioactive contaminated soil is ^{137}Cs, and it is evenly distributed. The activity concentration is 1 Bqg^{-1}. The activity level of ^{137}Cs is 6.03 10^{5} Bq for cylinder and 7.68 105 Bq for cube, respectively.

Regardless of the material of the container, and the materials involve soil and air in the model. The density of the soil is 1.5 gcm^{-3}, and the elements include H, O, Mg, Al, Si, K, Ca and Fe in the soil. The density of air is 1.29 10^{-3} gcm^{-3}, and the elements include C, N, O, and Ar in the air [13-15].

The working time is 250 days, and 8 hours per day for porter and paver.

Model establishment

The center of the cylinder and the cube is the origin of the coordinate system (0, 0, 0), the *Z*-axis is the direction of the container height, and the *X*-axis and *Y*-axis are the horizontal and vertical directions of the container, respectively. Figure 2 shows two established container models. The dose rates are simulated at the 2 mm, 10 mm, and 100 mm of the cylinder.

Simulation results

Figure 3 shows the simulation results of the dose rate at the distance of 2 mm, 10 mm, and 100 mm from the surface of the soil storage containers, when the activity concentration of the radionuclide ^{137}Cs is 1 Bqg^{-1} in the soil. From the figure, the trend line of the cube *x* direction is $D = -2.56\,d + 280$. The trend line of the cylinder *z* direction is $D = -2.56\,d + 275$. The trend line of the cylinder *x* direction is $D = -2.04\,d + 221$. In the trend line, *D* [nGyh^{-1}] represents the dose rate at different distances, *d* [mm] represents the different distance. Using the dose rate at 2 mm from the surface of the packaging container, the external dose of porter is calculated. The annual effective doses of the porter are 4.07 10^{-4} Sv (cylinder) and 4.10 10^{-4} Sv (cube), respectively. When the annual dose constraint value of the porter is 1 mSv per year, the activity concentration in the radioactive contaminated soil is 2.44 Bqg^{-1}.

SUBGRADE PAVING

Basic hypothesis

The main influencing factors of radiation dose are the concentration of radionuclide activity in contaminated soil, the area of subgrade, the thickness of subgrade and working time in paving workers. There-

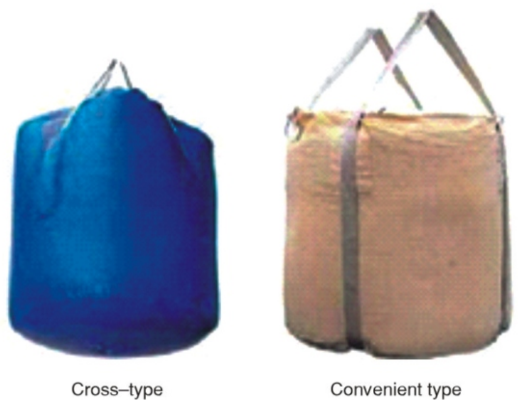

Figure 1. Japan Fukushima nuclear power plant accident removal soil storage container bag

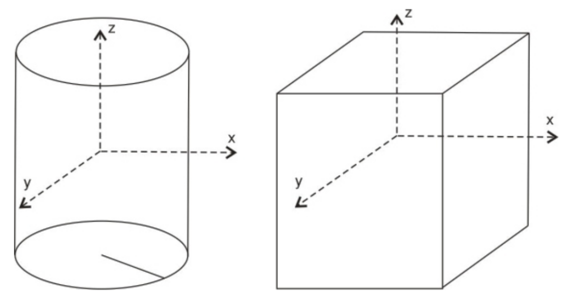

Figure 2. Model diagram of two radioactive contaminated soil storage containers

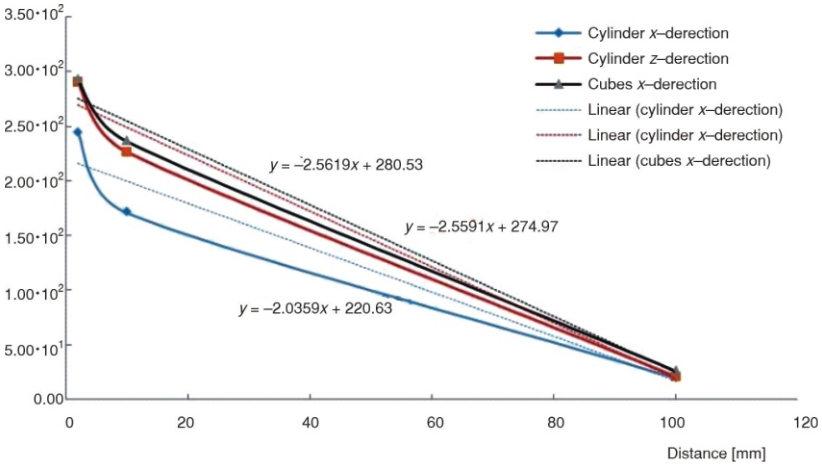

Figure 3. Dose rate at different distances from the surface of the packaging container

fore, the basic assumptions are made in this calculation as follows:

– The main contaminated nuclide is ^{137}Cs in radioactive contaminated soils, with the activity concentration of 1 Bqg^{-1} and uniform distribution.
– Conservatively, the attenuation mode of radionuclides in soil is only the decay of radionuclides themselves, excluding the infiltration of radionuclides caused by rainfall and irrigation.
– According to the Highway Engineering Technology Standard (JTG B01-2014) [16], the width of the road above 80 kmh^{-1} is 3.75 m per line. The paper assumes that the highway is 4 lines (3 lines + 1 emergency line). The width of the road is 4 lines 3.75 m per line is 15 m, and the soil density is 1.5 gm^{-3}.
– Paving workers working time is 8 hours per day, 250 days, and the respiratory rate of paving workers is 1.2 m^{-3}h^{-1}.
– According to *Technical Guidelines for Risk Assessment of Polluted Sites* (HJ 25.3-2019) [17], it is assumed that the daily intake of soil by pavers is 100 mg.
– The pavers are directly above the contaminated soil, without a covering layer and in the center of the filling area.
– Under the same conditions, the relationship between filling depth and annual effective dose of paving workers is analyzed. The results are shown in fig. 4. From the figure, it can be seen that the annual effective personal dose of paving workers increases gradually with the increase of roadbed depth when roadbed depth is less than 0.5 m. With the increase of subgrade depth, the dose of paving workers remain unchanged when roadbed depth is greater than 0.5 m. Therefore, the embankment filling depth is more than 0.5 m, assumed to be 1 m.

Model establishment

The RESRAD-ONSITE [18] model can calculate the dose and cancer risk according to the parameters and established scenarios. The model includes nine alternative irradiation pathways:

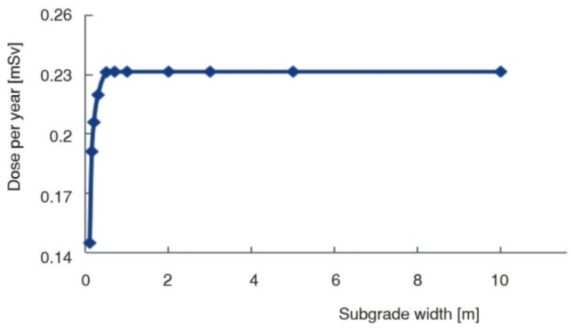

Figure 4. Relationship between the personal dose amount of paving workers and the depth of the roadbed caused by contaminated soil

– direct external irradiation of soil radionuclides,
– internal irradiation of contaminated soil by inhalation of air,
– internal irradiation of contaminated soil through intake,
– ingestion of plants grown in areas of contaminated soil,
– ingestion of animals feeding in contaminated soil area,
– drinking of milk coming from contaminated soil area,
– drinking of water coming from contaminated soil area,
– ingestion of aquatic organisms in the polluted water body, and
– inhaling radon gas released from the polluted soil.

The database for radionuclide transformation is recommended by ICRP 38 report and ICRP 107 report. The dose conversion factors are derived from ICRP Report 60 in the model.

The RESRAD-ONSITE 7.2 is used for calculation and analysis. The irradiation pathways include direct external irradiation of soil radionuclides, internal irradiation from inhaling contaminated soil and internal irradiation from contaminated soil. The database of radionuclide transformation is recommended by ICRP 107 report.

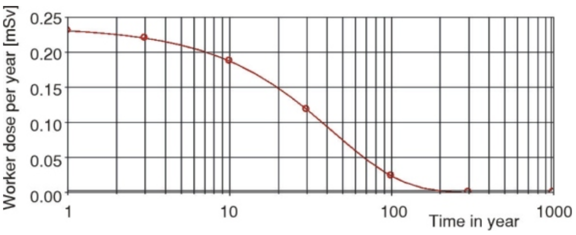

Figure 5. Worker dose due to paving operation

Calculation results

Figure 5 shows the changing trend of paver's dose on polluted roadbed over time. It can be seen that the maximum annual effective dose caused by paver is 0.23 mSv (the first year). When the annual effective dose caused by paver is 1 mSv per year, the activity concentration of ^{137}Cs is 4.26 Bqg^{-1} in polluted soil. Under the same condition, the method of deducing the acceptable activity concentration of radioactive residues in decommissioned site soil recommended in EJ1191-2005 [19] is used to deduce the activity of ^{137}Cs in contaminated soil, when the personal effective dose of paver is 1 mSv per year, the concentration of ^{137}Cs is 3.92 Bqg^{-1}. The RESRAD-ONSITE is different from EJ1191. The reason is that the contaminated roadbed is a square contaminated area, and the area correction factor should be taken into account when calculating the direct external radiation dose. The RESRAD-ONSITE and EJ1191 are inconsistent in choosing the area correction factor: RESRAD-NSITE encloses the square contaminated area in a circular area and divides the circular area into 12 circular areas, multiplying the area coefficient of each circular area by the contaminated ring [20]. In EJ1191, the area correction factor is recommended according to the size of the polluted area. When the area of the polluted site is 225 m^2, the area correction factor is between 0.55 and 0.8. The conservative value is 0.8.

The calculated results in this paper are compared with the controlled concentration levels of radionuclide ^{137}Cs in soil, given in the technical reports of the Japan Atomic Research Agency and the International Atomic Energy Agency (IAEA). It revealed that when slightly radioactive contaminated soil was used for road construction after the Fukushima nuclear power plant accident, the largest individual dose of the workers and the public was the exposure dose of the soil handling and paving workers in the Japan Atomic Research Agency. Moreover, when the exposed dose of road paving workers was 1 mSv per year, the activity concentration of radionuclides ^{137}Cs + ^{134}Cs (mainly ^{137}Cs) is 6.1 Bqg^{-1} in soil [21]. It required materials such as soil to be controlled or exempted, the dose caused by such materials to the public was less than or equal to 0.01 mSv per year in IAEA No. RS-G-1.7 [22]. Considering the occurrence of low probability events that may lead to higher irradiation, the effective dose that may be generated under such events should not exceed 1 mSv per year. Meanwhile, the equivalent dose of human skin is controlled. The recommended activity concentration of nuclide ^{137}Cs was 0.1 Bqg^{-1} for radionuclides of artificial origin in bulk.

From the above analysis, it can be seen that the results calculated in this paper are lower than those calculated by Japan Atomic Research Institute (when the exposure dose of road paving workers and porters is 1 mSv per year, the activity concentration of radionuclide Cs is 6.1 Bqg^{-1} in soil). In addition, it is lower than the activity concentration level of radionuclide ^{137}Cs in soil corresponding to the effective dose control level of 1 mSv per year under low-probability events in IAEA No. RS-G-1.7.

The reason for this phenomenon is the difference of parameter selected in the evaluation process. The main differences among the three results are external exposure dose conversion factor of ^{137}Cs and working time. The longer the working time, the greater the dose conversion factor, and the lower the activity control level of the radionuclide ^{137}Cs in the soil [18, 21-23].

CONCLUSIONS

The main pollution nuclide in the radioactive contaminated soil generated after the nuclear power plant accident is ^{137}Cs, which is mainly external irradiation. The main irradiated scene of workers and residents in the whole process of highway construction is analyzed for the ^{137}Cs contaminated soil. The irradiated scene of soil bag handling and roadbed paving are selected. The MCNP and RESRAD-ONSITE are used to calculate the exposure dose of the soil bag handler and paving workers.

The calculation results show that the recycling of slightly radioactive contaminated soil is feasible for the construction of highways after the nuclear power plant accidents. In addition, it needs to be discussed and analyzed from the following aspects:

On one hand, the dose control level under low probability events should be considered, according to the requirements of IAEA No. RS-G-1.7. On the other hand, the parameters used have a certain influence on the results in the assessment of the annual effective dose of the public. In the process of radiation impact assessment, the assessment parameters should be determined reasonably according to relevant national standards, so as to achieve safe recycling of slightly contaminated radioactive soil after nuclear accidents.

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AUTHORS' CONTRIBUTIONS

The idea of research on recycling of ^{137}Cs slightly polluted soil was from H. Chen, J. Kang, and B. Lian. The conceptualization, methodology, and analysis were made by all the authors. F. Wu, Y. Shi collected the data and did the analyses. H. Chen wrote the first original manuscript draft. F. Wu did the editing and revised the original manuscript draft.

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ПРОЦЕНА УТИЦАЈА ЗРАЧЕЊА ПРИ ИЗГРАДЊИ ПОДЛОГЕ АУТОПУТА УПОТРЕБОМ ЦЕЗИЈУМОМ СЛАБО КОНТАМИНИРАНОГ ЗЕМЉИШТА ПОСЛЕ НЕСРЕЋЕ У НУКЛЕАРНОЈ ЕЛЕКТРАНИ

После несреће на нуклеарној електрани Фукушима у Јапану генерисана је велика количина радиоактивно контаминираног земљишта што представља велике изазове у накнадном третману и одлагању, при чему рециклирање благо контаминираног земљишта може смањити количину која се обрађује и одлаже. У раду је анализирана изложеност радника зрачењу изазвана руковањем кесама за земљиште и асвалтирањем услед употребе ^{137}Cs контаминираног земљишта које се користи у изградњи подлоге аутопута. За симулацију ових догађаја коришћени су Монте Карло MCNP програм и RESRAD-ONSITE програм, при концентрацији ^{137}Cs у земљишту која одговара годишњој ефективној дози од 1 mSv. Резултати су показали да су годишње ефективне дозе за помоћног радника и асфалтера изазване контаминираним земљиштем од 1 Bqg^{-1} ^{137}Cs биле 0.36 mSv односно 0.23 mSv, респективно; да су при томе активности од ^{137}Cs биле 2.44 Bqg^{-1} и 4.26 Bqg^{-1}; да су резултати израчунавања у складу са резултатима прорачуна Јапанске агенције за атомска истраживања. Такође, резултати су нижи од нивоа концентрације активности који приближно одговара ефективном контролном нивоу годишње дозе од 1 mSv за мало вероватне догађаје према IAEA бр. RS-G-17.

Кључне речи: рециклирање, ^{137}Cs, земља