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The evaluation for radiation shielding ability of the soil materials and application to design for construction

L'évaluation de l'aptitude de blindage contre les radiations des matières du sol et de l'application pour la conception de construction

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ABSTRACT: The 2011 off-the Pacific coast of Tohoku earthquake affected Japan, wreaking severe damage to a nuclear power plant in Fukushima. During decommissioning, ensuring worker safety is important in relation to fuel debris retrieval. Given that background, the authors specifically examined the use of heavy bentonite-based slurry as a filling material in a nuclear reactor. Heavy slurry can shield gamma rays and neutron beams because of its high specific gravity and water contents. Also, soil materials are used for soil cover type storage facilities for radioactive waste without evaluation for shielding. This research was conducted to investigate and define the radiation shielding capability of soil materials for controlling nuclear accidents. To quantify the radiation shielding capability, the authors measured the transmitted radiation dose through soil materials under some conditions of pass length. Results show that the reduction of the gamma ray dose has a proportional relation with wet density of materials, and show that the reduction of the neutron beam dose is related with the volume water content of materials. The research described in this paper is a proposal for application to the design for construction using soils for decommissioning of the Fukushima Daiichi Nuclear Power Station.

RÉSUMÉ : L'édition 2011 au large de la côte Pacifique du tremblement de terre de Tohoku a touché le Japon, et il fait de graves dommages à la centrale nucléaire de Fukushima. Dans le déclassement, assurer la sécurité des travailleurs est la question la plus importante en particulier dans la récupération des débris de carburant. Sur ces milieux, les auteurs se concentrent sur lourde suspension à base de bentonite pour le matériau du réacteur nucléaire de remplissage. En outre, les matériaux du sol sont utilisés pour les installations de stockage de type de couverture du sol pour une partie des déchets radioactifs sans l'évaluation pour la capacité de protection contre les rayonnements. Le but de cette recherche est d'étudier et de définir la capacité de protection contre les rayonnements des matériaux du sol pour contrôler l'accident nucléaire. Pour quantifier la capacité de protection contre les rayonnements, les auteurs ont mesuré la dose de rayonnement transmise à travers les matériaux du sol sous des conditions de longueur de passage. Les résultats montrent la réduction de la dose de rayons gamma est en relation proportionnelle avec une densité humide de matériaux et une réduction de la dose de faisceau de neutrons est en relation avec la teneur en matières en volume d'eau.

KEYWORDS: radiation, slurry, soil cover

1 INTRODUCTION

During the decommissioning of Fukushima Daiichi Nuclear Power Station, ensuring worker safety is an important matter for fuel debris removal. According to the Mid-term and Long-Term Roadmap, removing fuel debris from the reactor container filled with water is the best way. Figure 1 depicts a nuclear reactor building. However, to avoid excessive exposure, it is better to use fill material that has greater radiation shielding properties than those of water. Under such circumstances, heavy bentonite-based slurry is developed for the shielding of gamma rays and neutron beams, which have strong penetration capability. At present, elucidation of some properties of heavy slurry is advancing for its application to decommission work. However, some debris designated as radioactive waste generated from the accident at Fukushima is retained in the soil covered facility, as shown in Figure 2. The soil cover thickness is greater than 1 m, but investigations of the radiation shielding capability of soil materials are insufficient to support a judgment about the necessary thickness for adequate shielding.

As explained above, soil materials have been used as radiation shielding materials since the accident at Fukushima Daiichi Nuclear Power Station occurred by 2011 off-the Pacific coast of Tohoku earthquake. Nevertheless, radiation shielding capabilities of the soils have not been evaluated quantitatively, and at present, a standard about the construction is not established. For this study, the authors measured the radiation dose through the soil materials, assuming the filling or covering materials in some cases of wet density and thickness. Results show gamma ray reduction dependence on the wet density, and neutron beam reduction dependence on the volume water contents of the materials. In addition, an important factor for damping energy of radiation is the distance passing through on the materials. For this reason, multiplying the wet density and thickness of soil materials presents a relational expression with gamma ray reduction. Neutron beam reduction is affected by a parameter by which the volume water content and thickness are multiplied.

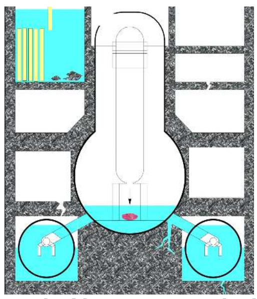

Figure 1. Nuclear reactor building No. 1 in Fukushima Daiichi Nuclear Power Station.

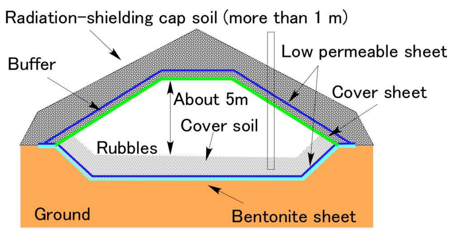

Figure 2. Soil-covered facility constructed for storing polluted rubble.

2 EXPERIMENTAL CONDITIONS

Heavy bentonite-based slurry, called super-heavy slurry, is shown in Figure 3. Super-heavy slurries have different flow behavior depending on their constituents. Therefore, one can create appropriate slurries capable of satisfying a particular required performance as filling materials. Radiation shielding capabilities are one of the most important characteristics for heavy slurries. Ascertaining the relation between the states and the radiation shielding capability of heavy slurry is important. Typically, heavy slurry is a compound of a Na-bentonite suspension, with barite and sodium pyrophosphate. The mixing ratio of heavy slurry used for this study is presented in Table 1.

Soil materials used in the test are clay (Clay sand, Kanto loam), silt (Showa DL clay), and sandy soil (Tohoku silica sand) anticipated for use in soil cover type storage facilities in Fukushima. Tohoku silica sand and Kanto loam were adjusted to elucidate radiation shielding capabilities at different water contents. Radiation sources are presented in Table 2.

Gamma rays are emitted in electron beams with frequency of 10^{19} – 10^{23} Hz. Most of an atomic nucleus after radioactive disintegration undergoes a transition from an excited state to a stable state by gamma ray emission. Therefore, gamma ray shielding is necessary for disposal facilities with polluted rubble, not only areas surrounding nuclear fuel. A neutron beam is a kind of particle beam that is classified by the velocity of neutron particles as a 'fast neutron beam', 'thermal neutron beam', or 'total neutron beam'. As described in this paper, the word 'neutron beam' signifies total neutron beams. Alpha rays and beta rays are not considered in this study because they are stopped easily through mutual interaction with other materials by the electric charges they have.

The test method used to measure the radiation shielding capability of soil materials is presented in Figure 4. The setup includes 1–4 acrylic vessels filled with soil materials. A radiation dose is measured through the materials when the soil material thickness is 10 cm, 20 cm, 30 cm, or 40 cm. A base was constructed 1 m above the ground to avoid any influence of radiation reflected by the ground surface. The radiation dose was measured using a survey meter fixed 50 cm from the radiation source, which was set close to the acrylic vessel.

Figure 3. Heavy bentnite-based slurry.

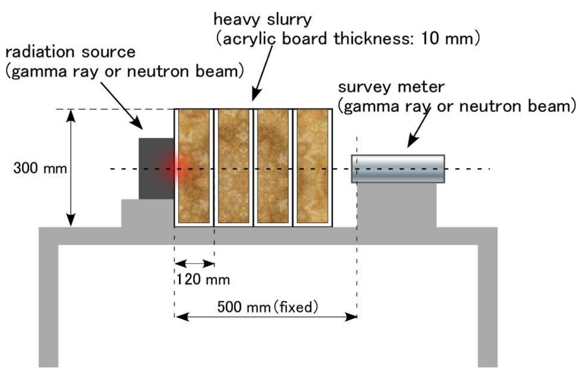

Figure 4. Method of radiation shielding capability test.

Table 1. Mixing ratio of heavy bentonite-based slurry.

Specific gravity *Gs*	Tap water (g)	sodium pyrophosphate (g)	Na-bentonite (g)	Barite (g)
2.5	100	0.2	7	400
1.8	100	0.2	10	140
1.1	100	0.2	12	10

Table 2. Radiation source used in the test.

	Source	Activity (MBq)	Dose (μSv/h)	Energy (MeV)
Gamma ray	^{137}Cs	3.68	1.13	0.662
Neutron beam	^{252}Cf	1.067	5.18	1.406

3 RADIATION SHIELDING TEST RESULTS

3 .1 *Factors contributing to radiation reduction*

Results of the test 10 cm thickness are shown in Figure 5 and Figure 6. From these results, one can ascertain the state parameters of soil contribute to gamma ray or neutron beam shielding. Radiation strength was analyzed as "radiation reduction", which means the ratio of radiation decrease with passage through the material. It is based on the radiation dose measured using empty vessels. When the reduction shows 100%, the radiation dose is 0. From Figure 5, gamma ray reduction can be confirmed as increasing with the wet density of soil materials. Gamma rays energy decreases because of collision with electrons of the atomic nucleus. Therefore, high existence of electrons is necessary for gamma ray shielding. For that reason, dense materials are usually the best gamma ray shielding materials. The energy of neutron beams, in other words neutron particle beams, decreases by collision with atomic nuclei. Based on the momentum conservation law, high hydrogen contents are effective for neutron beam shielding because the hydrogen mass is almost equal to that of a neutron particle. Figure 6 shows a result of analysis by the volume water content, which shows the existence of hydrogen. The results show that neutron beam reduction depends on the soil material water volume. Scatter of measured values results from unevenness of soil samples or neutron particles moving at different velocities.

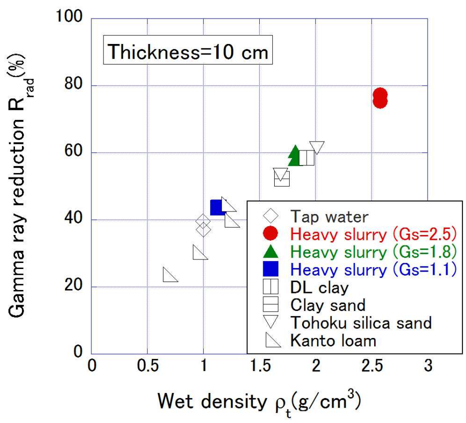

Figure 5. Relation between gamma ray reduction and wet density of soil materials.

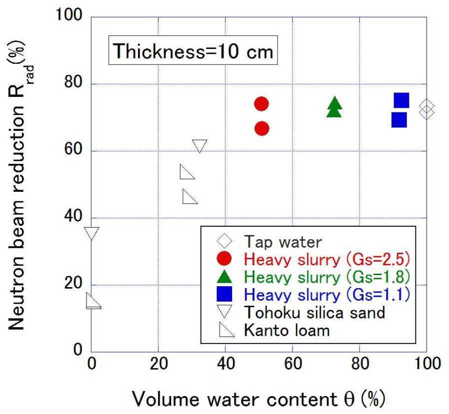

Figure 6. Relation between neutron beam reduction and volume water content of soil materials.

3 .2 *Radiation reduction with slurry thickness*

Radiation reduction changes associated with increasing heavy slurry thickness are shown in Figure 7 and Figure 8. Gamma ray reduction increases with thickness. It changes based on the relation presented above. Figure 7 shows that heavy slurry has greater gamma ray shielding capability than tap water does. However, heavy slurry has almost identical neutron beam shielding capability to that of tap water (Figure 8). Reduction differences among three types of slurries decrease with thickness. Distance is an important factor for radiation shielding, as is the wet density or volume water content. This test shows the same behavior for other soil materials used for cover.

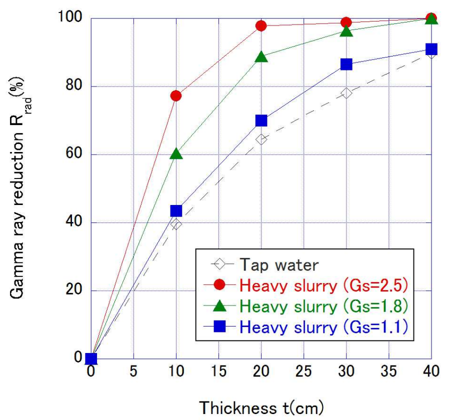

Figure 7. Relation between gamma ray reduction and heavy slurry thickness.

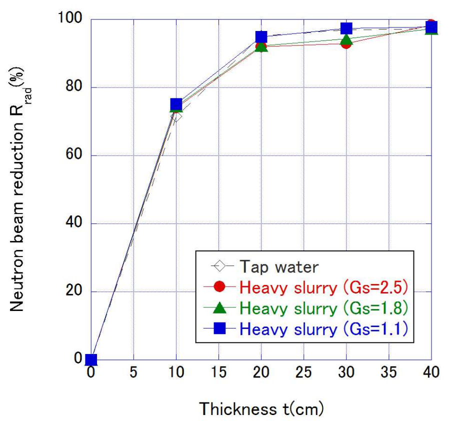

Figure 8. Relation between neutron beam reduction and heavy slurry thickness.

4 APPLICATION TO DESIGN SOIL CONSTRUCTION

The results presented above are expected to be associated with a certain state of soils to establish a method of designing soil structures for radiation shielding. Accordingly, it is necessary to define some quantities which show an unambiguous relation with radiation reduction. This study uses a parameter: the total of values obtained by multiplying the wet density and the thickness of materials through which radiation passes is equal to the probability of collision with an electron of the materials when radiation is passing through it. The parameter is named the 'total density of transit path'. Similarly, the collision probability of a neutron beam and hydrogen, named the 'total moisture density of transit path' is defined as multiplying moisture density (=volume water content/100 × water density) and thickness. Figures 9 and 10 present results showing that gamma rays and neutron beams tend to depend on the probability of collision, only one curve exists.

The relation between gamma ray reduction and the total density of transit path $\rho_t t$ is presented in Figure 9. It shows a polynomial curve with correlation (R=0.997) and presents two equations as presented below.

$$R_{rad} = -2.0\times10^{-6}x^2 + 7.5\times10^{-4}x^3 + -9.0\times10^{-2}x^2 + 5.0x - 11.8 \quad (1)$$

$$x = \sum \rho_t \times t \quad (2)$$

In that equation, ρ_t stands for the wet density. t signifies the thickness of each material. According to equations (1) and (2), the authors tried to apply it to design soil construction. Japan's Ministry of the Environment sets 0.23 μSv/h as the maximum radiation dose permitted for human exposure. The value 0.23 μSv/h includes 0.4 μSv/h emitted by natural resources. Therefore, the penetration permissible dose, the radiation dose permitted for emission from shielding material is 0.19 μSv/h. The necessary reduction of radiation can be calculated from the dose emitted by radioactive material to be contained and the penetration permissible dose. These parameters enable calculation of an unknown value, which is the wet density or thickness of radiation shielding soils in case of gamma ray. The design density can be found if the soil thickness is known. The reverse is also true. A flowchart of how to design the gamma ray shielding construction made of soil is presented in Figure 11. Actually, if the dry density is replaced by wet density to calculate $\rho_t t$ when constructing a radiation shielding facility, then it will support greater safety than when following the curve in Figure 9.

Figure 10 shows the relation between neutron beam reduction and total moisture density of transit path $\rho_m t$. An approximate curve (R=0.937) is shown as the following two equations:

$$R_{rad} = -9.8\times10^{-5}x^4 + 1.2\times10^{-2}x^3 - 5.2\times10^{-1}x^2 + 10.5x + 15.0 \quad (3)$$

$$x = \sum \rho_m \times t \quad (4)$$

In those equations, ρ_m is the moisture density calculated from volume water content θ and water density ρ_w. A difference exists especially between heavy slurry and soils used for cover. The behavior is expected to derive from the state of water, e.g., fixed or not because radiation reacts to ignition loss moisture. Therefore it is not fit to existence of water molecules by volume water content measured from drying at 110°C standardly as Japanese Industrial Standards. The trend presented above also appears in results of each neutron beam separated by velocity, thermal neutron beams, and fast neutron beams. Therefore, analyzing the peculiar ignition loss moisture is necessary for making revisions in the curve to lead to a better radiation shielding design. Suppressing the curve scatter will enable calculation of unknown values, which is volume water content or thickness, to produce a flowchart, as shown in Figure 11.

The results depend on the radiation sources they emit weak radiations than fuel debris or radioactive waste at Fukushima. These curves might take same shape even if different radiation sources used because figures 9 and 10 are shown by ratio and probability, relation between radiation and factor of damping energy. It is necessary to fit the maximum value of the curve to the actual value in order to prove that the data presented as above could apply to construction for shielding.

The research described in this paper is application proposal of nuclear engineering to civil engineering, especially geotechnical engineering. Soil materials exist everywhere can be flexible shield to cut off radiations. It is profitable at the perspective of people safety and construction costs to accommodate a theory of radiation shielding design at nuclear engineering to civil engineering construction properly.

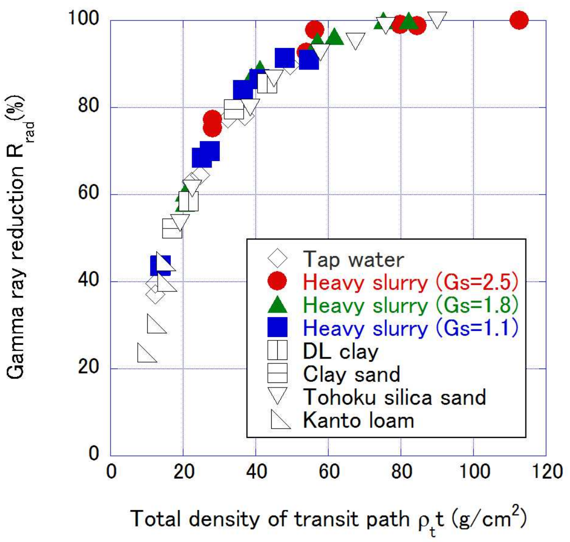

Figure 9. Relation between gamma ray reduction and total density of the transit path.

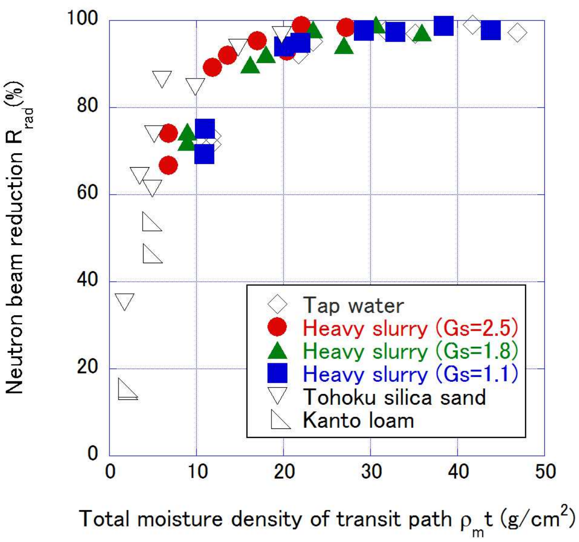

Figure 10. Relation between neutron beam reduction and total density of the transit path.

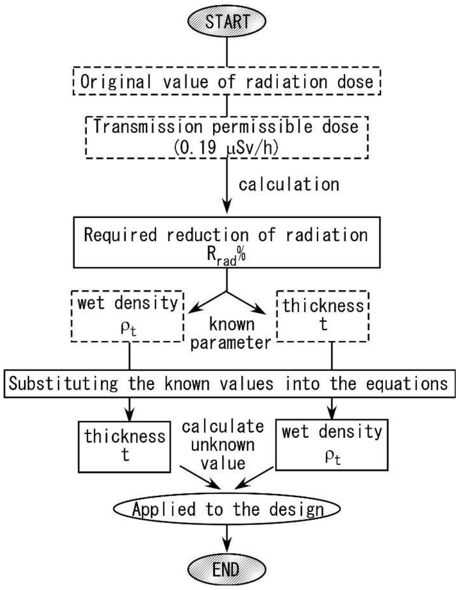

Figure 11. Flowchart of design to soil construction for gamma ray shielding.

5 CONCLUDING REMARKS

This paper presents a summary of the quantifying radiation shielding capability of soil materials its application to soil construction design. Results showed that gamma ray reduction is directly proportional to the wet density of soil materials if thickness occurs under the same conditions. Similarly, neutron beam reduction depends on the volume water contents of soils. From the perspective of constructing a radiation shielding structure using soil, the 'Total density of the transit path' makes a single curve relation to reduction of gamma ray independent of the soil material. 'Total moisture density of the transit path' makes a relation to neutron beam reduction, although some scatter is attributable to the respective soil characteristics. This study proved that heavy bentonite-based slurry has superb performance as a filling material intended for radiation shielding during nuclear power station decommissioning because it has greater gamma ray shielding capability and almost identical neutron beam shielding capability to those of tap water. These results are expected to be useful for recovery from the accident at Fukushima after results are incorporated into plans for construction work.

6 ACKNOWLEDGEMENTS

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