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Research papers

Reliability and risk assessment for radioactive release to a Quaternary aquifer considering specified limit as resistance and in situ groundwater condition as load

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A R T I C L E I N F O

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A B S T R A C T

Radioactive pollutants enter the subsurface hydrology environment commonly because of operation or accidental leakage from nuclear sites. In some occasions, heterogeneity in the groundwater system controls the fate of water transport in the aquifer; it determines how contaminated groundwater change at site boundary. Assumption of uniform and homogeneous conditions in subsurface hydrology will lead to unpredictable errors in the decision when initiating a protection program for groundwater. This study presents a novel process to establish a practical procedure of reliability and risk assessment for a Quaternary aquifer relating to hypothetical nuclear facility installed on the ground surface. This research performs reliability and risk analysis considering specified limit as resistance and in situ groundwater condition as load; it shows a safety state of the studied site regarding the records of radioactivity in the aquifer. It demonstrates a novel result of groundwater at different observation locations and natural environment discharge point associated to reliability issue, and represents recommendation for the use of groundwater or environmental monitoring as safety protection of the studied site.

1. Introduction

The entry of chemical pollutants into the natural environment is usually because of accident operations from industrial facility. Geological heterogeneities commonly control the fate of groundwater moving in the aquifer. In order to predict flow and transport in groundwater system under certain circumstances accurately, uniform and homogeneous conditions may not be adequate for the some cases. It perhaps raises possible uncertainty to the design of decisive program for remediation during the in situ investigation stage. Ivanov and Angelova (2017) represent the investigations of groundwater sources in Bulgaria and indicate concentrations of toxic elements or metal ions exceeding the maximum contaminant values. The main problems standing before the companies exploiting groundwater sources with chemical pollution were associated with the choice of an economically beneficial alternative guaranteeing the safety of water used for drinking, household and industrial purposes (Ivanov and Angelova, 2017). Moreno and Paster (2018) perform the prediction of pollutant remediation in a heterogeneous aquifer in Israel. Risk analysis for the migration of the plume showed that the ability of the current configuration of the remediation wells to control the plume is limited to the top layers of the aquifer. There is a significant risk that the plume will migrate downstream towards production wells, without being noticed using the present monitoring network.

Shih et al. (2002) and Shih (2007) derived analytical solutions for the transport of radioactive nuclides in fracture media. Shih (2004) used first order differential analysis to derive the analytical form of expectation and variance for contaminant transport by regarding uncertainties of both dispersion coefficient and retardation factor. Shih (2011) studied analytical one-dimensional transport considering multiple members of a decay chain in a single rock fracture. It used the input sources for constant, pulse, impulse, Heaviside, and exponential decay to verify the suitability of the solutions and demonstrate an application to a hybrid test site for a preliminary study for the disposal of spent nuclear fuel. However, the above-mentioned studies commonly used for the idealized groundwater system and cannot be applicable for the type of heterogeneous one.

The Great East Japan Earthquake and tsunami of March 2011 severely damaged three reactors at the Fukushima Daiichi nuclear power station and led to a major release of radiation into the environment (Marui and Gallardo, 2015). Groundwater flow through the crippled reactors continues to be one of the main causes of contamination and associated transport of radionuclides into the Pacific Ocean. It presents an overview of the methods that can manage groundwater

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contamination and mitigate the impact of hydrological pathways in the dispersion of radionuclides at Fukushima. A common remedial strategy to deal with contaminated groundwater is to extract the contaminated water and treat it at the surface prior to discharge or reinjection; the earlier studies provide many application cases (USEPA, 1995; NRMRL, 1995; Bass et al., 2000; Kirtland and Aelion, 2000; Khan et al., 2004).

Uncertainty associated with hydrogeological conditions in an aquifer is not fully quantifiable. It often lacks enough knowledge, like information regarding site data, predictable model or process, to determine future outcomes precisely. In addition to imperfect awareness, uncertain factors are usually subject to a certain level of error due to their heterogeneous characteristics. The purpose of reliability and risk analysis is to obtain statistical information to identify how to reduce the impact of uncertainty and make the best choices for decisions. Incorporating reliability and risk analysis into understanding the performance of a system is a way of improving the quality of decision-making process. The main purpose of this research is to provide a novel approach to measure uncertainty, quantifying risks associated with radioactive release in the subsurface water environment of a Quaternary aquifer by considering specified limit as resistance and monitored in situ groundwater condition as load. It regards the limitation as a designed radioactive capacity or scheduled safety strength of a natural subsurface water system, and in situ monitored groundwater condition is a recognized force or contamination load affecting on the natural environment. Finally, it addresses adequate deployment of a groundwater monitoring well accordingly. Advanced long-term remediation can become feasible, in no doubt, by checking water quality at a suggested location. This paper present a useful and achievable assessment including conceptual design, probabilistic method and reliability calculation, to illustrate the application of the research. The process used in the present study is also appropriate to the other risk-based studies of surface or subsurface hydrology system.

2. Background information

The studied site designed in 2010 and designated as a studied area with credible protection dedicated to the research and development for the purpose of nuclear safety and technologies. In order to explore unseen events related to a spill or leakage associated to radionuclides released in environment or other subsurface contamination in the future, a hypothetical and hybrid studied site (HHS) was built for the planned mission, undergoing a long time for nuclear research. It may require building standard procedures to evaluate any remedial actions taken in response to the quantity of the spill or leakage. Therefore, it uses the risk-based probability calculation and procedure to build any necessary steps for future remediation controls.

The site, HHS, is located in the north of Taiwan; recent alluvium with local thin sediments, lateritic terrace gravel with clay and gravel beds constitute geological strata in the Quaternary from the surface down to the bedrock. The thickness of the gravel bed is about 24 m (Table 1); water table approximately ranged from 16 m to 17 m below surface. The sandstone bed generally distributed nearly on the bottom of gravel layer. The groundwater well tapped in unconfined gravel aquifer with a diameter of 4 in. and depth of 24 m. Fig. 1 illustrates the conceptual layout of this study. The site was located on the top of a double plateau of a gravel formation; it presents a slope ranging from 45 to 65 degree from the top plateau to the second and groundwater level is higher than the ground in the second plateau. The strike and face of the slope trends to east north and east south, respectively. There is a natural spring discharging at the junction of the top and second plateau, and regards as the outlet of groundwater release from the subsurface of HHS. The equipped monitoring devices in a series of groundwater wells in aquifer system along the site boundary label as A to E (Fig. 1). Gross-beta activity is an indicator of beta-emitting isotopes in water. The occurring radioactivity in groundwater is to be indicative of radioactive releases from the site. The gross beta activity observed at the spring outlet and groundwater wells A to E are the load for a risk assessment. For the general purpose of investigation, a hypothetical value is used as a resistance or strength that stresses the radioactive release of groundwater into the human environment. This study specifies the rule that gross beta activity for groundwater must be less than 1.8 Bq/L; it designates as the limit of resistance (LR).

To address the impact of radioactive release in groundwater at the HHS regarding hydrological environment, it is necessary to observe in situ groundwater conditions and assess safety issues by risk-based probability calculations. However, it is cost-effective if one monitor groundwater condition in the key position of site boundary. The chance of unexceeding or exceeding the specified limit regard as the possibility of system safety or failure respectively. It then focuses the probabilistic calculation and risk assessment with uncertainty measures substantially.

Table 1
Well log of the studied site.

Groundwater well	A	B	C	D	E
	Depth from the ground surface (m)				
Gravel with sand	0–24.40	0–24.37	0–23.41	0–23.48	0–23.57
Sandstone	24.40	24.37	23.41	23.48	23.57
Groundwater level	16.11	17.36	17.45	17.66	17.03

3. Reliability and risk analysis

The key to designing in reliability and risk assessment for a system is to identify loads and resistances correctly; it refers to force and strength (capacity) on that system respectively. The resistance defines as the ability of system to achieve the determined purposes without failure when it is under loads. Sometimes, the resistance also indicates a rule to follow the defined limit. Therefore, recognizing the load, resistance and all factors associated with uncertainty is a necessary step in risk and reliability analysis. The earlier studies provided many cases associated with the reliability analysis considering load-resistance interference (Cornell, 1969; Ang and Cornell, 1974; Tung et al., 2005; Singh et al., 2007).

Many factors applied to measure the uncertainty of a system; one way to measure the degree of uncertainty is to apply statistical moments in various orders. Useful statistical moments in this case are mean and variance of random variables. Mean (μ_x) is the first central moment that illustrates the expected value of a variable (x), while variance ($\sigma_x{}^2$) is the second-order moment of a variable and demonstrates the scatter of a random variable. Coefficient of variation (CV) which is defined as the ratio of the standard deviation of variable (σ_x) to its mean, indicates to the level of uncertainty; it is also used as a normalized measure of uncertainty to be compared in various conditions or factors. Moreover, the systematic measure of uncertainty is the calculated probability density function (PDF) of desired uncertain variables. It suggests that derivation of the statistical moments and probability density function of random variables are the important parts of uncertainty analysis.

Reliability, or the probability of non-failure, define as an ability of system to satisfy their design functions and it is commonly measured by studying the interaction of load and resistance based on probabilistic analysis. When a system is reliable, the resistance of system (R) exceeds the load (L), while if load exceeds resistance, the system cannot achieve the defined purposes and it is unreliable. Analytically, the probability of reliability for a system p_s defined as (Tung et al., 2005):

$$P(L \leq R) = p_s = 1 - p_f, \tag{1}$$

where P is the probability, p_s is the probability of non-failure or