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Consideration of Typical Nuclear Power Plant Site Characteristics for Groundwater Flow

Chanhoi, Kim, Eric Yee*
658-91 Haemaji-ro, Seosaeng-myeon, Ulsan, South Korea, KEPCO International Nuclear Graduate School
** Corresponding author: mcchan78@naver.com*

1. Introduction

After the tragic Fukushima Daiichi nuclear power plant accident, continuous reports have been developing regarding radiation and groundwater contamination. Monitoring stations in drainage systems, trenches, and groundwater wells have detected a variety of radioactive isotopes, with the general fear of such contaminants reaching the ocean, thus impacting human health and ocean biota. Although steps have been taken to monitor, prevent, and remediate water resources at the power plant vicinity, much is still unknown about the plant facility, the subgrade, and the water flow. This is complicated by the extreme measures the plant owners have taken by pumping water into the disabled plant in order to cool the corium, making it difficult for workers to inspect the facility and mitigate radiation hazards.

One of most confusing aspects of the groundwater contamination issue at the Fukushima Daiichi nuclear power plant is the flow of groundwater, with conflicting reports saying there is very little water to significant amounts of water flowing towards the plant. Initially, different media outlets, reports, and figures show anywhere from uniform flow to nearly impossible flow situations, with a general improvement in groundwater flow feasibility over time as perhaps more knowledge of the subgrade or facilities is revealed. This situation highlights the importance of groundwater models, which traditionally use averaged and macro-scale adjusted subgrade properties. These are not necessarily bad practices, but some details may be lost in the process for more local scenarios. Therefore, this paper focuses on the site conditions of a typical nuclear power plant and its influences on local groundwater flow modelling.

2. Nuclear Power Plant Siting regarding Groundwater

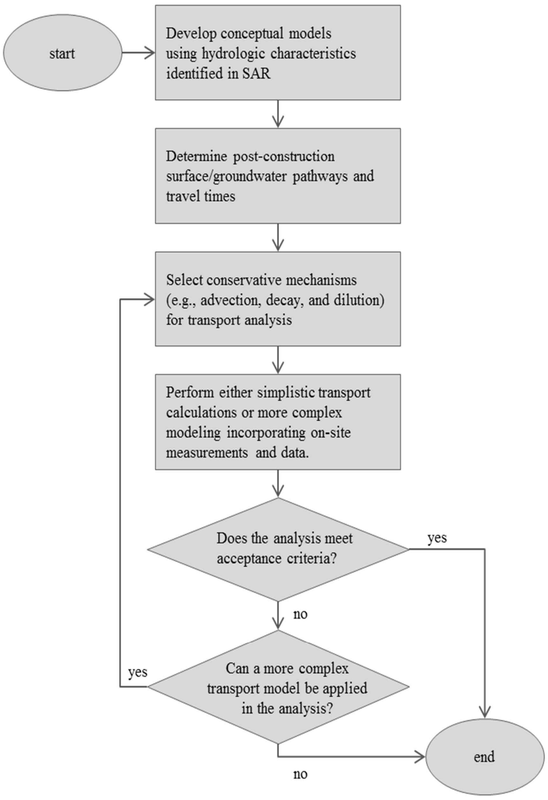
One of the most important factors in nuclear power plant siting is to study the groundwater flow and its properties, because it allows stakeholders to understand the existing and potential risk of groundwater contamination and also to prioritize any mitigation action required to reduce the risks [1]. There are three ways pertaining to a discharge of radioactive material from nuclear power plant which may contaminate the groundwater system in the nuclear power plant region either directly or indirectly as below

- Indirect discharge to the groundwater through seepage of surface water that has been contaminated by radioactive material discharged from a nuclear power plant.
- Infiltration of radioactive liquids from a storage tank and reservoir.
- Direct release from a nuclear power plant; an accident at the plant may induce such an event, and radioactive material could penetrate the groundwater system.

Therefore, there are several considerations to prevent and mitigate groundwater contamination for typical nuclear power plant siting, such as groundwater table depth, thickness of aquifers, confining beds, groundwater flow patterns, subsurface material properties, and groundwater travel time.

3. Groundwater Flow modeling at Nuclear Power Plant

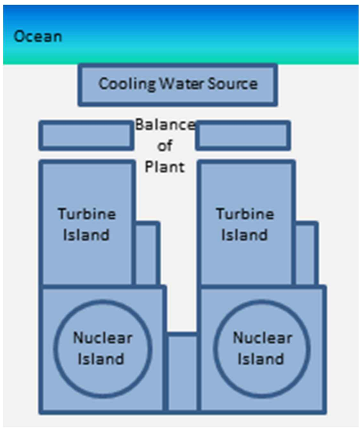
The modeling of groundwater flow is very important in the safety analysis of nuclear power plants and evaluating environmental impacts, modeling of groundwater flow is one of the key factors. Models are developed conceptually before and after construction to re-evaluate and apply to the hydrologic system. Once conceptual model is defined, it affects the construction activities. Construction activities may impact the previously defined hydrologic system temporarily and permanently by altering ground conditions which impact groundwater flow such as recharge, runoff, and drainage. As a result, a conceptual modeling of groundwater flow is defined as an overall understanding of the characteristics and properties of the hydrologic system based on an interpretation of the available data [1]. Developing a conceptual model for a nuclear power plant is an essential component of the licensing process. The purpose of modeling of groundwater flow is to develop plans or mitigate the impacts to the public health and safety during plant operation under normal operation and abnormal accidents. Developing conceptual models using hydrologic characteristics is the main factor to in developing a hierarchical approach for to analyzing the consequences of radioactive releases. Figure 1 shows the process which is proposed in ISG-014. This analysis is to help determine if there is a significant risk of groundwater contamination, by iteratively calculating and analyzing transport calculation and analysis mechanisms.



[Fig. 1 The hierarchical approach for analyzing radioactive consequences in groundwater based on ISG-014]

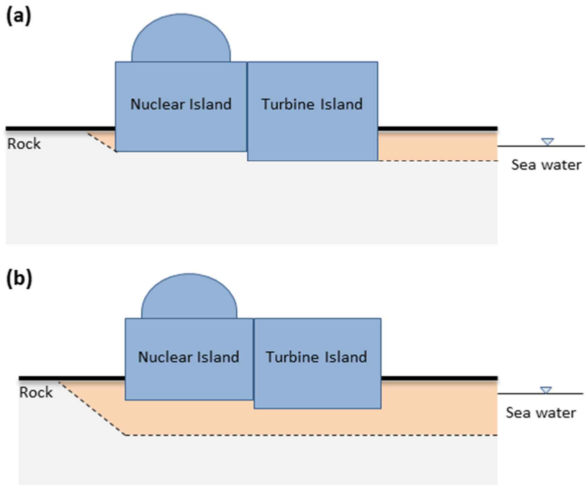
4. Typical Nuclear Power Plant

The nuclear power plants considered in this preliminary study are generic APR1400 types [2]. The APR1400 is a generation 3 pressurized light water reactor with a typical layout presented in Figure 2. Similar to most nuclear power plants, APR1400 nuclear power plants are built in pairs, each one connected by a compound building on the nuclear island side. Turbine buildings are built in a radial formation, with the turbine generators longitudinally perpendicular to the reactor containment building. The turbine island is located closer to the ocean or cooling water source where cooling water is usually pumped in and discharged through underground tunnels.



[Fig. 2 Generic APR1400 nuclear power plant layout]

Due to regulations and engineering practice, modern nuclear power plants such as the APR1400 generally have a common plan and profile. Nuclear power plants have to be near large bodies of water, typically coastal areas, thereby making geologic units more readily available. Additionally, the size and depth of the nuclear and turbine islands lead to the construction of large mat foundations. These two criteria generally lead to nuclear power plants commonly being founded on competent bedrock, as shown in Figure 3a. If bedrock is deeper than the nuclear power plant required depth, then the underlying soil is either treated or compacted, as shown in Figure 3b. Fill soils are usually placed on the turbine island side because the land is either reclaimed, or to make space for tunnels and balance of plant. Nuclear and turbine islands are not generally founded on sites with considerable soil deposits, although some engineers and scientists use soil sites for their studies [3].



[Fig. 3 Typical nuclear power plant profiles where nuclear and turbine islands are founded on (a) rock and (b) soil.]

5. Groundwater Modeling

Groundwater models are used to calculate the rate and movement of groundwater through the subsurface aquifer. Thus, they are utilized as tools for decision making in the management of water systems by predicting future groundwater flow.

Mass conservation is given by: the rate of mass accumulation = the rate of mass inflow – the rate of mass outflow. Laplace's equation combines Darcy's law and the mass conservation equation into a second partial differential equation, and the following general flow equation in three dimensions for inhomogeneous and anisotropic confined aquifer is derived as below

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S\frac{\partial h}{\partial t} + W \qquad (1)$$

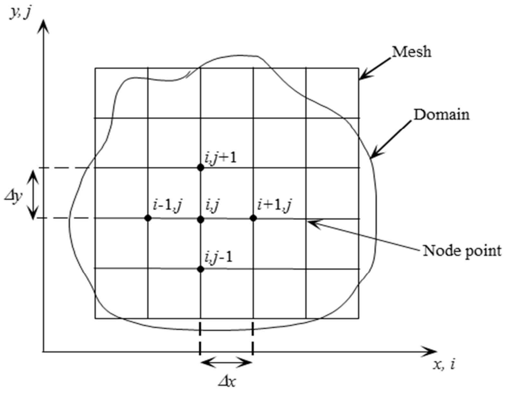
Where

K_x, K_y, K_z = hydraulic conductivity along the x, y, and z axes

h = hydraulic head
S = Storage coefficient which varies in value for confined and unconfined aquifers,
t = time
W = volumetric flux per unit volume

5.1 Method to solve groundwater flow equation

The groundwater flow equation has been solved analytically for a variety of homogeneous and boundary conditions, but due to the potential complexity of site properties and characteristics, in addition to transient cases, numerical methods are typically applied. The most common numerical methods are finite difference method (FDM) and finite element method (FEM), which provide a rationale for operating on the differential equations that make up a model and for transforming them into a set of algebraic equations, each with their own advantages and disadvantages. A large number of algebraic equations can be solved by iterative techniques or matrix methods. Some FDMs are iterative procedures that divide an aquifer into a grid (Fig 4.) and yield values for a finite number of points by converting a partial differential equation into a set of algebraic equations. In lattice points, the smaller $\Delta x, \Delta y$, the closer the approximate solution comes.



[Fig. 4 Finite difference grid]

The value of the head at the point represented by the indices (i,j) is $h_{i,j}$. In the finite difference approximation, derivatives are replaced by differences taken between nodal points. A central approximation to $\partial^2 h / \partial x^2$ at (x_0, y_0) is obtained by approximating the first derivative at $(x_0+\Delta x/2, y0)$ and at $(x_0-\Delta x/2, y_0)$ as below:

$$\frac{\partial^2 h}{\partial x^2} \approx \frac{\frac{h_{i+1,j}-h_{i,j}}{\Delta x} - \frac{h_{i,j}-h_{i-1,j}}{\Delta x}}{\Delta x} \qquad (2)$$

which simplifies to

$$\frac{\partial^2 h}{\partial x^2} \approx \frac{h_{i+1,j}-2h_{i,j}+h_{i-1,j}}{\Delta x^2} \qquad (3)$$

Similarly

$$\frac{\partial^2 h}{\partial y^2} \approx \frac{h_{i,j+1}-2h_{i,j}+h_{i,j-1}}{\Delta y^2} \qquad (4)$$

When the general groundwater flow equation is applied to a confined aquifer under steady state and homogeneous conditions, equation (4) becomes the so-called 5 point formula.

$$h_{i+1,j} + h_{i-1,j} + h_{i,j+1} + h_{i,j-1} - 4h_{i,j} = 0 \qquad (5)$$

6. MATLAB Procedure

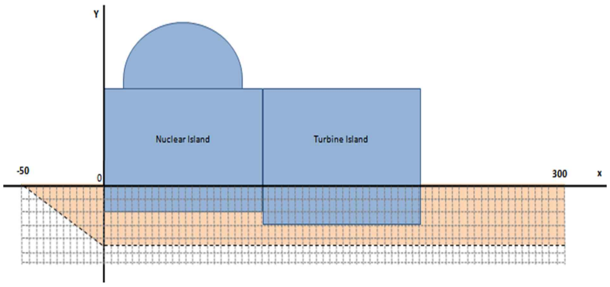
The iterative procedure applied to the finite difference method is well suited to computer programming. Although it is not extremely difficult for someone to implement their own finite difference or finite element algorithm to solve the groundwater flow equation for their specific situation, many engineers and scientists use the program MODFLOW [4], which utilizes finite difference techniques to model groundwater flow. However, in this study, MATLAB was used to implement a simple finite difference program for solving the groundwater flow equation. Although MODFLOW is a very powerful program when used properly, MATLAB appears to allow much more control over input, output, and graphics capabilities relative to MODFLOW and many of the graphics enhancement modules and programs were unavailable for use.

6.1 Implementation

A MATLAB program can be divided into three parts initialization (set initial and boundary condition), computation (solver – iterative procedure), and printout (plotting functions and date).

6.2 Initialization

According to figure 3 which represents a typical generation 3 pressurized light water reactor, the nuclear power plant site subsurface is discretized into a computational domain by using constant grid spacing of Δx and Δy in the x and y directions respectively to implement in MATLAB. Grid points are indexed by (i, j) in the usual way and the approximate value of head at grid point (i, j) is denoted by $h_{i,j}$. Figure 5 shows a rectangular grid with 350 (from -50 to 300) and 50 (from 0 to -50) grid points in the x and y direction respectively. Detailed boundary conditions of the rectangular grid will be described in detail in section 7 Boundary Condition.



[Fig. 5 Initialization of nuclear power plant sub-surface domain based on figure 3 (b)]

6.3 Computation

Equation (5) can be expressed as matrix form: Au=b. For practical problems, A is likely to be a large matrix which makes the direct solution in matrix form computationally inefficient [5]. More efficient methods use iterative approaches where an initial estimate for u is updated to form a better estimate. This process is repeated until the distance between successive estimates is less than pre-defined tolerance. In this study, the 5 point formula for general groundwater flow in a confined aquifer under steady state and homogeneous conditions is computed using Jacobi Iteration where equation (5) is changed to allow multiple iterations.

$$h_{i,j}{}^{m+1} = (h_{i+1,j}{}^{m} + h_{i-1,j}{}^{m} + h_{i,j+1}{}^{m} + h_{i,j-1}{}^{m})/4 \quad (6)$$

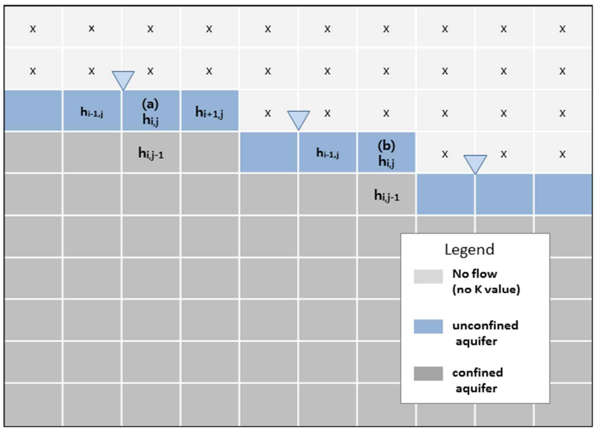
A modification to equation (6) is necessary to allow Jacobi Iteration for unconfined, steady state, homogeneous conditions. Usually, Jacobi Iteration needs 5 cells, but only 2 or 3 eligible cells surround an unconfined aquifer cell due to a modeled zero hydraulic conductivity above the water table level. Figure 6 shows a simplified 10 x 10 computational domain which includes unconfined aquifer cells, defining the water table, in blue. Cell (a) has only three available head values surrounding it and cell (b) has two head values. Therefore, equation (6) is modified as blow.

For cell (a)

$$h_{i,j}{}^{m+1} = (h_{i+1,j}{}^{m} + h_{i-1,j}{}^{m} + h_{i,j-1}{}^{m})/3 \quad (7)$$

For cell (b)

$$h_{i,j}{}^{m+1} = (h_{i-1,j}{}^{m} + h_{i,j-1}{}^{m})/2 \quad (8)$$



[Fig. 6 Simplified computational domain including water table]

For each grid point (i, j), $h_{i,j}$ at the next iteration (m+1) is found in equation (6) through (8), depending on the condition. Once an iteration has been completed for all grid points, the difference between $h_{i,j}{}^{m+1}$, $h_{i,j}{}^{m}$ is computed. If,

$$|h_{i,j}{}^{m+1} - h_{i,j}{}^{m}|_{\infty} < tolerance \quad (9)$$

where tolerance is a pre-defined value equal to 5×10^{-4}, then the iteration terminate and the solution is $h_{i,j}{}^{m+1}$, otherwise the iteration continues.

6.4 Printout

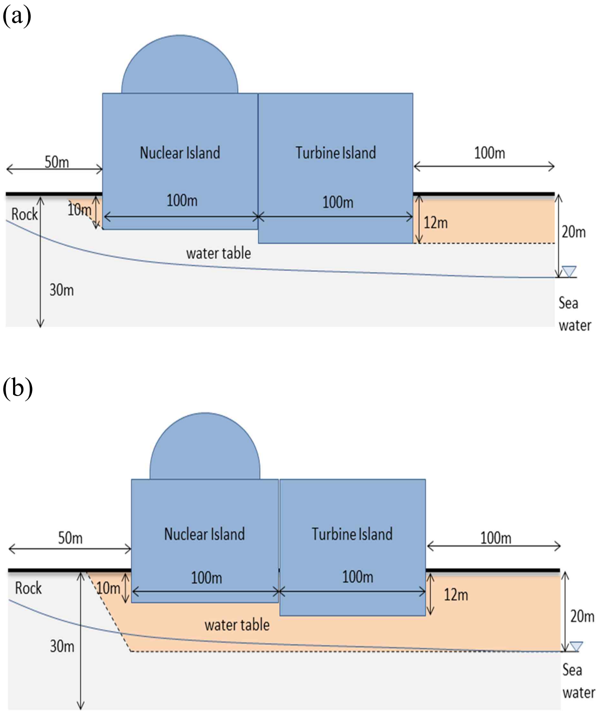
MATLAB was coded to print contours of the computed heads, the computed nodal flows, the computed horizontal flows across cell faces, and the computed vertical flow across cell faces. When horizontal flow is used as an output of the model, these results are cumulated along the cell faces upward from the bottom of the model. This gives the stream function which yields stream lines.

7. Boundary Condition of the model

In Fig. 3, typical nuclear power plant profiles where the nuclear and turbine islands are founded on (a) rock and (b) soil are discretized into a computational domain by using constant 1m grid spacing of Δx and Δy with 350m and -50m in the x and y directions respectively. Each conceptual model has left and right fixed heads, hydraulic conductivity, and the water table below the plant assuming bottom of the model is impervious as below.

- Fixed Head Left: 25.5m, Fixed Head Right: 20.5m
- Table 1: Hydraulic conductivity

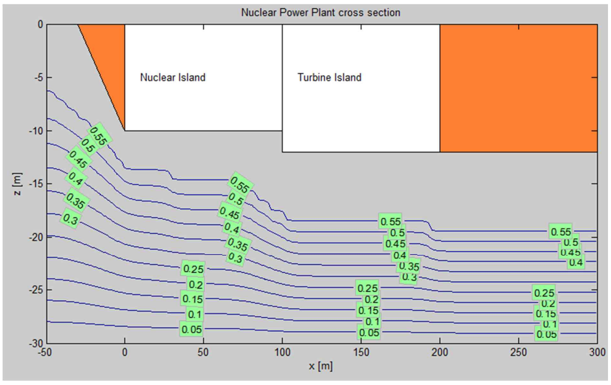
Material	Hydraulic conductivity (m/sec)
Coarse Sand	10×10^{-5}
Weathered Granite	3×10^{-5}



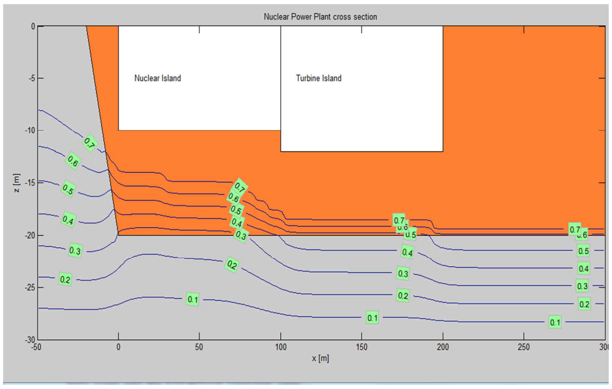
[Fig. 7 typical nuclear power plant profiles boundary condition founded on (a) rock and (b) soil]

8. Results

Preliminary groundwater flows within the site is shown in Figure 8 when the nuclear power plant is founded on rock and in Figure 9 when the nuclear power plant is founded on soil. The finite difference grid simulating a typical nuclear power plant provides the calculation of the pathway and the amount of groundwater flow. As expected, there was more flow in the soil profile.



[Fig. 8 Typical Nuclear Power Plant founded on rock. Numbers on flow lines indicate amount of flow in m^2/day]



[Fig. 9 Typical Nuclear Power Plant founded on soil. Numbers on flow lines indicate amount of flow in m2/day]

Obviously, a nuclear power plant on rock has stronger foundational support relative to a nuclear power plant founded on soil. Results suggest that the groundwater flow rate from a nuclear power plant founded on soil is higher than on rock due to a relatively higher permeability. When it comes to radioactive material leakage accident, lower groundwater flow rates are much easier to control and enact mitigation measures than higher flow rates. Table 2 shows the range of flow according to the site conditions.

Table 2: The amount of flow rate

Site condition	Max(m^2/day)	Min(m^2/day)
Rock foundation	0.55	0.05
Soil foundation	0.7	0.1

9. Conclusion

Site-specific data from the hydrologic system investigation must be prepared and utilized to evaluate the existing groundwater conditions and to identify pathway of groundwater flow toward subsurface and plant facilities before and after nuclear power plant construction by installing monitoring wells. These investigation data, evaluation and identification provide the basis for developing an overall conceptual model of groundwater. With this conceptual model, assumption of radioactive material release, for instance, the liquid radioactive waste from a ruptured tank in the compound building through cracks in the foundation wall enter the groundwater system, can be evaluated.

The results of this study suggest that the groundwater flow conceptual model can be applied to predict the future flow of groundwater to mitigate the consequences of accidents such as radioactive material leakage. However, mixed hydraulic conductivity and volumetric water flux such as drainage and seepage are not considered. When the numerical analysis in this study is combined with the dilution and dispersion of contaminants model, the result will be used to predict the particle location within model domain.

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