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Research article

Simplified Groundwater Flow at Nuclear Power Plants

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Abstract

As a result of the Fukushima Daiichi nuclear power plant disaster, significant amounts of radioactive materials have been introduced into the environment. Local and international organizations continue to monitor the situation and its effect on aquatic ecosystems as well as on human health. One of the many concerns after such an accident is the civil and construction work required to address such issues; however, multiple studies tend to consider nuclear power plant sites as being founded on soil when in reality such installations are founded on rock. Using real nuclear power plant structural geometries and field data, 2-D numerical simulations were conducted to estimate the amount of groundwater flow that could be expected. The results show the amount of groundwater flux to range from 0.07 to 46 m^2/day, which from an engineering perspective is not that large. Because of this, maintenance and environmental safety workers could expect some groundwater intrusion when their excavations reach the rock boundary.

1. Introduction

One of the most important factors in nuclear power plant (NPP) siting, operation, and maintenance is local groundwater flow, which needs to be studied. Groundwater studies allow stakeholders to understand the existing and potential risk of groundwater contamination and also to prioritize any mitigatory action required to reduce these risks [1-3]. There are three potential types of accidents with high probability pertaining to a discharge of radioactive material from NPPs that may contaminate the groundwater system in the NPP region: 1) Indirect discharge to the groundwater through seepage of surface water that has been contaminated by radioactive material discharged from a NPP, 2) Infiltration of radioactive liquids from a storage tank and/or reservoir, and 3) Direct release from a NPP; an accident at the plant may induce such an event, and radioactive material could penetrate the groundwater system.

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Moreover, groundwater contamination due to nuclear power generation became a big issue after the tragic Fukushima Daiichi 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. Although steps have been taken to monitor, prevent, and remediate water resources in the power plant vicinity, much is still unknown about the plant facility, the subgrade, and the water flow around the plant. This has been complicated by the extreme measures the plant owners have taken by pumping seawater 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 NPP 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 showed 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 was revealed [4-6]. This situation highlights the importance of groundwater models, which traditionally use averaged and macro-scale adjusted sub-grade properties. These are not necessarily bad practices, but some details may be lost in the process for more local scenarios.

General studies on the mechanics of groundwater flow involving the distribution and transport of matter have been conducted over the years with a focus on radioactive waste disposal in the nuclear industry [7-17]. Most of these studies tend to focus on components of the transport process that do not heavily depend on flow velocity as radioactive contaminants will decay and thus change in composition with time [11-17], while others provide some insight and integration of the unsaturated zone and its influence in the transport process [14-16]. Many of these studies confirm the need for *in situ* parameters and their influence on water flow.

Due to such concerns and the highly variable results regarding groundwater flow around NPPs, this study focuses on describing the groundwater flow beneath a typical South Korean APR1400 NPP [7]. A simple yet flexible finite difference model is developed, taking into account structural geometries and ground characteristics, to describe the two-dimensional flow regime, which is shown to be low. Additionally, because contaminant transport mechanisms rely on velocity, in addition to other components, the results also suggest transport from groundwater flow might not be as concerning as surface water scenarios.

2. Materials and Methods

2.1 Modelling

2.1.1 Typical nuclear power plants

The NPPs considered in this preliminary study are generic APR1400 types [18]. The APR1400 is a generation 3 pressurized light water reactor with a typical layout as presented in Figure 1. APR1400 power plants are built in pairs, and 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 like many power plants.

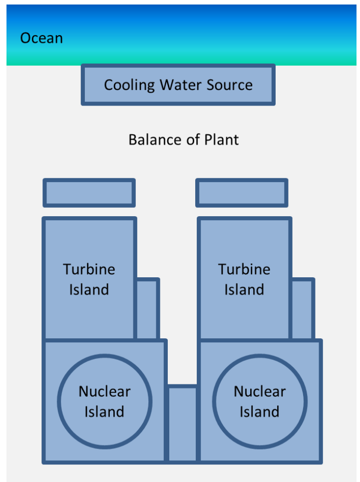

Figure 1. Generic South Korean nuclear power plant indicating general plant arrangement and layout

Due to regulations and engineering practice, modern NPPs such as the APR1400 generally have a common plan and profile. NPPs have to be near large bodies of water, typically in 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 NPPs commonly being founded on competent bedrock, as shown in Figure 2a. If bedrock is deeper than the NPP required depth, then the underlying soil is either treated or compacted, as shown in Figure 2b. 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 [19-23].

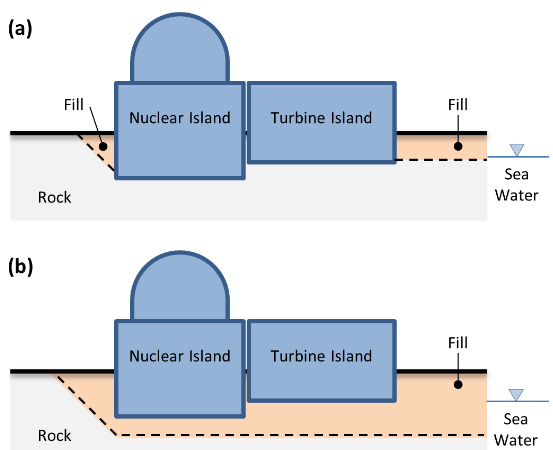

Figure 2. Typical nuclear power plant profiles where nuclear and turbine islands are founded on (a) rock and (b) soil.

2.1.2 Groundwaer flow modelling

Groundwater models are used to calculate the rate and movement of groundwater through an aquifer, which is a geologic zones that can store water. This movement is basically dictated by Darcy's law, which summarizes the fundamental physics of groundwater flow by relating the velocity vector to the gradient of hydraulic potential. Applying the conservation of mass to Darcy's law in two dimensions for a nonhomogeneous and anisotropic aquifer results in the following equation:

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

where K_x, K_y = hydraulic conductivity along the x (horizontal) and y (vertical) axes, S = Storage coefficient which varies in value for confined and unconfined aquifers, t = time, and W = volumetric water flux. The groundwater flow equation has been solved analytically for several 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 method used to solve the groundwater flow equation is the finite difference method, FDM. FDM requires a discretization of the model into various control cells. An example discretization is shown in Figure 3. The groundwater flow equation is solved for each cell using finite differences, with the outputs being inputs to neighboring cells. This requires several boundary conditions.

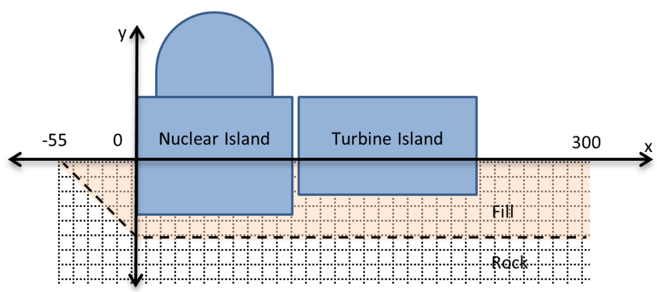

Figure 3. Example initialization of NPP subsurface domain

2.2 Modelling parameters

2.2.1 Boundary conditions

Figure 4 shows boundary conditions for typical NPP profiles where the nuclear and turbine islands are founded on (a) rock and (b) soil with fixed dimensional values. The computational domain is discretized using constant 1 m grid spacing of Δx and Δy with a total of 350 m (from -50 to 300) and 50 m (from 0 to -50) in the x and y-directions, respectively. Thus, cell-spacing was set at 1. The width from left side of model to the nuclear island is 50 m. The widths of the nuclear island, turbine island, and the distance from turbine island to the sea shore are 100 m, 100 m, and 100 m, respectively. Excavation level differs for each model, 12 m for NPP based on rock foundation and 20 m for soil foundation. Each model has left and right fixed heads. The fixed head on the left side boundary was set at 45.5 m and 40.5 m for the right side boundary in each model. The sea water level is 9.5 m from ground-level. The groundwater level is not fixed and it will be calculated for unconfined conditions.

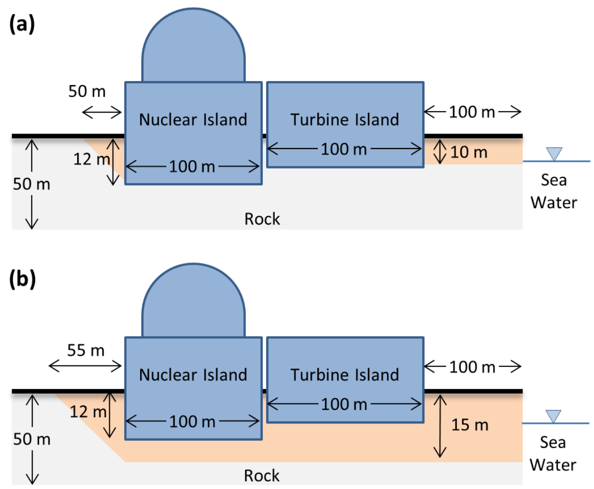

Figure 4. Boundary conditions founded on (a) rock and on (b) soil

In this study, MATLAB was used to implement a simple finite difference program for solving the groundwater flow equation. MATLAB allows more control over input, output, and graphics capabilities relative to other FDM and groundwater flow computer programs. Also, in this study, an iterative method is applied to calculate the confined and unconfined aquifer to better simulate actual groundwater conditions. This verification process can be coded to go through a maximum of 5 iterations. Once the iteration process has been completed for all cells, the difference between newly computed hydraulic heads and prior hydraulic heads can be calculated. When the difference is lower than pre-defined tolerance of 0.01, the iterations terminate and the program should have arrived at flow equilibrium. MATLAB version 2012b was used for these calculations.

2.2.2 Ground parameters

Hydraulic conductivity describes the ability of the aquifer to allow water flow. Hydraulic conductivity is dependent on the fluid (viscosity and density) and the geological medium, such as soil and rock. The dimensions of connected pore spaces are physical attributes of the medium that control the vertical and horizontal hydraulic conductivity. At South Korean NPP construction sites, double packer tests are normally carried out for field hydraulic conductivity tests in accordance with procedures given in British Standards [24]. Tests were distributed to provide samplings of major layers, and also to evaluate potential variability at the same depths in multiple layers. NPPs in South Korea use the same test method to estimate field conductivity values [25]. The results are shown below in Table 1.

Table 1. Hydraulic conductivity of weathered granite in South Korean NPPs

	Softly Weathered	**Moderately Weathered**	**Highly Weathered**
Number of tests	55	37	417
Conductivity (m/s)	$9.86 \times 10^{-7} - 5.10 \times 10^{-4}$	$3.98 \times 10^{-6} - 4.01 \times 10^{-3}$	$9.35 \times 10^{-5} - 4.95 \times 10^{-3}$

On the other hand, typical hydraulic conductivities for unconsolidated sedimentary sand are shown below in Table 2.

Table 2. Hydraulic conductivity in soil

	Coarse Sand	Medium Sand	Fine Sand
Conductivity (m/s)	$9 \times 10^{-7} - 6 \times 10^{-3}$	$9 \times 10^{-7} - 5 \times 10^{-4}$	$2 \times 10^{-7} - 2 \times 10^{-4}$

For this study, mean values from both Tables 1 and 2 were applied to the groundwater model, with the values represented in Table 3.

Table 3. Hydraulic conductivity of weathered granite in South Korean NPPs

Material	Description	Conductivity, k_x (m/s)
Rock	Softly Weathered	1.43×10^{-6}
	Moderately Weathered	3.69×10^{-6}
	Highly Weathered	9.35×10^{-4}
Soil	Coarse Sand	3×10^{-4}
	Medium Sand	2×10^{-5}
	Fine Sand	1×10^{-5}

The horizontal hydraulic conductivity for the whole aquifer is assumed to be 10 times the value of the vertical hydraulic conductivity, which is consistent with anisotropy ratio given in the literature [19]. In this study, the ratio of vertical conductivity, k_y, and horizontal conductivity, k_x, is assumed to be 0.1.

3. Results and Discussion

Sample calculated groundwater flows within the NPP site are shown in Figures 5-8, when the NPP is founded on rock. Figures 9-12 show results when the NPP is founded on soil. These figures are not to scale and numbers labelled on stream lines show the amount of flow per second (m^2/s). The amount of groundwater flow between stream lines is constant from start to end (from left to right in the above Figures), as there is no leakage or drainage.

Figures 5 and 6 both have softly weathered rock as the base foundation and thus the lowest levels of hydraulic conductivity out of all the bedrock scenarios listed in Table 3. The difference is that Figures 5 and 6 use coarse sand and fine sand as backfill, respectively. This makes the scenario shown in Figure 5 the most resistant to groundwater flow and it shows with low flows represented as stream lines. Figures 7 and 8 help make a comparison in the sense that the moderately weathered rock foundation and medium sand backfill scenario is less resistant to flow than the scenario shown in Figure 5, but more resistant to flow with the highly weathered rock foundation and fine sand backfill scenario shown in Figure 8. The scenario shown in Figure 8 is the least resistant from our parameters and shows a 3 order of magnitude difference in flow rates compared to the most resistant scenario shown in Figure 5.

Figure 9 is the most flow resistant scenario of fine sand and softly weathered bedrock and interestingly enough, it shows an order of magnitude difference in flow between the soil fill and bedrock foundation. Figure 10 lessens the flow resistance parameters, but the resultant flow does not seem to change significantly as shown in the stream lines. Both Figures 11 and 12 have highly weathered bedrock but with coarse sand and fine sand as backfill, respectively. This makes the scenario shown in Figure 12 the least resistant to water flow when soil acts as a foundation. Interestingly, there is no significant difference in flow between the different backfills when there is highly weathered bedrock involved.

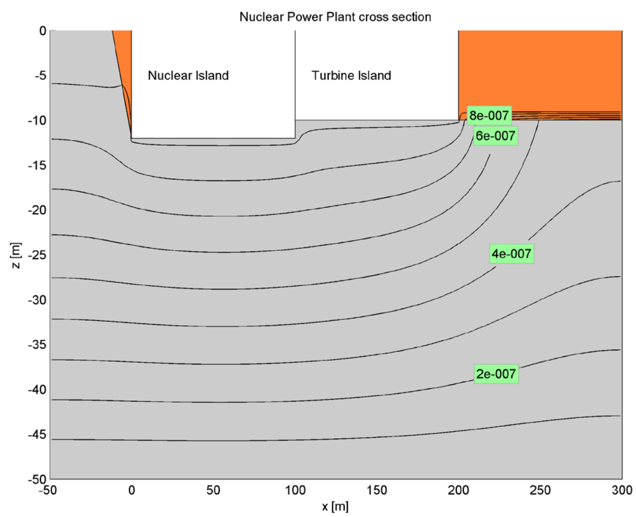

Figure 5. Sample groundwater flow for a softly weathered rock foundation and coarse sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

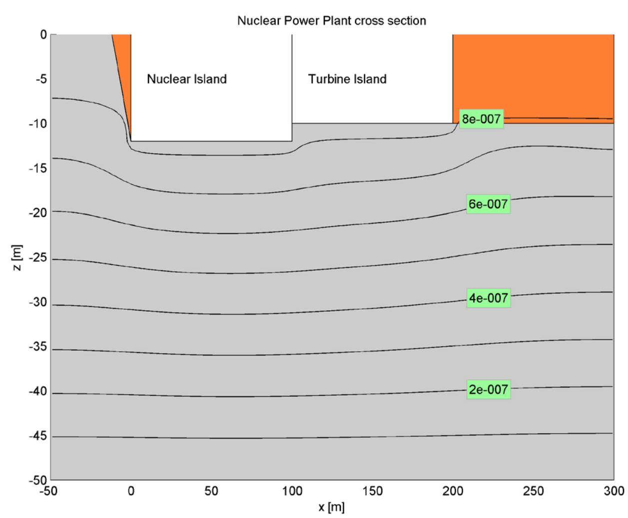

Figure 6. Sample groundwater flow for a softly weathered rock foundation and fine sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

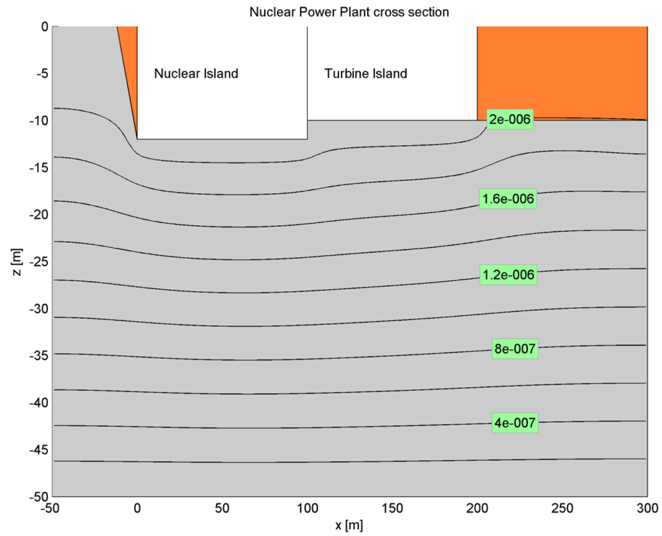

Figure 7. Sample groundwater flow for a moderately weathered rock foundation and medium sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

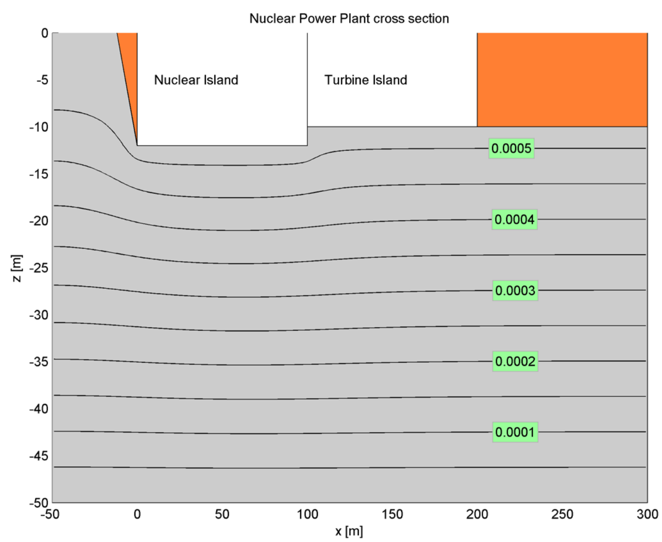

Figure 8. Sample groundwater flow for a highly weathered rock foundation and fine sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

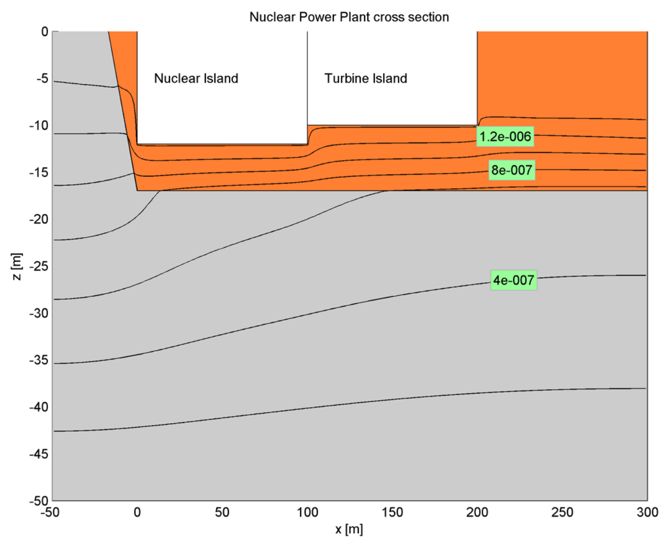

Figure 9. Sample groundwater flow for a fine sand soil foundation on softly weathered rock and fine sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

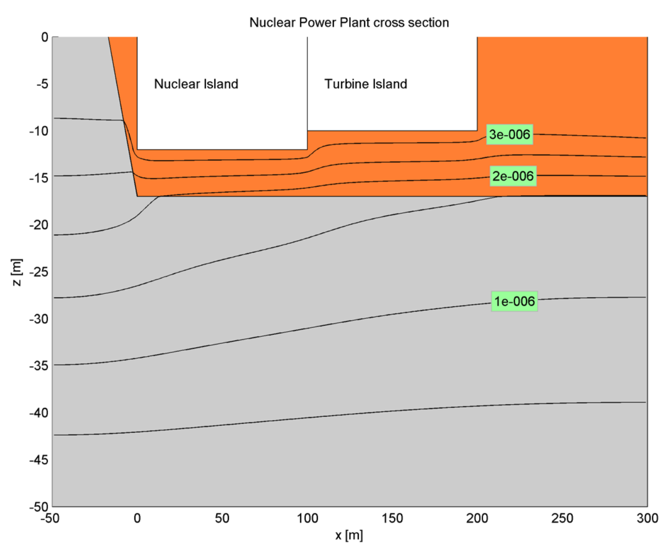

Figure 10. Sample groundwater flow for a medium sand soil foundation on moderately weathered rock and medium sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

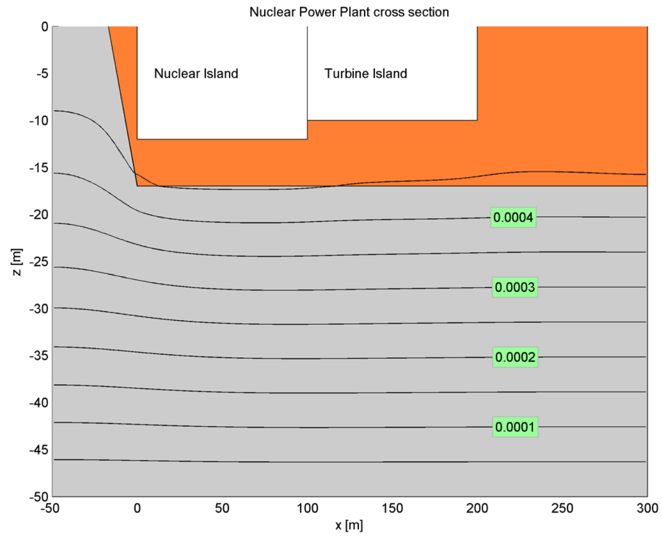

Figure 11. Sample groundwater flow for a coarse sand soil foundation on highly weathered rock and coarse sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

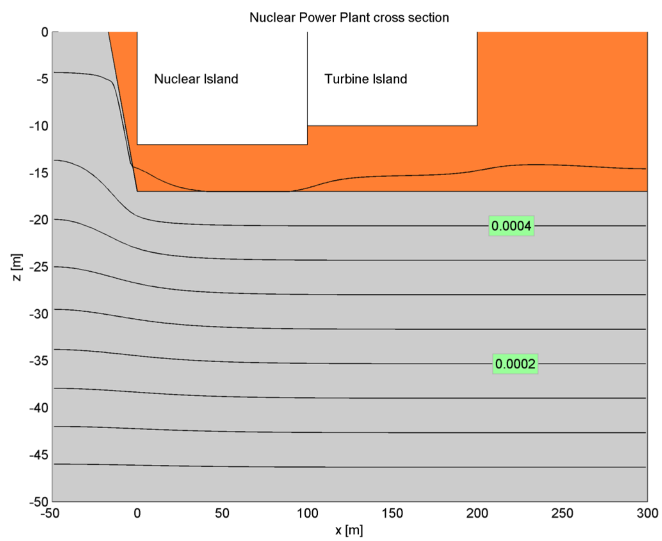

Figure 12. Sample groundwater flow for a fine sand soil foundation on highly weathered rock and fine sand backfill. Numbers labelled on stream lines show the amount of flow per second (m^2/s).

In both rock and soil foundation models, different flow rates were estimated due to varying hydraulic conductivities and indirectly due to geometry. The groundwater table was similar in all scenarios due to the fixed boundary conditions reflecting real NPP environments. Table 4 shows the flow rate, Q_x, towards the sea, in these scenarios. Results suggest the groundwater flow rate around a nuclear power plant founded on soil is higher than on rock due to a relatively higher permeability. The figures generally show little flow in the fill soil region from the turbine building when the NPP is founded on rock, partially due to the fact that the sea water level is near the fill-rock boundary. Interestingly, the scenarios where highly weathered rock was involved resulted in similar horizontal flow rates.

Table 4. Summary of groundwater flux

Foundation	Rock	Soil	Flow, Q_x (m^2/s)
Rock	Softly Weathered	Coarse Sand	$9.2x10^{-7}$
		Medium Sand	$8.5x10^{-7}$
		Fine Sand	$8.4x10^{-7}$
	Moderately Weathered	Coarse Sand	$2.3x10^{-6}$
		Medium Sand	$2.1x10^{-6}$
		Fine Sand	$2.1x10^{-6}$
	Highly Weathered	Coarse Sand	$5.3x10^{-4}$
		Medium Sand	$5.3x10^{-4}$
		Fine Sand	$5.3x10^{-4}$
Sand	Softly Weathered	Coarse Sand	$3.8x10^{-6}$
		Medium Sand	$1.9x10^{-6}$
		Fine Sand	$1.4x10^{-6}$
	Moderately Weathered	Coarse Sand	$8.7x10^{-6}$
		Medium Sand	$3.3x10^{-6}$
		Fine Sand	$2.6x10^{-6}$
	Highly Weathered	Coarse Sand	$4.8x10^{-4}$
		Medium Sand	$4.5x10^{-4}$
		Fine Sand	$4.5x10^{-4}$

For highly weathered rock cases, the results suggest approximately 40-45 m^2/day can be expected to flow through while for more intact rock, approximately 0.07-0.3 m^2/day can be expected to flow through. Although both cases appear to be orders of magnitude different, in the bigger picture, these are small numbers considering construction, maintenance, and environmental safety issues.

4. Conclusions

Using MATLAB, typical nuclear power plant profiles, separated by rock and soil foundational materials were constructed. Even though nuclear power plants are not generally founded on sites with considerable soil deposits, the conceptual model of soil as a foundational material is considered useful in understanding groundwater flow patterns under nuclear power plant facilities. A MATLAB program was written to solve the groundwater flow equation and to present results in a graphical format. The solver iterates through solution matrices until unconfined conditions are satisfied. This is ideal as it does not force the use to dictate a groundwater table, but instead solves for it. Iterations cycle through a hydraulic head solution until a certain tolerance, which was defined as the difference in hydraulic head from one cycle to the next, is met.

Subsurface properties at the model nuclear power plants were taken from the literature. Horizontal hydraulic conductivities for rock materials ranged from 1.4×10^{-6} m/s to 9.4×10^{-6} m/s and 1×10^{-5} m/s to 3×10^{-4} m/s for soil materials, which were primarily sands of varying grades. Vertical hydraulic conductivities were assumed to be 10% of the horizontal values as suggested by the literature. Nuclear power plant profile geometries were categorized into soil or rock based on the material immediately below the power plant mat foundation. Both profiles show soil backfill due to excavation and construction. The natural material was rock, which extended down approximately 50 m, after which we assume the groundwater flow profile would not have a significant impact on the overall groundwater flow field and was also suggested in calculations. Fixed heads to confine the boundary on groundwater entry and exit below the nuclear power plant were assumed to reflect the groundwater table. Thus, the groundwater table was estimated at being approximately 4.5 m below the surface 50 m away from the nuclear island, while the average sea level was assumed to be approximately 9.5 m from the surface at 100 m away from the turbine island.

The results of the MATLAB solver show groundwater flux to be greater when there is more soil at the site (i.e. when the material immediately below the mat foundation is soil), which is expected since the hydraulic conductivity of soil is much higher than rock. Stream lines suggest water would flow into the soil materials and then exit further downstream to meet sea level. This behavior suggests particles have the potential to move from rock to soil regimes as well as transferring from soil to rock to the sea. Moreover, these results suggest construction and maintenance plans should consider groundwater flow when conducting works near the rock boundary. Water intrusions relatively near the ground surface of the excavation would suggest the source to be other than groundwater.

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