Preliminary Dispersion Analysis for a Korean Nuclear Power Plant Site Using Realistic Urban–Terrain Modeling

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1. Introduction

Atmospheric dispersion around nuclear power plant (NPP) sites is a major consideration for emergency preparedness and consequence assessment. Near-field dispersion around an NPP site is strongly controlled by surrounding terrain and built environments (e.g., coastal topography, mountainous terrain, and building clusters), which can generate complex flow features such as separation and recirculation. These local effects often dominate the transport pathways and dispersion patterns, and therefore, accurate prediction of dispersion patterns requires high-fidelity, site-specific modeling.

This study presents a preliminary dispersion analysis framework that explicitly incorporates realistic Korean NPP site surroundings, including terrain and nearby buildings, over a multi-kilometer-scale computational domain. The goal is to establish a practical, high-resolution modeling workflow that couples (i) a turbulence-resolving ABL flow solver, (ii) an LDM for pollutant transport, and (iii) realistic, site-specific urban-terrain geometry. The resulting framework is intended to provide baseline insights into near-field dispersion characteristics under representative meteorological conditions, serving as a foundation for subsequent detailed analyses (e.g., source-term scenarios and dose evaluation).

2. Methodology

2.1 Explicit Incompressible Smoothed Particle Hydrodynamics (EISPH)

Smoothed Particle Hydrodynamics (SPH) is a meshless, particle-based numerical method originally developed for astrophysical simulations and extended to a wide range of fluid dynamics problems. [1] In SPH, the fluid domain is discretized into a set of particles, each carrying physical properties (e.g., velocity, pressure, density), and field quantities are evaluated through a kernel-weighted interpolation over neighboring particles:

$$\langle f(r_i)\rangle = \sum_j \frac{m_j}{\rho_j} f(r_j) W(r_i - r_j, h) \tag{1}$$

where m_j and ρ_j are the mass and density of neighboring particle j, h is the smoothing length, and W is a kernel function (here, the Wendland $C2$ kernel). Spatial derivatives are obtained analytically from the kernel gradient, eliminating the need for special computational treatments. This feature makes SPH particularly attractive for large-scale urban-terrain flow simulations, where complex and irregular geometries would otherwise demand computationally expensive mesh generation and refinement.

In the present study, Eulerian SPH framework is adopted rather than the traditional Lagrangian (particle-tracking) approach. This choice provides enhanced numerical stability and accuracy for high-Reynolds-number flows around bluff bodies such as buildings and terrain features.

To satisfy the incompressibility constraint, an Explicit Incompressible SPH (EISPH) formulation is adopted. Rather than solving a global linear system at each timestep, the pressure Poisson equation (PPE) is resolved via a single explicit iteration using neighbor-particle information:

$$P_i^{n+1} = \frac{b_i + \sum_j A_{ij} P_j^n}{\sum_j A_{ij}} \tag{2}$$

where A_{ij} and b_i are the terms derived from the discrete SPH Laplacian and the predicted velocity divergence, respectively. This explicit treatment substantially reduces computational cost compared to implicit ISPH while maintaining pressure-velocity coupling through a predictor-corrector projection scheme:

$$\begin{aligned} \boldsymbol{u}^* &= \boldsymbol{u}^n + \Delta t \cdot \boldsymbol{f}_{adv}, \\ \boldsymbol{u}^{n+1} &= \boldsymbol{u}^* - \frac{\Delta t}{\rho} \nabla P^{n+1} \end{aligned} \tag{3}$$

The timestep is constrained by both advective and viscous CFL conditions to ensure numerical stability.

To resolve turbulent structures in the atmospheric boundary layer (ABL), Large Eddy Simulation (LES) is employed, wherein only scales larger than the local filter width are directly resolved and the subgrid-scale (SGS) stress is modeled. This study adopts the Deardorff one-equation SGS model [2], which transports subgrid-scale turbulent kinetic energy (TKE, k_{sgs}) as an additional prognostic variable:

$$\frac{\partial k_{sgs}}{\partial t} = P + B - \epsilon + T \tag{4}$$

$$\nu_t = C_k \Delta \sqrt{k_{sgs}}$$

where P, B, ϵ, and T denote production, buoyancy, dissipation, and diffusion terms, respectively. The eddy viscosity ν_t is derived from local filter length scale Δ, and turbulent kinetic energy. Compared to algebraic SGS models (e.g., Standard Smagorinsky), the Deardorff model explicitly accounts for buoyancy effects and energy backscatter, making it well-suited for thermally stratified ABL flows.

Building surfaces are treated using the Direct Forcing Immersed Boundary Method (IBM) [3], in which a body force is applied to fluid particles in the vicinity of boundary markers to enforce the no-slip condition. This approach allows complex building geometries to be introduced without conforming the particle arrangement to each surface.

The ground surface boundary condition follows the Monin–Obukhov Similarity Theory (MOST) [4], which prescribes wall shear stress as a function of local wind speed, roughness length, and atmospheric stability:

$$\tau_{i3}|_{wall} = -u_*^2 \frac{\boldsymbol{u}_i}{\boldsymbol{u}(z)}$$
$$\boldsymbol{u}(z) = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_M\left(\frac{z}{L}\right)\right] \quad (5)$$

where u_* is the friction velocity, $\kappa \approx 0.4$ is the von Kármán constant, z_0 is the aerodynamic roughness length, L is the Monin–Obukhov length, and ψ_M is the momentum stability correction function. The Monin–Obukhov length L is computed iteratively from the bulk Richardson number using a Newton–Raphson procedure, enabling the simulation to represent neutral, stable, and unstable atmospheric conditions.

2.2 Lagrangian Dispersion Model (LDM)

Pollutant transport is computed using a Lagrangian Dispersion Model (LDM), in which individual tracer particles are tracked through the time-varying flow field. [5] Each particle position X evolves according to:

$$\frac{d\boldsymbol{X}}{dt} = \overline{\boldsymbol{U}}(x,t) + \boldsymbol{u}'(t) \quad (6)$$

where $\bar{U}$ is the resolved SPH velocity field interpolated at the particle location, and u' is the turbulent velocity fluctuation. The fluctuation is further decomposed into resolved and subgrid-scale (SGS) components:

$$\boldsymbol{u}_L = \boldsymbol{u}_r + \boldsymbol{u}_s \quad (7)$$

The SGS component u_s is evolved via a Langevin stochastic differential equation:

$$d\boldsymbol{u}_{si} = -\frac{\boldsymbol{u}_{si}}{T_{L,s}}dt + (f_s C_0 \epsilon)^{1/2} d\xi_i$$
$$T_{L,s} = \frac{2\sigma_s^2}{f_s C_0 \epsilon}, \qquad \sigma_s^2 = \frac{2}{3}k_{sgs} \quad (8)$$
$$f_s = k_{sgs}/(k_{res} + k_{sgs})\text{is}$$

Where $T_{L,s}$ is the SGS Lagrangian time scale, σ_s^2 is the SGS velocity variance, $C_0$is the Kolmogorov constant, $\epsilon$is the SGS dissipation rate, and f_s is a weighting factor that partitions the stochastic forcing between resolved and SGS turbulence. $d\xi_i$ is an increment of a standard Wiener process. This formulation ensures consistency with the resolved LES flow field while accounting for the dispersive effect of subgrid-scale eddies that are not explicitly captured by the SPH solver.

The LDM is one-way coupled to the SPH-LES solver: at each timestep, the resolved velocity field and SGS quantities (k_{sgs}, ϵ) are passed from the flow solver to the LDM, and particle positions are updated accordingly.

This coupling strategy was verified against the analytical solution for 3D advection-diffusion from a point source, confirming accurate reproduction of mean plume trajectory, variance growth, and concentration distribution. (Figure 1)

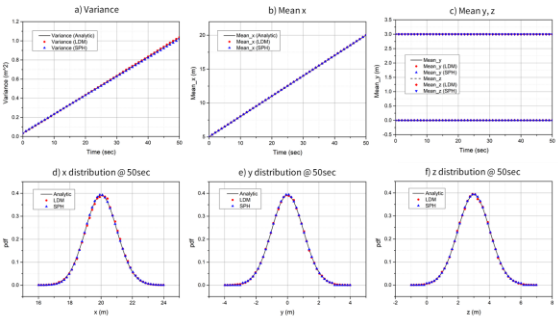

Figure 1. Verification of the LDM and SPH scalar transport against the analytical advection–diffusion solution

2.3 Urban modeling

Realistic site geometry is constructed using building footprints and elevation data extracted from OpenStreetMap (OSM), to represent the surrounding terrain.

The processing pipeline proceeds as follows: raw geographic data are extracted and converted to STL surface meshes, which are then loaded into Blender software for geometry inspection and cleanup. Immersed boundary marker points are subsequently distributed uniformly over all building and terrain surfaces using Python scripting, and SPH fluid particles are initialized to fill the computational domain excluding the solid regions.

The resulting 3D geometric model for the target Korean NPP site(Kori) is shown in Figure 1, illustrating the terrain relief and surrounding building clusters over a multi-kilometer domain.

The terrain features are represented explicitly as part of the IBM solid boundary, so that topographic effects—including flow channeling, separation at ridgelines, and wake recirculation in valleys—are directly resolved by the flow solver rather than parameterized.

3. Realistic Urban Dispersion Simulation

3.1 Simulation setup and Urban-Terrain Modeling

The target site selected for this preliminary analysis is the Kori Nuclear Power Plant (NPP). Kori site is situated in a coastal environment characterized by significant topographic complexity, including mountainous terrain and direct proximity to the sea.

Several residential and industrial structures are present within the immediate vicinity of the plant(1km-2km), and the region falls within the designated emergency planning zone (EPZ) as defined by Korean nuclear safety regulations. These site characteristics make Gori NPP a representative and practically relevant test case for high-fidelity near-field dispersion analysis.

The computational domain spans approximately 4 km × 3 km × 800 m (including the buffer), encompassing the Kori NPP site and its surrounding terrain and built environment. Site geometry was reconstructed using building footprint and height data from OSM. The reconstructed 3D geometry of the Kori NPP site is shown in Figure 2, illustrating the terrain relief and building distribution. SPH fluid particles were then uniformly initialized throughout the domain at a particle spacing of 3.0 m, yielding approximately 80 million fluid particles in total.

Key simulation parameters are summarized in Table 1. All computations were performed on a single NVIDIA Tesla A100 GPU, leveraging the GPU-parallelized SPH solver.

Table 1. Key simulation parameters

Parameter	Value
Scheme	SPH-LES + LDM
Domain size	4,000m x 3,200m x 800m
Particle spacing	3.0 m
Time step	0.01 sec
Total SPH particles	~ 80,000,000
LDM particles per source	100,000
Simulation Time	300s
GPU specification	Single NVIDIA Tesla A100

Inflow conditions were prescribed using a logarithmic mean wind profile consistent with neutral atmospheric stability, with turbulent fluctuations generated via a recycling method applied at the inlet plane.

$$U(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{9}$$

Where U_{ref} is the reference wind speed at reference height z_{ref}, and α is the power law exponent depending on the terrain roughness and atmospheric stability.

The ground and building surfaces were treated with MOST-based wall shear stress boundary conditions, a free-slip condition was applied at the domain top, and periodic boundary conditions were imposed at the lateral faces. For the LDM, a continuous point release was assumed at the NPP stack location, with particles released at a constant rate throughout the simulation period.

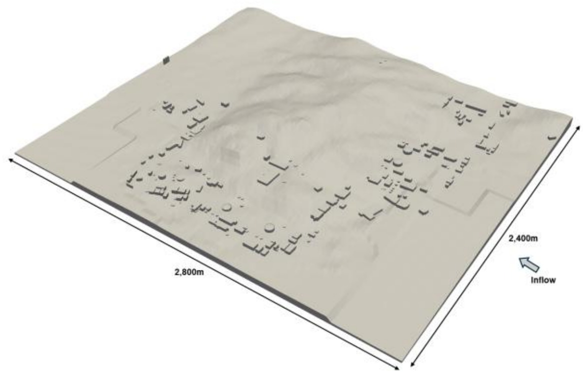

Figure 2. Reconstructed 3D urban–terrain geometry of the Kori NPP site

3.2 Simulation results

Figure 3 presents the instantaneous vorticity field resolved by the SPH-LES solver over the Kori NPP site. The flow field exhibits spatially complex turbulent structures throughout the domain, with particularly elevated vorticity observed in the wake regions downstream of the terrain ridgeline and in the immediate vicinity of building clusters. The mountainous terrain to the generates significant flow deflection and separation, producing a broad recirculation region over the flatter ground area where the residential zones are located. These terrain-induced flow features are directly resolved by the SPH-LES solver without any geometric simplification, demonstrating the capability of the present framework to capture realistic, site-specific ABL dynamics at the kilometer scale.

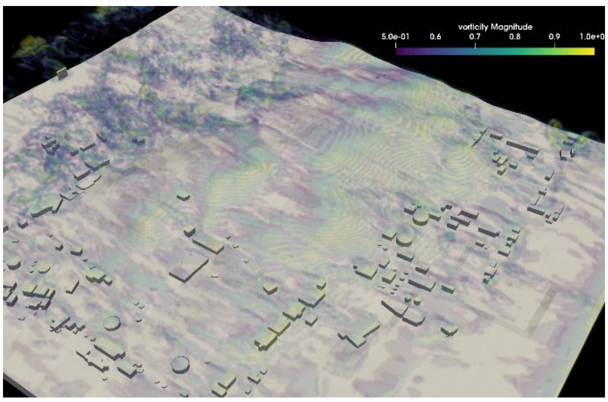

Figure 3. Instantaneous vorticity magnitude field resolved by the SPH-LES solver over the Kori NPP site

Figure 4 presents instantaneous snapshots of the LDM particle distribution for a representative release scenario, colored by local particle concentration. The released plume is advected downwind by the mean flow while simultaneously being dispersed laterally and vertically by the resolved and SGS turbulence. The dispersion pattern is strongly modulated by the underlying terrain, with the plume trajectory following the local wind channeling induced by the terrain ridgeline and building blocks. The stochastic SGS component of the LDM introduces realistic turbulent fluctuations in the plume trajectory that would be absent in a purely Eulerian scalar transport approach, resulting in a more physically representative concentration field.

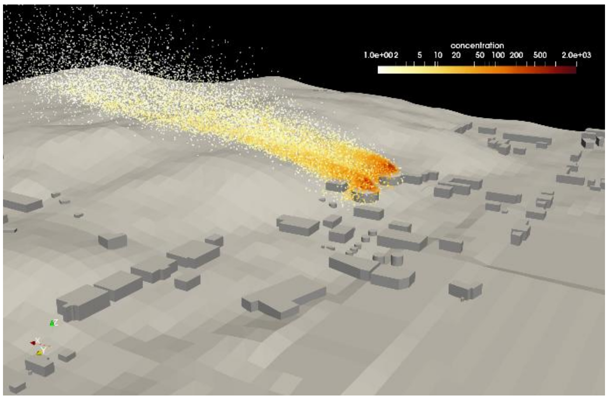

Figure 4. Instantaneous LDM particle distribution colored by concentration for a release scenario at the Kori NPP site

Overall, these preliminary results demonstrate that the proposed SPH-LES-LDM framework can produce physically consistent, high-fidelity dispersion prediction over a realistic multi-kilometer NPP site, accounting explicitly for the influence of surrounding terrain and built structures.

4. Conclusion

This study presented a preliminary near-field dispersion analysis framework for a Korean nuclear power plant site, combining a meshless SPH-LES flow solver with a Lagrangian Dispersion Model and realistic site-specific urban–terrain geometry reconstruction model. The Kori NPP site was selected as the target domain, and a computational domain of approximately 4 km × 3 km × 800 m was established to capture the complex topographic and built-environment features surrounding the plant.

The SPH-LES solver, employing the Deardorff SGS model and MOST-based surface boundary conditions, successfully resolved the turbulent ABL flow over the site, capturing terrain-induced flow separation, and wake recirculation without requiring any geometric simplification or mesh generation. The coupled LDM produced physically consistent dispersion patterns, with plume trajectories and lateral spreading strongly influenced by the local terrain channeling and building wake effects.

The present results serve as a proof of concept, demonstrating that the proposed framework can provide high-fidelity, site-specific dispersion predictions at the kilometer scale on a single GPU. The following directions are identified for future work. First, quantitative validation of both the flow field and dispersion concentration against wind tunnel experiments or field observation data is required to establish predictive confidence. Second, thermally stratified atmospheric conditions corresponding to stable and unstable ABL states should be incorporated through full MOST boundary condition integration. Third, advanced performance models, such as multi-GPU parallelization or multi-resolution algorithms will be explored to further extend the feasible domain size and reduce computational turnaround time. Finally, the validated framework will be applied to source-term accident scenarios around actual NPP sites, enabling radiological consequence assessment and supporting proactive nuclear emergency preparedness.

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