Examination of Conservatism in Ground-level Source Release Assumption when Performing Consequence Analysis

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1. Introduction

Interest in consequence analysis is increasing after Fukushima Dai-ichi Nuclear Power Plant (NPP) accident and steady progress have been made in level 3 Probabilistic Safety Assessment (PSA). State-of-the-Art Reactor Consequence Analyses (SOARCA) report [1] could be a good example of the projection of this effort and domestic researches are in progress as well.

Even though capability and reliability of models have been enhanced as a part of the progress in this area, many assumptions are still made due to lack of knowledge and for conservative estimation. One of these assumptions frequently assumed is the assumption of ground-level source release. The user manual of a consequence analysis software HotSpot [2] is mentioning like below:

"If you cannot estimate or calculate the effective release height, the actual physical release height (height of the stack) or zero for ground-level release should be used. This will usually yield a conservative estimate, (i.e., larger radiation doses for all downwind receptors, etc)."

This recommendation could be agreed in aspect of conservatism but quantitative examination of the effect of this assumption to the result of consequence analysis is necessary.

The source terms of Fukushima Dai-ichi NPP accident have been estimated by several studies using inverse modeling [3,4,5] and one of the biggest sources of the difference between the results of these studies was different effective source release height assumed by each studies. It supports the importance of the quantitative examination of the influence by release height.

Sensitivity analysis of the effective release height of radioactive sources was performed and the influence to the total effective dose was quantitatively examined in this study.

2. Methods and Results

It is necessary to set fixed conditions to perform sensitivity analysis.

Detailed source term was excluded in this study because the objective of this study is not detailed consequence analysis but sensitivity analysis. Therefore Fukushima Dai-ichi NPP accident level source term [6] was used for this study.

Average wind speed and air temperature of Korea during 10 years (2005-2014) were acquired from Korea Meteorological Administration – National Climate Data Service System (KMA-NCDSS) [7].

Neutral atmospheric stability condition was considered and aerodynamic surface roughness length was set as 100 cm reflecting fairly level forested plateau (70-120 cm) [8]. However, it is one of issue to solve that how we estimate the representative value taking account of combination of spatially varying surface roughness especially in intricate topographic conditions of Korean NPP sites. Developing air dispersion code that can accommodate and handle spatially varying surface roughness might be the best solution [9].

Variables fixed for the sensitivity analysis are listed in Table 1.

Table 1: Fixed variables for the sensitivity analysis

Fixed variable	Value
Source term: Fukushima Dai-ichi NPP accident level source term [6]	I-131: 5× 10^{17} Bq Cs-134: 1× 10^{16} PBq Cs-137: 1× 10^{16} PBq
Wind speed [7]	2.1 m/s
Air temperature [7]	12.8℃
Atmospheric stability class	D (neutral)
Surface roughness length [8]	100 cm

2.1 Sensitivity Analysis of Effective Plume Height

Previous studies estimating Fukushima source terms using inverse modeling method considered difference source release height and it was the one of major source of uncertainty. Table 2 shows source release height assumed by previous studies.

Table 2: Source release height assumed by previous studies

	Release height	Condition
Katata et al. [3]	20 m 120 m	Primary Containment Vessel Top of stack
Stohl et al [4]	0-50 m 50-300 m 300-1000 m	Wall or roof openings Exhaust stack Explosions
Hirao et al [5]	15 m	One value fixed

State-of-the-art capability of level 2 PSA provides detailed source release information including release height, heat and etcetera in accordance with various accident scenarios. Effective plume height can be calculated using this information. But five case of effective plume heights (h_{eff} = 0 m, 20m, 50 m, 100 m, and 300 m) were chosen as manipulated variable refer to the information listed in Table 2 because too many kinds of effective plume heights could be calculated considering various kinds of accident scenarios.

Difference between the dose assuming ground level release (h_{eff} = 0 m) and the dose assuming another effective plume height is large in short downwind distance range and becomes smaller at longer downwind distance. Table 3 shows the ratio of the dose assuming ground level release divided by the dose assuming each effective plume heights. Higher effective plume height, larger difference naturally. When effective plume height is assumed 300 m, differences in short distance range are very large because it takes time to be dispersed to the ground for the plume which starts to be dispersed at 300 m height. The fact that dose is calculated by ground-level concentration should be remembered to understand this phenomena.

Table 3: Ratio of the dose assuming ground level release (h_{eff} = 0 m) divided by the dose assuming each effective plume height (h_{eff} = 20, 50, 100, and 300 m)

Downwind Distance [km]	Effective Plume Height			
	h_{eff} = 20m	h_{eff} = 50m	h_{eff} = 100m	h_{eff} = 300m
	Ratio: Dose when h_{eff} = 0 m divided by Dose when h_{eff} = above value			
0.1	6.52E+00	2.63E+04	1.36E+17	Too large
0.2	2.05E+00	2.44E+01	1.08E+05	Too large
0.3	1.73E+00	6.33E+00	4.32E+02	Too large
0.4	1.55E+00	3.67E+00	5.24E+01	4.40E+13
0.5	1.49E+00	2.81E+00	1.87E+01	4.29E+09
0.6	1.43E+00	2.41E+00	1.02E+01	2.21E+07
0.7	1.41E+00	2.16E+00	7.19E+00	7.74E+05
0.8	1.39E+00	2.00E+00	5.42E+00	7.62E+04
0.9	1.37E+00	1.86E+00	4.48E+00	1.44E+04
1	1.38E+00	1.83E+00	3.93E+00	4.31E+03
2	1.36E+00	1.64E+00	2.32E+00	4.24E+01
4	1.32E+00	1.56E+00	1.92E+00	7.35E+00
6	1.27E+00	1.51E+00	1.77E+00	4.38E+00
8	1.32E+00	1.51E+00	1.73E+00	3.52E+00
10	1.31E+00	1.51E+00	1.69E+00	3.09E+00
20	1.32E+00	1.45E+00	1.61E+00	2.23E+00
40	1.24E+00	1.38E+00	1.50E+00	1.90E+00
60	1.28E+00	1.43E+00	1.54E+00	1.88E+00
80	1.28E+00	1.41E+00	1.53E+00	1.77E+00

Figure 1 and 2 shows the percent ratio of the dose assuming ground level release divided by the dose assuming each effective plume heights at relatively shorter distance and at relatively longer distance respectively. The case of 300 m effective plume height was excluded in the figures because difference is relatively too high compared to other cases.

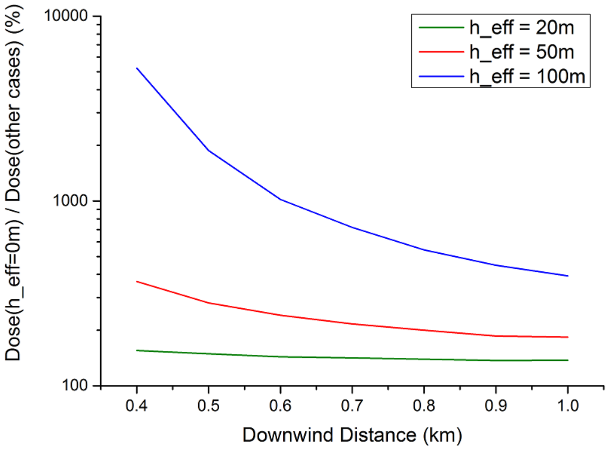

Figure 1. Percent ratio of the dose assuming ground level release divided by the dose assuming each effective plume height (downwind distance: 400 m – 1 km)

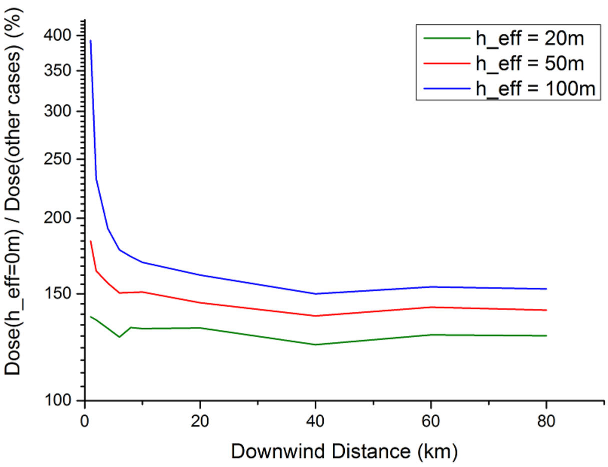

Figure 2. Percent ratio of the dose assuming ground level release divided by the dose assuming each effective plume height (downwind distance: 1 km – 80 km)

Every case except the case of h_{eff} = 300 m become below 400% ratio after 1 km downwind distance. However, ratio is dramatically increasing at the distances shorter than 1 km.

If we assume plant site boundary as 1 km, the influence of effective plume height could be considered not to be serious because it decreases dramatically followed by downwind distance and the population in site boundary is relatively low. However, when we consider the standard of Quantitative Health Objective (QHO) in U.S [10] like below, :

"The latent cancer QHO is defined in terms of the risk to an average individual within 10 miles, and the early fatality QHO in terms of the risk to an average individual within 1 mile of the plant."

it cannot be neglected due to large dose differences in short distance range that could influence to early fatality. When we concern the fact that early fatalities have threshold doses, results of estimations could be totally different in some cases.

During performing this sensitivity analysis, it was concerned to be necessary to consider surface roughness length together, so sensitivity analysis adding surface roughness length was carried out as well.

2.2 Additional Consideration with Surface Roughness

Some examples of surface roughness length representing land conditions referred to the references [1, 8] are listed in Table 4.

Table 4: Surface roughness lengths for some land conditions

Land Condition	Surface Roughness Length (z_0)
Smooth desert [8]	0.03 cm
Grass [8]	3 cm
SOARCA [1]	10 cm
Fairly level wooded country [8]	50 cm
Fairly level forested plateau [8]	70-120 cm
Central business district [8]	330 cm

The results when we consider the 100 cm and 3 cm of surface roughness length were compared and described in Figure 3 and 4. Relatively shorter distance range (400 m – 1 m) was considered in Figure 3 and relatively longer distance range (1 km – 80 km) was considered in Figure 4. Dashed lines indicate 3 cm of surface roughness cases.

The percent ratio is much larger in short distance range when we consider 3 cm of surface roughness length compared to 100 cm of surface roughness length. It is caused by the different degree of turbulent diffusion because the surface with lower surface roughness generates lower vertical turbulent diffusion. In 3 cm of surface roughness length case compared to 100 cm case, it takes more time to reach to the ground for the plume due to lower vertical diffusion, therefore, the ratio becomes larger in short distance due to higher difference of ground level concentration compared to the result with ground-level release assumption.

In longer downwind distance range, situation becomes different. Normally, ground level concentrations in longer distance range after reach of plume to the ground appear to be higher with lower surface roughness because lower vertical turbulent diffusion leads lower dilution.

In this sensitivity analysis, it was found that the difference between the dose with assumption of ground-level release and the dose with having some effective plume height becomes greater with lower surface roughness length in short distance such as below 5 km. But this distance could be changed with local meteorological conditions like wind speed, atmospheric stability and etc.

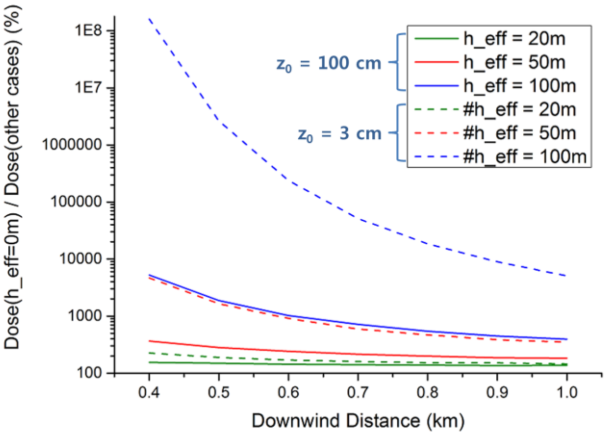

Figure 3. Percent ratio of the dose assuming ground level release divided by the dose assuming each effective plume height (downwind distance: 400 m – 1 km) (straight line: z_0 = 100 cm, dashed line: z_0 = 3 cm)

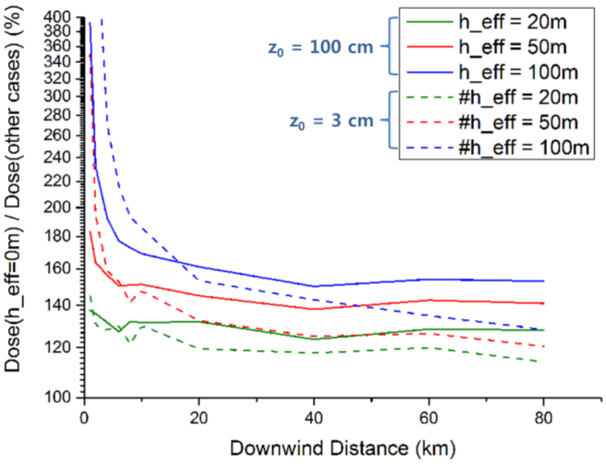

Figure 4. Percent ratio of the dose assuming ground level release divided by the dose assuming each effective plume height (downwind distance: 1 km – 80 km) (straight line: z_0 = 100 cm, dashed line: z_0 = 3 cm)

Limitation of analysis

HotSpot [2] code was used to perform above analyses and it cannot consider downwind movement of plume during plume rise and spatially-varying surface roughness length.

3. Conclusions

Effective plume height was found to be highly effective when we consider relatively short downwind distance (below 5 km) in this study. It could influence both early fatality and latent cancer fatality estimation but the results of early fatality estimations could be totally different in some cases due to existence of threshold dose. In those cases, ground-level source release assumption over-estimates early fatalities.

Above 20% difference is maintained even at longer distances, when we compare the dose between the result assuming ground-level release and the results assuming other effective plume height. It means that we cannot ignore the influence of ground-level source assumption to the latent cancer fatality estimations.

In addition, the assumption of ground-level release fundamentally prevents detailed analysis including diffusion of plume from effective plume height to the ground even though the influence of it is relatively lower in longer distance.

When we additionally consider the influence of surface roughness, situations could be more serious. The ground level dose could be highly over-estimated in short downwind distance at the NPP sites which have low surface roughness such as Barakah site in UAE.

From this reasons, the ground-level source release should be carefully assumed even though it could be a good solution for the conservative estimation when we do not have detailed information about physical characteristics of source release.

When MACCS software is used for the level-3 PSA, MELMACCS could provide not only chemical information of the source such as inventory and chemical group of source term but physical information of source release. It is highly recommended to use and apply this information to level-3 PSA rather than just assuming ground level source release.

4. Further Work

Further sensitivity analysis estimating not only concentration and dose but also early and latent fatality could be carried out. But estimation could be intricate following the scenarios including mitigating actions such as evacuation, sheltering and relocation. The selection of appropriate scenarios and proper approach should be considered, first.

Acknowledgement

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