International Journal of Smart Home
Vol. 10, No. 3, (2016), pp.149-158
http://dx.doi.org/10.14257/ijsh.2016.10.3.15

Evacuation Safety Evaluation of Inundated Stairs Using 3D Numerical Simulation

Du Han Lee[*1], Myounghwan Kim[2] and Dong Sop Rhee[3]

[1, 2, 3]*Korea Institute of Civil Engineering and Building Technology*
[1]*dhlee@kict.re.kr*, [2]*narrowgate@kict.re.kr*, [3]*dsrhee@kict.re.kr*

Abstract

Recently heavy rainfall have caused inundations in urban areas of Koera. Especially, inundation of undergroudn stairs makes people's evacuation difficult. In this study, inundated flow condition of stairs are simulated numerically using commecial 3 D CDF model(FLOW 3D). From the results, critical evacuation conditions are evaluated according to flow depth and slopes of stairs. It is found that flow depth only over the 20cm could cause the danger in the evacuation along stairs. In the flow depth over 0.36cm, every people including young male, could not escape alone without any help. Inlet flow depth is more important factor than stair slopes. Inundation depth to underground stairs should be managed to keep below 0.2 m.

Keywords: *Critical Evacuation Condition, Inundated Stairs, Safety Analysis, 3 D Numerical Simulation*

1. Introduction

Recently floods of urbanized areas in Korea are increased by heavy rainfall due to the global climate changes. These rainwater flooding is caused by heavy rainfall exceeding over the design rainfall. Underground facilities such as subway stations and underground shopping arcades are susceptible to inundation by heavy rainfall.

Rainwater floods of urbanized areas occurred in Korean cities of Seoul, Incheon and Pusan in recent years (Figure 1). In these floods, underground facilities were inundated by inflow from entrance stairs (Figure 2).

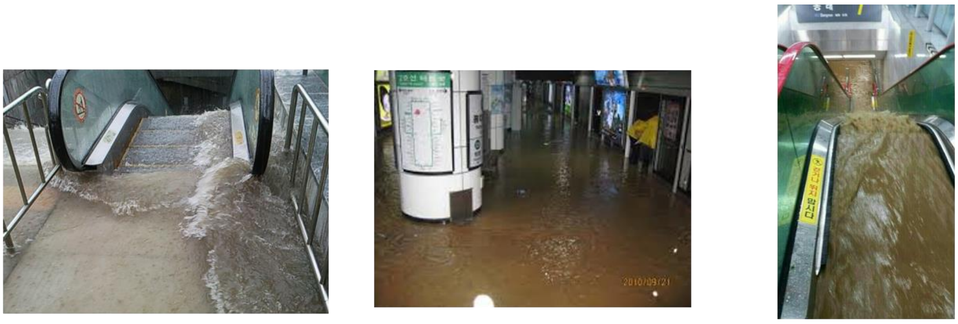
Most important matter in inundation of underground facilities is safe evacuation of people. Although stairs are the only evacuation passages in the inundation, they are not designed considering safe evacuation in inundation condition.

Kwanghwamun, Seoul(2010) Kangnam, Seoul(2011) Dongrae, Pusan(2014)

Figure 1. Rainwater Flooding of Korean Cities

[*] Corresponding Author

ISSN: 1975-4094 IJSH



Kwanghwamun, Seoul(2010) Hongdae station, Seoul(2011) Dongrae station, Pusan(2014)

Figure 2. Inundation of Underground Facilities

In this study, evacuation safety of underground entrance stairs are investigated by 3D CFD model. Critical evacuation conditions are evaluated by criteria presented by Ishigaki *et al.*, (2011)[1].

2. Previous Studies

Criteria of safe evacuation conditions (Table 1 and Figure 3) were suggested by Ishigaki *et al.*, (2011) by using a real size model of stairs. They evaluated the force due to the inundation with water depth, h, and flow velocity, u and suggested specific force, $M0 = u2h/g + h2 /2$ as main factor.

There are no case studying hydraulic features of stairs in inundation condition. However, flow over stairs is very close to flow over stepped spillways. Sorensen [2] suggested characteristics of flow structures and energy dissipation on stepped spillways. Chamani *et al.*, [3] analyzed skimming flow, corner vortex, and air entrainment of stepped spillways. Chen *et al.*, [4] analyzed numerically corner vortex and air entrainment by using VOF (Volume of Fluid) scheme.

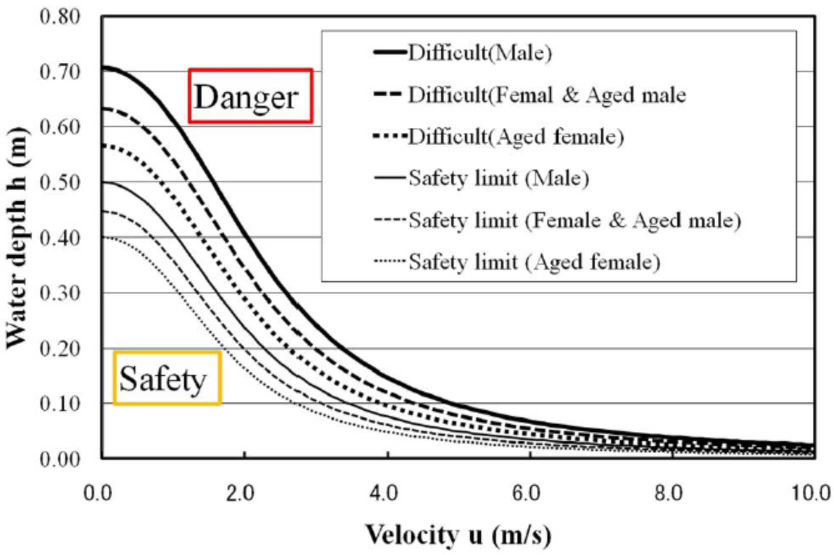


Figure 3. Criteria of Safe Evacuation by Water Depth and Velocity

Table 1. Criteria of Safe Evacuation by the Specific Force (Ishigaki *et al*., 2011)

	Limit of safe evacuation	Difficult without any help
Male	0.125	0.250
Elderly male	0.100	0.200
Female	0.100	0.200
Elderly female	0.080	0.160

3. Numerical Simulation

3.1. Governing Equations

For the simulation of flow over stairs, a full three dimensional computational fluid dynamic (CFD) model (FLOW 3D) was applied. Mass continuity and x-direction momentum conservation equations used are shown below (Hirt, 1981[5]):

$$\frac{V_F}{\rho c^2}\frac{\partial p}{\partial t} + \frac{\partial u A_x}{\partial x} + \frac{\partial v A_y}{\partial y} + \frac{\partial w A_z}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_F}\left(uA_x\frac{\partial u}{\partial x} + vA_y\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + f_i \quad (2)$$

$$f_i = \left\{wsx_i - \left[\frac{\partial}{\partial x}(A_x\tau_{ix}) + \frac{\partial}{\partial y}(A_y\tau_{iy}) + (A_z\tau_{iz})\right]\right\}\frac{1}{\rho V_F} \quad (3)$$

where V_f is the fractional volume open to flow, c is the speed of sound, t is time, $A_i(A_x$, A_y and $A_z)$ are the fractional areas open to flow, u_i denotes the velocity in i-direction, f_i are the viscous acceleration terms, wsx_i are the wall shear stresses, and τ_{ix}, τ_{iy}, τ_{iz} are the viscous stresses.

Implementation of the complete CFD model involved iteratively solving for pressure and velocity at each computational node and time step to simultaneously satisfy the momentum and continuity equations. Water depth was treated as a free surface boundary, and fluid interfaces were treated using the volume-of-fluid (VOF) technique, which only requires computation and storage of the volume fraction as one additional variable. Time step size was automatically adjusted to maintain stability and ensure that fluid fraction advection did not exceed computational cell volumes.

3.2. Geometry of Modeling

Stair model in this study has been constructed based on the Korean regulation of criteria on house construction published by ministry of land, infrastructure and transport. Three types of stairs having different slope are considered. The specifications of stairs are presented by Table 2. Case A is mild sloped stair and slope angle is 23.2 degree. Case B is normal sloped stair and slope angle is 27.2 degree. Case C is steep sloped stair and slope angle is 32.7 degree. Meshes are constructed as Figure 2 and number of total mesh is about 200,000. The whole computational domain and geometry are presented in Figure 4.

Table 2. Specification of the Stair Models

Models	Types	Width (m)	Step Width (m)	Step Height (m)	Total Length (m)	Total Height (m)	Slope (°)
Case A	Mild	1.20	0.28	0.12	6.72	2.88	23.2
Case B	Normal	1.20	0.28	0.14	5.60	2.88	27.2
Case C	Steep	1.20	0.28	0.18	4.48	2.88	32.7

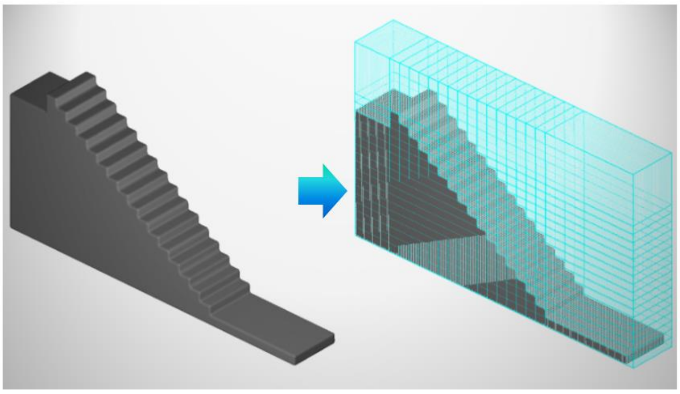
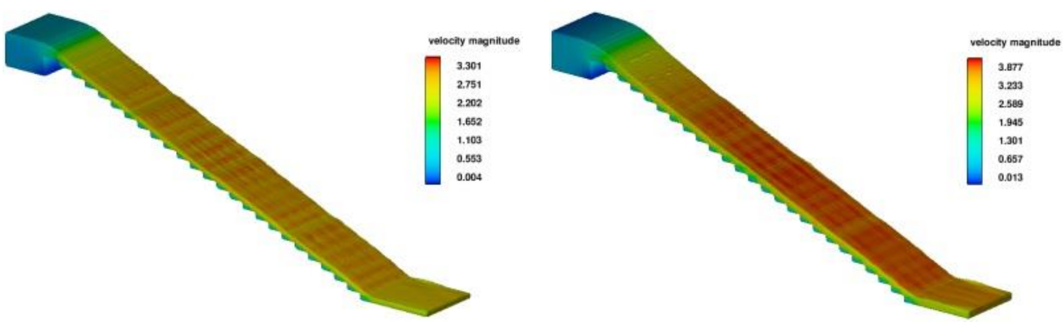


Figure 4. Geometry and Mesh of the Stair Model

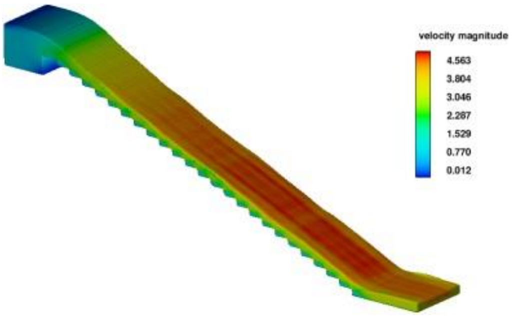
4. Results

Inlet discharge conditions are 0.3 m³/s, 0.5 m³/s, 0.7 m³/s and 1.0 m³/s. Outlet boundary conditions are applied as Neumann conditions for all cases. RNG turbulent model and VOF scheme are applied.

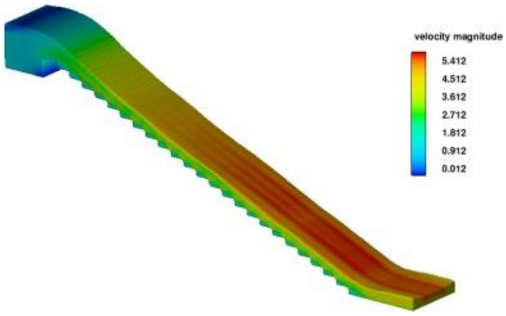
Simulation results with discharge conditions are presented as Figure 5, Figure 6 and Figure 7. For all cases velocity and water depth increase with discharge increase. In the low flow conditions, local high velocity is observed at the edges of steps, however, these local high velocity zones are disappeared in the high flow conditions. For case A, case B and case C, local high velocity due to the stair edges are detected with discharge below 0.7 m³/s. In the case of discharge with 1.0 m³/s, high velocity is observed in the downward of stairs due to the acceleration of flow.



(a) Q = 0.3 m³/s (b) Q = 0.5 m³/s

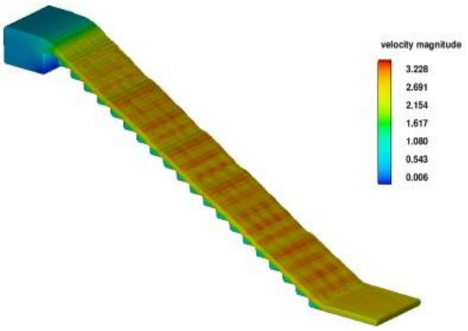


(c) Q = 0.7 m³/s

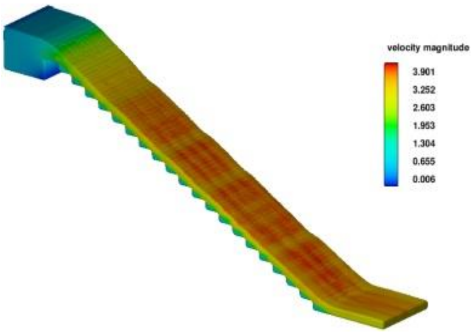


(d) Q = 1.0 m³/s

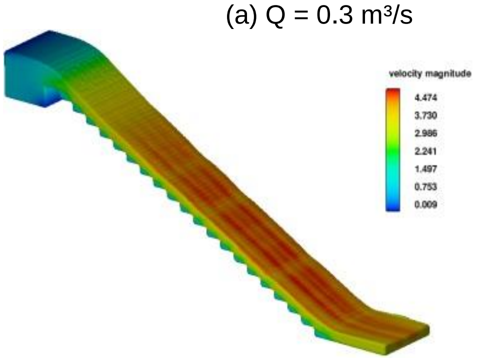
Figure 5. Velocity Distribution (Case A)



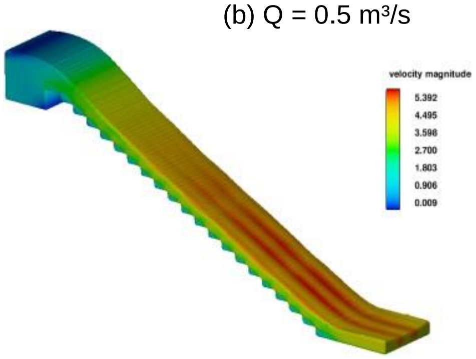
(a) Q = 0.3 m³/s



(b) Q = 0.5 m³/s

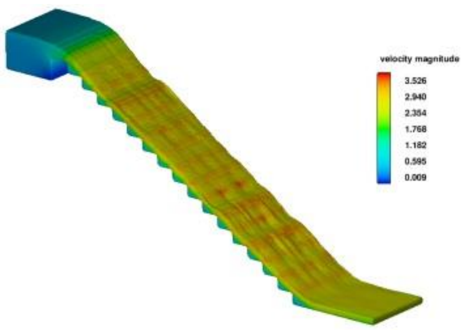


(c) Q = 0.7 m³/s

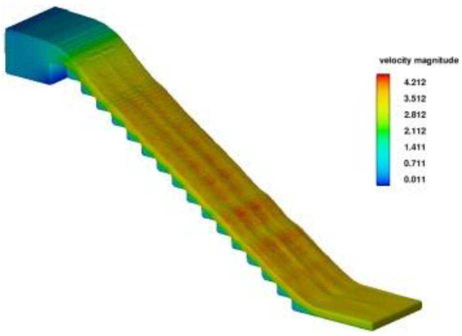


(d) Q = 1.0 m³/s

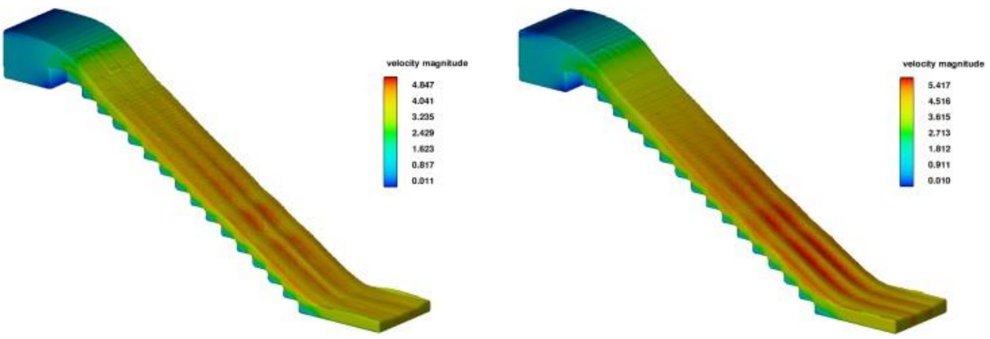
Figure 6. Velocity Distribution (Case B)



(a) Q = 0.3 m³/s



(b) Q = 0.5 m³/s



(c) Q = 0.7 m³/s (d) Q = 1.0 m³/s

Figure 7. Velocity Distribution (Case C)

From the results, variation of velocity and flow depth are analyzed as Figure 8. Velocity is depth average value. In the upper zone of stair, velocity shows relatively low value and maximum velocity is observed in the middle of stair.

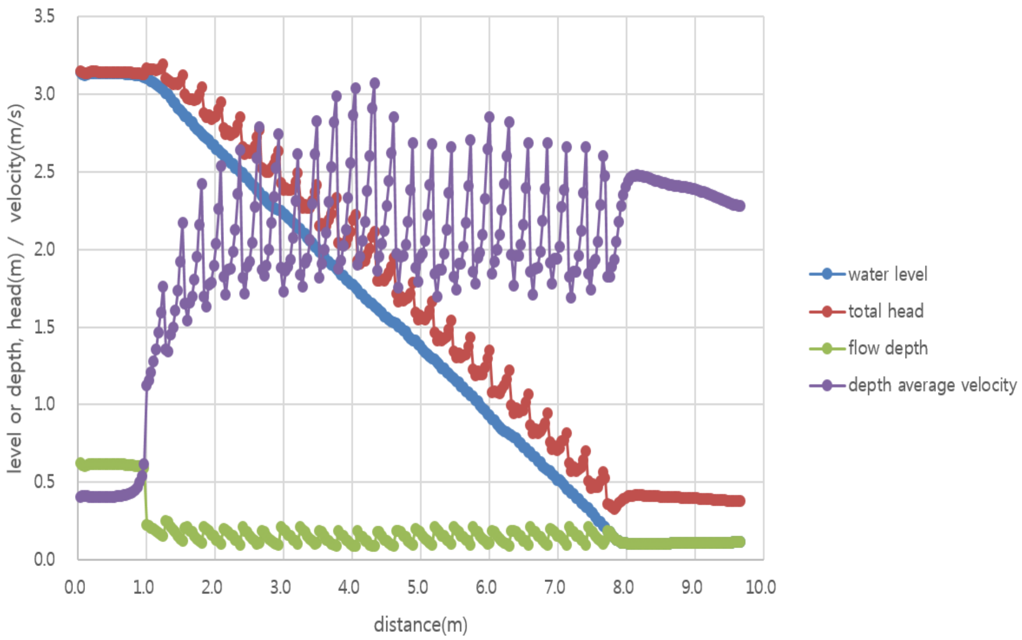


Figure 8. Hydraulic Features Along Centerline (Case A, Q = 0.3 m³/s)

To evaluate the local distribution of specific force for low flow condition, 2 dimensional specific force distribution is analyzed as Figure 9. Locally high specific force is observed in the upper and middle zones of stairs and these high velocity is detected near the edges of stair.

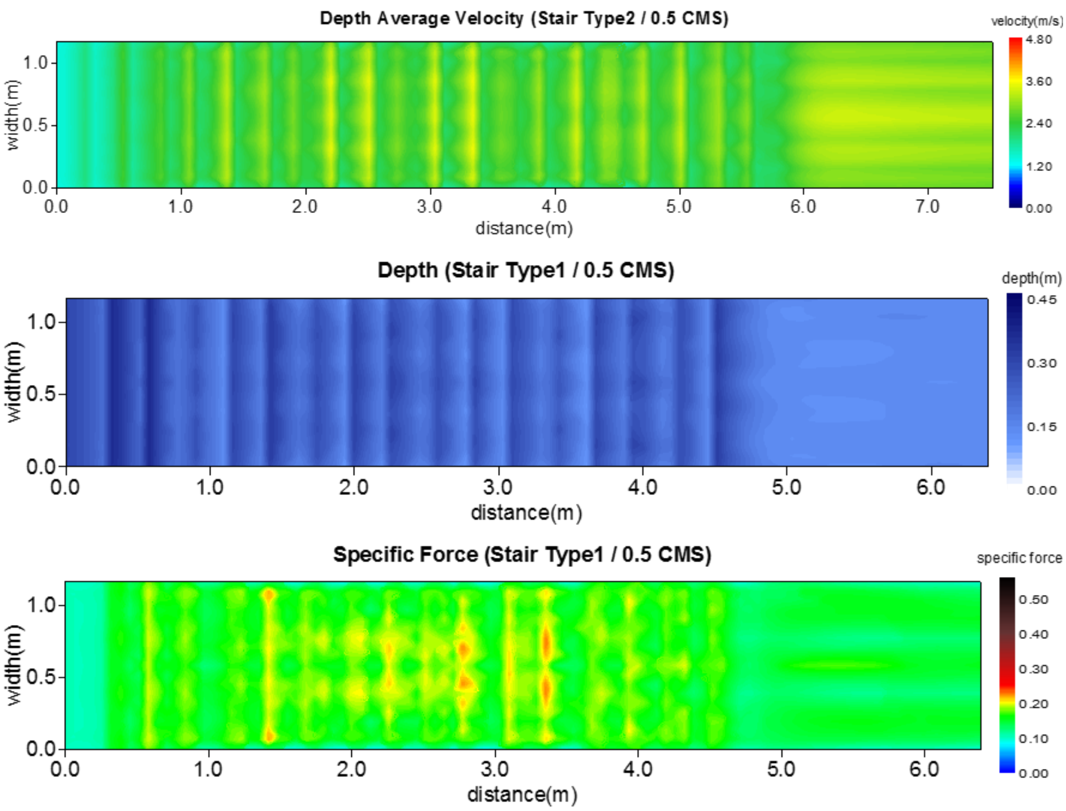


Figure 9. 2 D specific Force Distribution (Case A, Q = 0.5 m³/s)

Using velocities and water depths, specific foresee are evaluated along the center lines of stairs (Figure 10). Evaluated specific forces are compared with criteria of safe evacuation (Table 1).

In the case of Q=0.5 m^3/s, specific forces show from 0.12 – 0.20 which means that every people including male, can't evacuate safely and elderly female and young female can't escape alone. As shown in Table 4, elderly female could be dangerous only in the water depth of 20cm. With flow depth over 0.36cm, every people including young male can't escape with any other help.

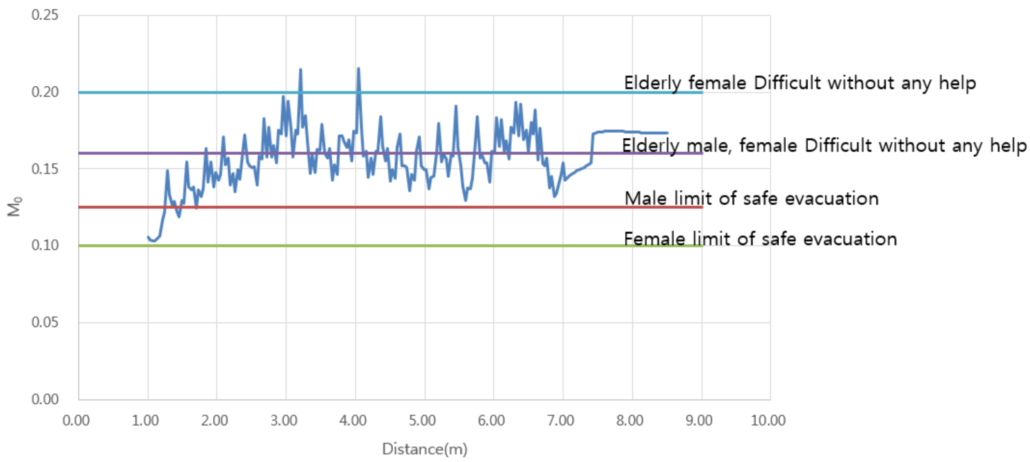


Figure 10. Specific Force Evaluation (Case B, Q=0.5 m3/s)

From the results (Figure 5, Figure 6 and Figure 7) evacuation safety for three types of stairs are evaluated as Table 3. It is found that stair slopes are not critical factor and inflow discharge and flow depth are more important factors. When inlet depth is over 0.2 m, elderly female is difficult to evacuate safely. When inlet depth is over 0.35 m, even young male can't evacuate alone.

Table 3. Evacuation Safety for Inundated Stairs

Types	$0.3\ m^3/s$	$0.5\ m^3/s$	$0.7\ m^3/s$	$1.0\ m^3/s$
Mild	Inlet depth: 0.20 m Over limit of safe evacuation for female	Inlet depth: 0.30 m Over limit of safe evacuation for male	Inlet depth: 0.37 m Over limit of evacuation for male	Inlet depth: 0.45 m Over limit of evacuation for male
Normal	Inlet depth: 0.21 m Over limit of safe evacuation for female	Inlet depth: 0.30 m Over limit of safe evacuation for male	Inlet depth: 0.36 m Over limit of evacuation for male	Inlet depth: 0.44 m Over limit of evacuation for male
Steep	Inlet depth: 0.22 m Over limit of safe evacuation for female and elderly male	Inlet depth: 0.22 m Over limit of safe evacuation for male	Inlet depth: 0.35 m Over limit of evacuation for male	Inlet depth: 0.44 m Over limit of evacuation for male

5. Conclusion

In this study, flow over stairs are simulated by 3D CFD model to investigate the flow characteristics and safe evacuation conditions. For the simulation of flow over stairs, a fully three-dimensional computation fluid dynamic model, FLOW-3D is applied. Inlet discharge conditions are $0.3\ m^3/s$, $0.5\ m^3/s$, $0.7\ m^3/s$ and $1.0\ m^3/s$. RNG turbulent model and VOF scheme are applied. Stair model is constructed based on the Korean regulation of criteria on house construction published by ministry of land, infrastructure and transport.

From the results, it is found that flow depth only over the 20cm could cause the danger in the evacuation along stairs. In the flow depth over 0.36cm, every people including young male, could not escape alone without any help. Inlet flow depth is more important factor than stair slopes. Inundation depth to underground stairs should be managed to keep below 0.2 m.

Acknowledgments

This study was done in support of the "Development of Urban Flood Mitigation Technology (Smart Flood Management)" that Research Projects of the KICT(Korea Institute of Civil Engineering and Building Technology) in 2016.

References

[1] T. Ishigaki, T. Ozaki, T. Inoue,H. Shimada and K. Toda, "Drainage System, Rainwater Flooding and Underground Inundation in Urban Area", 12th International Conference on Urban Drainage, Porto Alegre/Brazil, **(2011)**.

[2] R. Sorensen, "Stepped Spillway Hydraulic Model Investigation", Journal of Hydraulic Engineering, ASCE, vol. 111, no. 12, **(1985)**, pp. 1461-1472.

[3] M. R. Chamani, and N. Rajaratnam, “Characteristics of Skimming Flow over Stepped Spillways”, Journal of Hydraulic Engineering, ASCE, vol. 125, no. 4, **(1999)**, pp. 361-368.
[4] Q. Chen, D. Guangqing, H. Liu, “Volume of Fluid Model for Turbulence Numerical Simulation of Stepped Spillway Overflow”, Journal of Hydraulic Engineering, ASCE, vol. 128, no. 7, **(2002)**, pp. 683-688.
[5] C. W. Hirt and B. D. Nichols, “Volume of fluid (VOF) method for the dynamics of free boundaries”, Comput Phys, vol. 39, no. 1, **(1981)**, pp. 201-225.

Authors

Du Han Lee, Research Fellow, River and Costal Research Division, Korea Institute of Civil Engineering and Building Technology

Myounghwan Kim, Researcher, River and Costal Research Division, Korea Institute of Civil Engineering and Building Technology

Dong Sop Rhee, Senior Researcher, River and Costal Research Division, Korea Institute of Civil Engineering and Building Technology