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Agent-based Flood Evacuation Simulation of Life-threatening Conditions Using Vitae System Model

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ABSTRACT

The Vitae System model is referenced to provide a systematic framework for the adaptive evacuation strategy in a life-critical situation by integrating its three fundamental elements - survivability, vitality and communication. A preliminary model is proposed in the context of evacuation from a water related hazard. A multi-agent based evacuation simulation system is prototyped combining hydraulic model data for the case area of the Oike underground space in Kyoto, Japan. The impact of facility arrangement on evacuation decision-making is demonstrated.

Keyword: Vitae System model, Underground flooding, Agent-based modeling, Evacuation simulation, Decision-making

I. INTRODUCTION

In many cases unexpected flooding occurs so quickly and with insufficient warning that it allows little or no time for evacuation. There is an increasing need to prepare for events such as flash floods, landslides, and underground inundation in urban areas. Particular attention should be given to evacuation in an enclosed space, where evacuation is difficult due to its complexity in structure. Early evacuation is highly recommended for those spaces (e.g. underground malls), but difficulties still exist within minority populations who either respond late, become injured or are even totally unaware of the approaching hazard. Therefore, they are already in a life-threatening situation when they implement coping actions. Addressing these concerns is significant in evacuation planning, disaster education and training.

Much research has focused on estimating loss of life due to flooding. General functions or extended functions were derived for flood mortality (DeKay and McClelland (1993), Jonkman et al., (2002), Koshimura et al., (2006)). Penning-Rowsell et al., (2005) applied a method to assess the flood risk to people taking into account flood hazard, people vulnerability and area vulnerability that are indicated by the speed of onset, nature of the area and flood warning. Among them, the nature of the area is categorized according to stories such as multi-story apartments, two-story buildings and single-story buildings, in which an underground space is not clearly categorized. Elders aged 75 or over and the chronically ill were counted to measure people vulnerability. This method is suitable for risk assessment of non-critical situations.

Evacuations under life-threatening conditions in urban areas have not received much attention in the literature. A life-threatening situation is a very critical life and death situation. In general, there is no systematic analysis of different events particularly deaths caused by a flood disaster connected with facility configuration and design. In Fukuoka in 1999, for instance, a female employee who worked in an underground restaurant was killed by the intrusion of flood water. The female employee called the manager for help at 10:30am. The manager then rushed to the scene and contacted the emergency center at 11:15am. The rescue team arrived at 11:24am but the woman had drowned. Regarding this event, on the one hand, given the rapid rate with which a flood can develop, time becomes the overriding critical factor in emergency egress and rescue. Therefore, the communication mechanism needs to be discussed to improve the efficiency. On the other hand, what and how to do in order to survive after calling for help produces the problem of evacuation strategy in critical situations. This issue in many agent-based simulations for flood evacuation is simply omitted. People usually are considered dead or placed in the “difficult to evacuate” group once the hazard reaches a certain level. In terms of water depth, the level is widely defined as 70 cm or 1 m according to physical evacuation experiments (Ishigaki et al., 2005). For example, Takahashi T. (1989) used 70 cm as the walking threshold in the evacuation system. Toda K. (2006) grouped evacuees into “difficult to evacuate” when inundation reaches 50 cm and “impossible” when the inundation is over 1 m or the overflow on the staircase is over 30 cm.

Multi-agent based modeling is an increasingly powerful modeling technique for simulating individual interactions in a dynamic system and is distinctive in its ability to simulate a situation where the future is unpredictable (Lampert 2002). For this reason, multi-agent technology is widely used in various disaster management and community preparedness issues. So far, there is no generally accepted theory that is able to provide a framework for agent-based evacuation simulation. In this paper, the Vitae System model is referenced to provide a systematic framework for the adaptive evacuation strategy in a critical situation by integrating its three fundamental elements - survivability, vitality and communication.

This article is structured as follows: Section 2 contains an overview of the Vitae System and a preliminary model for its three elements. The application of this model is demonstrated in an agent-based study in Section 3. Concluding remarks are presented in Section 4.

II. VITAE SYSTEM MODEL

The Vitae System Model is a new conceptual framework for integrated disaster risk management (Okada, 2006). This model is intended to view cities, regions and communities as vital integrity with robustness and resiliency in its coping capacity. The model is depicted as a triangular diagram with three nodes as fundamental functions i.e., (i) survivability, (ii) vitality and (iii) communication.

In this paper, the Vitae System Model is applied to address people’s instinctive capacity to respond instantaneously to an external shock in the context of disaster evacuation. It provides systematic logic to interpret a special type of evacuation decision-making in a critical situation where people have to survive first for a relatively short period of time. When survivability is at least temporally guaranteed, we assume that vitality (such as one’s stamina and energy, spiritual perseverance, etc.) counts so as to maintain the survival status. In the entire process, interactive communication with the surrounding environment and other agents determines the success of self–help and mutual aid.

The chance of survival under very critical situations is considered to rely very much on accessible surrounding facilities and people’s sensibility. In many actual cases people may eventually survive a flood disaster if they instantaneously make an appropriate decision and action, for example, jumping onto a stage or hanging onto a pole which happens to be there as a part of the environment. Such a facility or place may be regarded and used as a provisional shelter. It is evident that the capability of creatively using the surrounding facilities is instrumental to this choice. The success of making such a decision and action is considered to depend very much on the knowledge and capability of the evacuee’s “sensibility” so as to immediately judge the situation and perform adaptive actions. Without such sensibility, people will be killed immediately once the hazard reaches the level of a life-threatening situation. To address these concerns, the structure and facility layout inside a building, as well as people's evacuation decision –makings and behavioral aspects are considered in the modeling of its three elements.

A.Survivability (S)

As shown in Table Ⅰ, the inundation depth is used to measure the hazard level. The characteristics of existing facilities in size (height, width), mass and layout reflect the environmental vulnerability, and people's vulnerability resides in their sensibility.

TABLE I. Indicators of survivability for underground evacuation

Factors	*Type of Indicators*	*Indicators*
Hazard	Environment	Inundation situation
Vulnerability	Environment	Facility and its characteristics in size and layout etc
	People	Lack of Sensibility

Given the above basic assumptions, the survivability function is defined as follows:

$$S_t \quad f(\quad, u_t, u_m) \quad \begin{array}{lll} & when & 1\ and\ u_l \quad u_t \quad u_m \\ 0 & when & 0\ or\ u_t \quad u_m \end{array} \qquad (1)$$

where u_t is inundation level at time t, u_l is the threshold water level above which walking against a flood becomes almost impossible, $\sigma = 1$ if people have sensibility and thus instantaneously take temporary refuge, and $\sigma = 0$ if people do not have such sensibility and thus are unable to do so.

Note that survivability is defined only for life-threatening states. It corresponds to either the dichotomous states of one's survivability, i.e. "scarcely surviving" as indicated by ε taking on a very small positive value such as 0.000001, or becoming immediately killed as indicated by zero. u_m represents the maximum endurance level of flood inundation.

The critical situation is considered to start from the moment when the hazard reaches the level of u_l. According to a hydraulic experiment (Ishigaki et al., 2005), it is difficult to escape using a staircase when the overflow is above 30 cm. When the inundation is over 70 cm, it is very difficult to walk in flooding water, so u_l is set as 70 cm in this research.

There is another moment when people face the critical state leading to death as shown in Equation (1). Besides the case in which they have no sensibility ($\sigma = 0$), people will also be killed (even if people have sensibility ($\sigma = 1$) and have so far successfully survived by taking instantaneous refuge in a nearby provisional shelter) if the overwhelming flood hazard exceeds the level of u_m . On the contrary, if people have sensibility ($\sigma = 1$) and the hazard level is not as high as u_m , then survivability is considered to be equal to ε .

Given the environmental layout of the surroundings, if an evacuee finds an instantaneous refuge, then the evacuee will shelter in it while waiting for help. In this case, the chance that is provided for an evacuee who has sensibility to survive depends totally on the progress of inundation. However, if no facilities or places serving as a provisional shelter are available, the only choice is to resort to others for help.

In a critical situation, there may be many instantaneously adaptive strategies to survive flooding in an underground space. As presented by S.N. Jonkman (2008), one basic empirical fact of flood events is that there are always survivors even if the water is extremely deep; people tend to find debris, trees, attics, roofs, and other ways to stay alive. In this research, two types of instinctive refuge are considered including a platform (e.g. auto vending machine, locker) and a pole. It should be noted that each evacuation strategy has its specific limitations determined by the physically enduring hazard level u_m. Here $u_m \quad \min[h_p \quad h_e, h_c] - h_f$ in which h_p is the height of an evacuee, h_e is the height of instinctive refuge, h_c is the height of the ceiling in an underground space, and h_f is the vertical length of a person's face. Details are illustrated in Fig. 1. For the case of a platform, the enduring leve u_m is equal to the sum of the height of the platform and the height of the evacuee minus the length of his or her head. But if $h_p + h_e$ exceeds the height of the ceiling h_c, then $u_m \quad h_c - h_f$. For the case of a pole, we assume that people can climb up to the top of the pole and the pole connects to the ceiling, so that the enduring level is not determined by the height of the evacuee h_p but by the height of the ceiling, h_c. Therefore, how long an evacuee can stay alive after sheltering in a chosen provisional place is determined by the time interval before the hazard reaches the level of u_m. We use T_{id} to represent the effective interval as shown in Equation (2). T_{id} actually indicates the efficiency of a specific evacuation strategy subject to the flood hazard and surrounding environmental vulnerabilities. The higher the platform, the longer T_{id}. If the flood hazard is increasing at a constant rate, then it follows that $u_t \quad\quad t($ $is\ a$ constant). The slower the increasing rate, the longer T_{id}.

$$T_{id} \quad T\{u_t \quad u_m\} \quad t_0 \tag{2}$$

Where t_o represents the time when an evacuee starts to shelter in a provisional place.

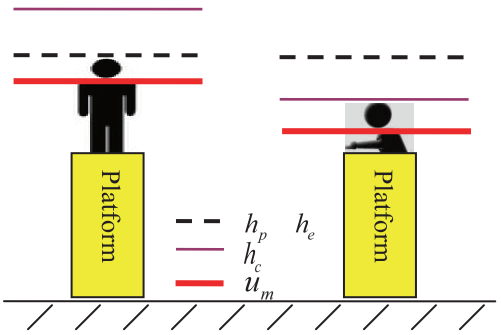


Figure 1. Calculation diagram of u_m

B.Vitality (V)

In this research, vitality is defined as physical or mental vigor or energy (Merriam Webster dictionary). In the process of an evacuation, vitality will decrease over time as the physical consumption of vigor. Under critical situations, vitality varies with the different evacuation strategies. For example, it requires more energy to shelter on a pole than on a platform.

As there are no physical experimental data to estimate the energy cost when people shelter on a pole or a platform, we assume that evacuees are normally healthy and they share the same linear decreasing ratio of energy cost. Therefore, the normalized level of vitality is indicated as:

$$V_t \quad V_0(\mathrm{y}) - \quad (R_i)t \quad (t\ \text{:minute}) \tag{3}$$

Where V_0(y) records the initial vitality possessed at the beginning of an evacuation, $\lambda(R_i)$ is the energy decreasing ratio, which varies depending on the evacuee's decision in the instinctive shelter $R_i(R_1 \quad platform, R_2 \quad pole)$. In this research, we assume a short-term stay for no longer than 12 hours so that vitality decrease due to no food and water is not considered. In terms of sheltering on a platform, apart from the energy taken to climb up, it costs almost nothing, which means that $\lambda(R_1) = 0$. For the choice of the pole, we assume the decreasing rate of energy cost as 0.1. Therefore, the following equation is derived.

$$V_t \quad V_0(\mathrm{y}) - \quad (R_i)t \quad \begin{matrix} V_0(\mathrm{y}) & when\ R_i \quad R_1 \\ V_0(\mathrm{y}) - 0.1t & when\ R_i \quad R_2 \end{matrix} \tag{4}$$

Seniors and children walk slower than adults due to their weak physical status. Therefore, the difference of the normal average walking speed for each age group can be viewed as initial vitality that people possess, which is defined as 1.4 m/s for the adult group (aged 18-69), 1.2 m/s for the child group (aged 6-17) and 1.0 m/s for the senior group (aged 70 or over). The normalization process views the adult vitality as 1, so we obtain the normalized initial vitality:

$$V_0(y) \quad \begin{matrix} 1\ if\ \ y\ is\ an\ adult \\ 6/7\ if\ \ y\ is\ a\ child \\ 5/7\ if\ \ y\ is\ a\ senior \end{matrix} \tag{5}$$

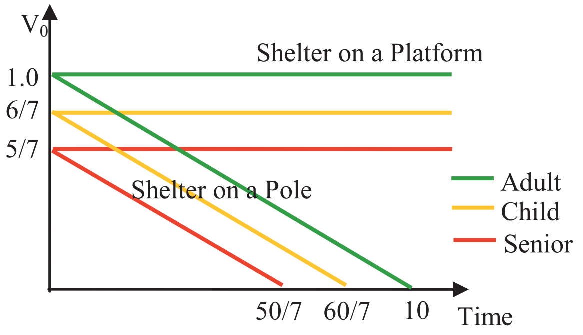


Figure 2. Vitality change upon evacuation strategy and time

It should be noted that how long people can endure given the chosen strategy depends upon not only T_{id} but also vitality. Therefore, the enduring time takes on the smaller value of the above two periods of time as shown in Equation (6).

$$T \quad \min[T_{v \quad 0}, T_{id}] \tag{6}$$

Where T represents the enduring time, and $T_{v=0}$ represents the period of time when people used up their energy. T_{id} is calculated as shown in Equation (2).

C.Communication (C)

In the context of an evacuation from an underground flooding, the communication is classified into four types:

(1) Accessibility and escapable capacity to staircase or emergency exits

(2) Evacuation guidance

(3) External resources and information

(4) Voluntary help and rescue

The mechanism of communication is presented in Fig. 3. From an individual agent's viewpoint, communication can occur with the surrounding environment, nearby evacuees and outsiders. The communication with the surrounding environment is a one way communication mode, which determines the success of self help. The process illustrates how people sense the signals (i.e. hazard progress and facilities) from the environment and make instantaneous decisions on a provisional refuge in order to survive the flood. The communication results for different people vary greatly depending on their sensibility. The interactive communication between evacuees is embodied in possible mutual help, which provides a mechanism by which information can progress through the population (Gwynne et al., 2006).

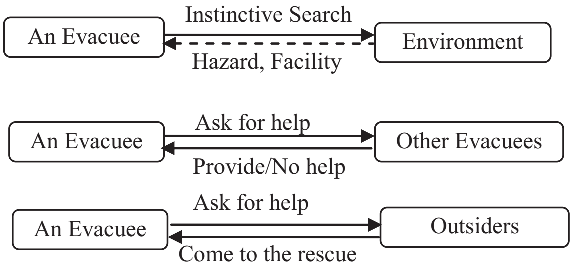


Figure 3. Communication behavior

The voluntary help provider needs to satisfy three conditions that the helper should be in a young age group, be under a non-critical situation and be willing to provide voluntary help. Moreover, an evacuee may resort to asking for help from outsiders such as the police, NGOs, the fire brigade and family members. But the external help is effective only up to the point where people can no longer endure the flood water. Otherwise, people will be killed even with external help.

III. VITAE SYSTEM BASED AGENT MODELING AND SIMULATION

A.Agent modeling

Agent modeling is based on the behavioral understanding of underground evacuation in critical situations. The survivability is firstly calculated at every simulation step. If the survivability is equal to 0 then it will lead to a failed evacuation. If not, the model shows an image of how people try to survive. The three functions in the Vitae System are integrated to provide a strategic change in the evacuation decision. If an evacuee finds an instinctive refuge, then the evacuee will shelter in it while waiting for help. The enduring time T_{id} is calculated by Equation (2) and vitality is calculated by Equation (4). If external help is available during this time period, then a successful evacuation will be claimed. If someone nearby willingly provides voluntary help, then the evacuee and the help provider will form a group sharing the same fate. But if neither external help nor nearby help arrives in time, people will be killed eventually.

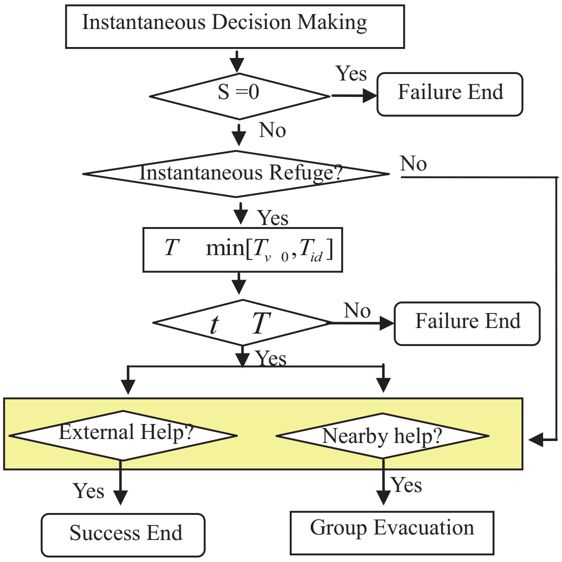


Figure 4. Modeling for evacuation in critical situation

B.Case Study

- Hydraulic experiment

The Oike underground space in the center of Kyoto city, Japan is used as the case area. The Kamo River runs on its near east side. The Oike underground space is a structure of multiple stories including a shopping mall, a subway station concourse and a parking lot (B1F), another parking lot on the second basement floor (B2F), and a subway platform on the third basement floor (B3F) as shown in Fig.5. The horizontal area of B1F and B2F is about 650 m*40 m and the B3F is about 100 m*8 m with the ceiling height as 2.7 m. In this research, the hydraulic experiment data in the Oike underground space in Kyoto, Japan is combined to indicate how a hazard progresses in the entire location. As explained in the paper by Toda et al. (2005), the inundation flow is configured by means of a 1/100 scaled hydraulic model where the discharge of 100 m^3/s overflows from the Kamo River at the upstream site of Oike Bridge. This over-

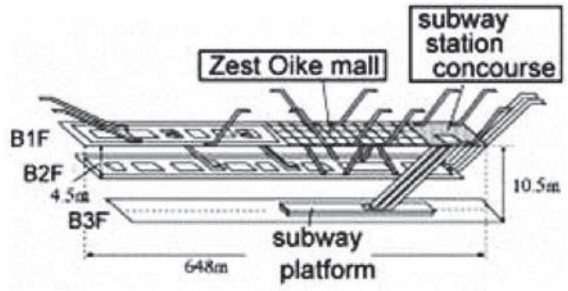


Figure 5. Structure of the Oike underground space in Kyoto

flow may occur due to a 100-year flood in the Kamo River basin. It is found that when the inundation flow invades a multi-storied underground space, the inundated area spreads rapidly, and the water depth rises very quickly. On the subway platform on B3F, the water depth has a rapid rise from 15 minutes to 20 minutes after the inundation. It is critically dangerous since the staircase in the escape route is impassable in this case. The data is 30 minutes long with intervals of 1 second. Given the same physical settings in the Oike underground space, we extract the hydraulic data at 1 minute intervals (0 s, 60 s etc). The evacuation simulation step is set as 2 seconds.

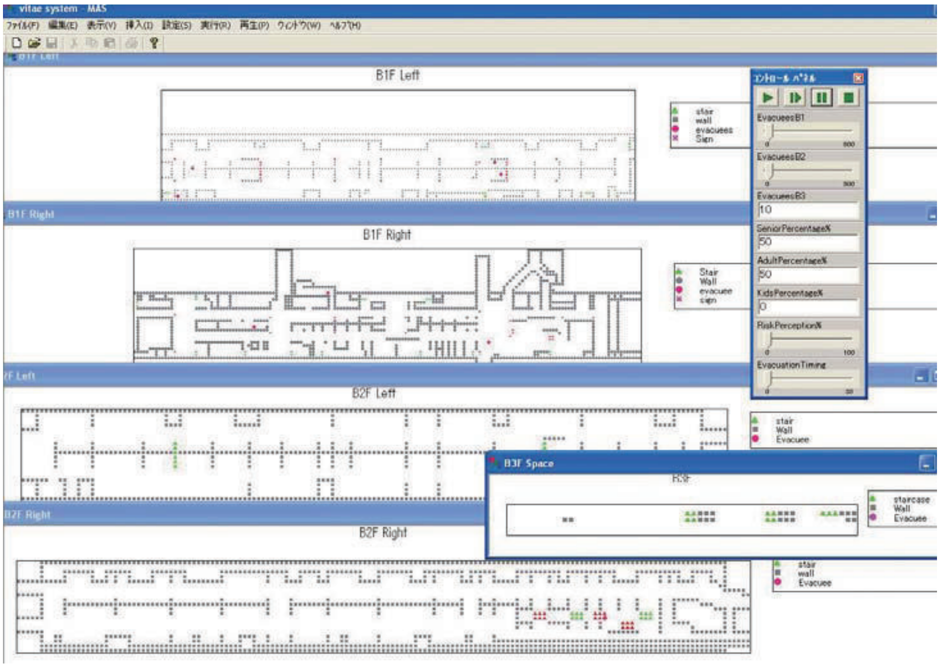
- Agent type

There are two types of agents: one is a static agent including staircase, wall, corridor, exit sign, pole and high platform, and the other type is a moving agent like individual evacuees. The dynamic developing flooding data is linked to static agents as attributes.

- Initial settings and parameters

The spatial unit is a 2 m x 2 m grid. The simulation unit is an individual evacuee. The initial location and inherent qualities of people like age are randomly given to each individual. The health and mobility status is assumed to be normal when the evacuee is generated. The height of an agent is set as 1.6 m and each person occupies a 0.4 m × 0.4 m space, which is the typical size of each person's space (Burstedde C. et al., 2001).

In the simulation, the parameters include sensibility (%) representing the proportion of evacuees with sensibility, evacuation timing (minutes) after the inundation, number of evacuees for each story and age structure of evacuees (%). The evacuation starting time as a parameter makes it possible for the simulation to start from any situation such as the beginning of the inundation, appearance of an inescapable staircase, or water depth over the upper limit of walking capability.



EvacueesB3: 10
SeniorPercentage%: 50
AdultPercentage%: 50
KidsPercentage%: 0

Figure 6. Interface of Vitae System based evacuation simulation system

● Simulation and results

Based on KKMAS, a Multi-Agent Simulator provided by Kozo Keikaku Engineering Inc., an evacuation system was developed for the case area of the Oike underground space in Kyoto, Japan. The simulation interface is shown in Fig. 6. It has three independent but connective spaces. B1F left and B1F right represent the space of B1F, and B2F right and B2F left represent the space of B2F. The staircases in B3F connect directly to B1F. Some staircases in B2F connect with B1F and some of them directly lead to the ground surface. A similar arrangement also exists in B1F.

The hydraulic experiment shows that the water depth reaches a level close to the threshold of 0.3 m around 15 minutes after the inundation. Therefore, we set the evacuation starting time from 15 minutes to 30 minutes. The evacuation under critical condition is considered applicable to a small number of people. For this reason, the total evacuees are set as 5 evacuees in B3F with the age structure being 20% child, 60% adult and 20% senior. We assume that 100% of people have sensibility and there is no external help within the time period that people could sustain the flood.

Liu et al. (2010) demonstrated the effectiveness of the adaptive evacuation strategy. In this paper, the focus is given to the influence of the facility layout on evacuation. The following three scenarios of configuration were conducted: one is the standard arrangement near the staircase; the second case is the left cornered arrangement and the third case is the scattered set in B3F.

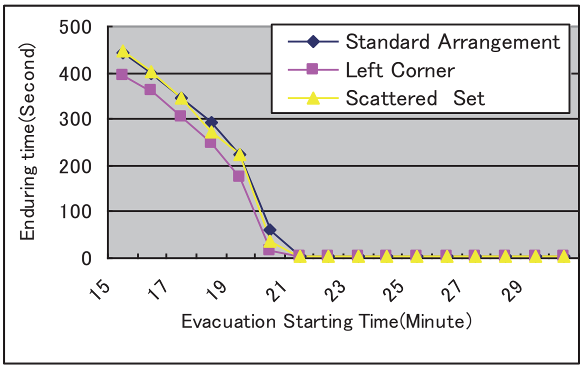


Figure 7. Simulation results for “enduring time”

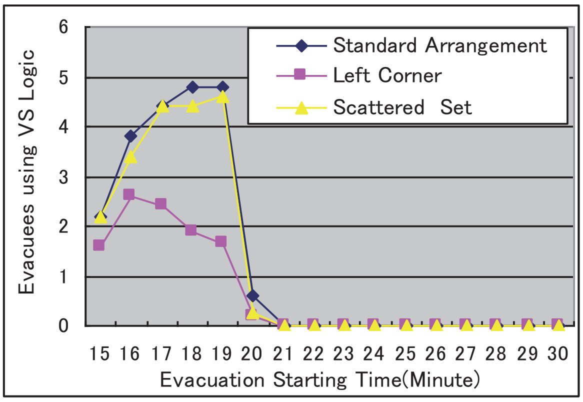


Figure 8. Simulation results for “evacuees using VS logic”

As shown in Fig. 7, the result of enduring time shows that it is almost the same for the case of standard setting and scattered setting. However, enduring time is shorter for the case of left corner setting because the staircase is located in the center and right side of the B3F space. Due to the rapid rise of water depth and the distance from the staircase to the provisional shelter, some evacuees were unable to reach the instinctive shelter.

“Evacuees using Vitae System (VS) logic” means the number of people who evacuate in an adaptable way. As shown in Fig. 8, there is a rapid rise from 15 minutes to 20 minutes after the flooding for the case of standard setting and scattered setting, which means that more and more people have to take adaptive actions according to the situation in which survival is still possible. For the case of the left corner, the rapid trend stops at 16 minutes after the flooding and after that decreases until 20 minutes. The common element is that once people evacuate 21 minutes after the flooding, those instantaneous shelters cannot help evacuees since shelters will be submerged by the torrent, which makes them invisible to evacuees. The simulation results illustrate the applicability and limitation of the adaptive strategy developed in the current research.

In addition, the simulation provides a clue for the rescue team to judge whether they will arrive in time. For example, if a person evacuates 15 minutes after the flooding, then his or her enduring time is about 450 s. If the rescue team arrives after that, the person will likely be already dead.

IV. CONCLUSIONS

As an application of the Vitae System Model in disaster evacuations, the Vitae System provides a new perspective for the evacuation simulation particularly for life-threatening situations. The integration of three functions in the Vitae System helps to interpret the evacuation strategy for disasters including but not limited to an underground flood. Based on this logic, an elementary model was proposed and a multi-agent based evacuation simulator was developed combining the hydraulic experiment data for the case of the Oike underground space in Kyoto, Japan. The simulation result shows the effectiveness and limitation of the adaptive evacuation strategy developed in the current research. It reveals the need to develop more in-depth knowledge on the adaptive and feasible strategies to cope with sudden critical situations and pass the knowledge to people in order to build their adaptive capability.

There is a need to extend the above model through a systematic analysis of life-threatening situations by incorporating more water characteristics (e.g. flow velocity and experiment results of human stability in water) and people's vulnerabilities (e.g. mobility, health status). Physical and psychological experiments plus literature survey in related fields for vitality change, and empirical and physical interpretation of communication mechanisms are also required for information classification, sharing and transfer. These issues will be addressed in our future research.

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