Development of System to Assist Decisions to Stop Trains and Evacuate Passengers to Avoid Sudden Hazards due to Local and Intensive Short Bursts of Heavy Rain

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Local and intensive short bursts of heavy rain which may cause sudden hazards such as unexpected flooding are becoming more frequent in Japan. Moreover, these rains may be causing heavy rain to fall only over a limited area which may be narrower than the distance between rain gauges along railway lines. Therefore, current safety measures of train operation based on observation data measured by these gauges may not work well for these hazards. To address this problem, we developed a system that assists train stop and assists passenger evacuation to avoid those hazards. In this paper, first, we mainly describe the calculation algorithm and functions of the system. Next, we carry out simulations to confirm the validity and accuracy of calculations made by the system.

Key words: local and intensive short bursts of heavy rain, avoiding hazards train stops, passenger evacuation, assist system

1. Introduction

Current safety measures of train operation to avoid hazards due to rain are mainly based on the observation data measured by rain gauges generally installed at intervals of about ten kilometers along railway lines. For example, when precipitation exceeds a regulatory threshold value, train operation is to be stopped to avoid hazards due to the rain.

However, local and intensive short bursts of heavy rain (hereinafter referred to simply as ‘short bursts of heavy rain’) are becoming more frequent mainly in urban areas in Japan, and may cause sudden hazards such as unexpected flooding that may not be picked up by current safety measures. That is because short bursts of heavy rain can occur over areas which are narrower than distance between rain gauges. Moreover, since short bursts of heavy rain are difficult to forecast until about 30 minutes before they occur, it is also difficult to take preemptive safety measures such as suspension of train operation before such rain starts. Thus, train dispatchers are forced to determine and order avoidance measures of these hazards at extremely short notice immediately after a short bursts of heavy rain that generate a sudden hazard is forecasted along a railway line. This means that there is a huge burden on train dispatchers, and some kind of support to alleviate this responsibility is required.

To provide useful information for train dispatchers when there is a warning forecast of short bursts of heavy rain, we developed a system that assists decisions to stop trains and evacuate passengers (hereinafter referred to simply as ‘the system’) to avoid these hazards [1, 2]. The system is able to rapidly calculate the possible stopping points of trains to avoid hazards and identify evacuation routes for passengers, assuming unexpected situations based on forecasted data of short bursts of heavy rain provided by external agencies. Since the system is developed on the basis of GIS (Geographic Information System), calculation results can be projected on a digital map.

In this paper, first, we outline the calculation algorithm and functions of the system. Next, we describe simulations carried out on a real railway line in the Tokyo metropolitan area to confirm the applicability, the usefulness, and the accuracy of the system.

Although the system can handle short bursts of heavy rain which may cause various sudden hazards such as unexpected flooding, gust, landslide, etc., we focus on unexpected flooding in this paper. Figure 1 shows the calculation flow when short bursts of heavy rain are forecast along a railway line. Note that, (a) in the figure is forecast data of short bursts of heavy rain by the public external organization. (b) in the figure is a forecasted data of flooding calculated by the method described later, and this is an input data to the system.

2. Calculation algorithm and functions of the system

2.1 Outline of the system

The system can calculate the following items based on a quantitative criterion:

- Stop points of trains in operation that minimize risks of unexpected flooding due to short bursts of heavy rain
- Evacuation routes of passengers from points where trains are stopped to evacuation sites along railway lines when an unexpected situation which forces passengers to evacuate oc-
Input data is the forecasted data of flooding composed of the following elements:

- Forecasted areas of flooding in a mesh unit with a side length of 25 meters
- Forecasted time of flooding in each area

Forecasted data of flooding is calculated using the method described by Watanabe et al. [3, 4] based on forecasted data of short bursts of heavy rain from Nowcast [5].

### 2.2 Detail of the calculation algorithm

Even if unexpected flooding due to short bursts of heavy rain does occur along a railway line, the flooding is not extensive in most cases which means that not all trains in operation at the time are at risk from the flooding. Therefore, different trains may require different safety measures depending on the relationship between the distribution of forecasted areas of flooding and locations of each train at that time. Considering these conditions, we decided that the calculation algorithm of the system should follow these three steps:

1. **Classification of a target railway line into three sections** based on distributions of forecasted areas of flooding
2. **Classification of trains in operation into three train groups** based on locations of each train and the classification result of the railway line
3. **Calculation of stop points of trains and evacuation routes of passengers** from the points where trains stop

Since trains can stop at any points on railway lines except certain sections such as tunnels, there are an almost infinite number of points where trains may stop (hereinafter referred to simply as ‘potential stopping points’), which makes calculation difficult. Therefore, in the calculation algorithm, in order to reduce the computational load, potential stopping points on a target railway line are limited to stations or arbitrary points between stations that are preinstalled discretely. Locations of all potential stopping points are common to both up and down directions and the number of these points should be sufficiently larger than the number of trains in operation on a target railway line. If a potential stopping point is an arbitrary point or a station with a platform for both the up and down direction, the number of trains that can be stopped at the point is one in each direction. If a potential stopping point is a large station with multiple platforms, the number of trains that can be stopped at the point is equal to the number of platforms in the station in each direction.

#### 2.2.1 Classification of a target railway line into the three sections

According to the distribution of forecasted areas of flooding, a target railway line is classified into the three sections, DH (Direct hazard), IH (Indirect hazard) and NH section (non-hazard), as in Table 1 in a block section unit. Since locations of block sections in each of up and down directions are not always same, this classification is carried out in each direction. Figure 2 shows an example of classification result in one direction. The specific section in the figure represents a section where trains should avoid stopping such as censoring sections of railway crossings.

As DH sections have some parts that overlap with forecasted areas of flooding, to avoid direct risks of flooding, trains should avoid stopping in DH sections as much as possible. If trains have no choice but to stop in DH sections, stop points of trains should be decided in consideration of passenger evacuation if a train suffers damage by unexpected flooding even after trains have stopped.

#### 2.2.2 Classification of trains into the three train groups

Based on the relationship between the location of each train at the time when short bursts of heavy rain are forecasted, locations of classified sections, and remaining time until flooding occurs in each forecasted area of flooding that overlap DH sections, trains are classified into the three train groups as shown in Table 2. This classification is applied for both the up and down directions.

#### 2.2.3 Calculation of stop points of trains and evacuation routes of passengers

1. **DH train group**

   If trains stop at a potential stopping point in a DH section, as...
mentioned in 2.2.1, there is still the possibility that the train may suffer damage by flooding even after it has stopped. Therefore, stop points of trains belonging to DH train groups should be decided in consideration of passenger evacuation in such situations. Moreover, the time for passengers to get from where the train is stopped to the evacuation sites along the target railway line should be as short as possible.

Stop points of trains and evacuation routes of passengers are calculated by (1). This formula calculates the stop point minimizing the passenger evacuation time.

\[
\text{Minimize } \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} AT_{ij}^k
\]

where
- \( I \): Set of a train belonging to DH train groups
- \( J \): Set of a potential stopping point in DH sections where train \( i \in I \) can stop
- \( K \): Set of an evacuation site that can be evacuated from potential stopping point \( j \in J \)
- \( AT_{ij}^k \): Evacuation time from potential stopping point \( j \in J \) to evacuation site \( k \in K \) when train \( i \in I \) stops at potential stopping point \( j \)

Evacuation times are calculated by (2).

\[
AT_{ij}^k = \frac{L_{ij}^k}{V} + \frac{Q_i}{\Delta q_j}
\]

where
- \( L_{ij}^k \): Length of the evacuation route from potential stopping point \( j \in J \) to evacuation site \( k \in K \)
- \( V \): Average walking speed of passengers (constant value)
- \( Q_i \): Number of passengers on train \( i \in I \)
- \( \Delta q_j \): Number of passengers that can get off per unit time at potential stopping point \( j \in J \)

This formula considers not only the time required for passengers to evacuate from stop points of trains to evacuation sites but also the time required for passengers to get out of the trains. The number of passengers that can get off per unit time \( \Delta q_j \) differs depending on whether potential stopping point \( j \) is a station or an arbitrary point. That is because, at stations, passengers can get off at the same time from all doors of trains, but at arbitrary points, passengers have to get off one by one from some designated doors of trains. When potential stopping point \( j \) where train \( i \) stopped is a large station also serving as evacuation site \( k \), evacuation time \( AT_{ij}^k \) is zero. In addition, when train \( i \) stopped at potential stopping point \( j \) on an elevated section where there is no possibility of being affected by flooding, evacuation time \( AT_{ij}^k \) is also zero.

Constraints are defined according to conditions of real railway lines: the number of platforms in each station, locations of block sections (signaling systems), locations of censing sections at railway crossings where trains should avoid stopping, etc. In addition, the relationship between the number of passengers on trains and capacities of evacuation sites are also taken into account. For example, in the case that a large number of passengers are on a train, evacuation sites that can be selected as the evacuation destination from the stop point of the train are limited to the sites which have enough capacity for all the passengers from the train.

(2) IH train group

There are no predicted areas of flooding within or along IH sections. Therefore, there is no risk of flooding on a train which stops at a potential stopping point in IH sections, and passengers do not have to evacuate outside of the train. However, if a train stops at an arbitrary point that is a potential stopping point, passengers may be forced to wait in the train for a long time until operations resume. Therefore, trains in the IH group should preferably stop at stations in IH sections when possible.

Optimal stop points of the trains are calculated by (3). The formula calculates stopping points that minimize the waiting times of passengers in trains, and does not calculate evacuation routes.

\[
\text{Minimize } \sum_{l \in L} \sum_{m \in M} CT_{lm}
\]

where
- \( L \): Set of a train belonging to IH train groups
- \( M \): Set of a potential stopping point in IH sections where train \( l \in L \) can stop
- \( CT_{lm} \): Waiting time of passengers on train \( l \in L \) when train stops at potential stopping point \( m \in M \)

If potential stopping point \( m \in M \) is a station, waiting time \( CT_{lm} \) is zero. In other words, the aim of the formula is to stop trains at stations as much as possible. Constraints are the same as calculation for DH train groups described above.

(3) NH train group

Since trains belonging to NH train groups can continue operation without being affected by flooding, stop points of the trains are not calculated.

Figure 3 shows an example of calculation result of stop points of trains and evacuation routes of passengers in one direction. In the figure, \( I = \{ i_1, i_2, i_3 \} \) expresses DH train groups and \( L = \{ l_1, l_2, \ldots, l_3 \} \) expresses IH train groups.

![Fig. 3 Example of calculation result of stop points of trains and evacuation routes of passengers in one direction](image)
3. System to assist decisions about where to stop train and evacuate passengers

3.1 Outline of the system

The system is developed based on GIS and has the following main functions:
- Database function to store various data used for calculation
- Automatic calculation function of stop points of trains and evacuation routes of passengers based on the calculation algorithm
- Display function to help to visually understand calculation results

3.1.1 Database function

The database of the system mainly stores the following data:
- Map data of target railway lines and their vicinities
- Basic data of target railway lines such as kilometrage, locations of block sections, locations of station, etc.
- Various preset data of target railway lines such as locations of potential stopping points, locations and capacities of evacuation sites, locations of specific sections, etc.
- Basic data of trains such as operation schedules, the number of passengers on the trains, etc.
- Forecasted data of flooding (input data)

These data can be updated freely. Therefore, the system can handle various types of railway line.

3.1.2 Calculation function

The system can automatically calculate stop points of trains and evacuation routes of passengers in both up and down directions. In the calculation, the following are considered:
- Potential stopping points and evacuation sites which overlap forecasted areas of flooding are excluded.
- All evacuation routes are calculated so as not to pass over forecasted areas of flooding.
- If a station has a platform that trains in both of up and down directions can enter, the priority of entering the platform is given the train that can arrive there earliest.
- Evacuation routes from stop points of trains are calculated only for evacuation sites that can accommodate passengers on the trains.

3.1.3 Display function

The system can display calculation results and various data in the database on a monitor as shown in Fig. 4. The system can show dynamically locations of trains and status of flooding over time.

3.2 Simulation using the system

In order to confirm the validity and accuracy of calculation results by the system, simulations using the system were carried out. The target railway line of the simulations was a real railway line from among the major railway lines in the Tokyo metropolitan area. The entire of the railway line is double-track, and is about 50 km long. The frequency of operation outside rush hours is about 10 trains per hour in both the up and down directions.

Two patterns of forecasted data of flooding were used in the simulations. One was the virtual forecasted data of flooding which we created. The other was the actual forecasted data of flooding based on actual data of short bursts of heavy rain that occurred along the railway line on one day in 2019. In the simulations, the following conditions were set:
- Intervals between potential stopping points were hundreds of meters which is longer than the length of trains operated along this target railway line.
- Trains were operated according to the timetable of the target railway line.
- All evacuation sites around the target railway line had enough capacity to accommodate all the passengers on the trains.

The specifications of the PC used for the simulation was as follows: OS - Win10 Pro 64bit, CPU - Intel Core i7-6700 (3.40GHz) and RAM - 8GB.

3.2.1 Result of the simulation using virtual forecasted flooding data

The calculation time of the simulation was about 2 seconds. As shown in Fig. 5, the following results were obtained:
- All trains belonging to the DH train group in both the up and down directions were able to stop at points unaffected by the flooding.

Fig. 4 Example of displayed calculation result of the system
• All evacuation routes and evacuation sites where are destinations of these routes were unaffected by the flooding.
• Since all trains belonging to the IH train group in both of up and down directions were able to stop at stations, there was no situation where passengers were forced to wait on the trains for a long time.
• All trains belonging to the NH train group in both the up and down directions were able to continue operation without being affected by the flooding.
• No trains stopped in the specific section.

3.2.2 Result of the simulation using actual forecasted flooding data

The calculation time of the simulation was about 16 seconds. As shown in Fig. 6, the following results were obtained:
• No trains were classified into the DH train group or stopped in the DH section.
• Since all trains belonging to the IH train group in both the up and down directions were able to stop at stations, no passengers were forced to wait on the trains for a long time.
• All trains belonging to the NH train group were able to continue operation without being affected by the flooding.
• No trains stopped in the specific section.

The reason no trains were classified into the DH group is that times remaining before flooding in the forecasted areas of flooding overlapping the DH section were relatively long, and the trains were able to pass over the DH section or stop in the IH section before flooding in those areas occurred.

Another simulation assuming the extreme situation that the flooding occurs immediately at forecasted areas of flooding overlap the DH section was also carried out. The used data was almost the same as the actual forecasted data of flooding, and only the time of flooding in the forecasted areas overlapping the DH section was changed.

The calculation time of the simulation was almost the same as the previous simulation. Figure 7 shows an excerpt of the simulation result. Although some trains were classified into the DH train group unlike the previous simulation, the system still managed to calculate stopping points for these trains and evacuation routes from these points which were not affected by the flooding.
These results therefore confirmed the validity and accuracy of calculations by the system in simulations of various situations.

4. Conclusions

Short bursts of heavy rain are becoming more frequent mainly in urban areas in Japan, and may cause sudden hazards such as unexpected flooding. Since short bursts of heavy rain may occur in a range narrower than installation intervals of rain gauges along railway lines, current safety measures based on the observation data measured by rain gauges may not avoid sudden hazards due to such rain. Moreover, as short bursts of heavy rain are difficult to forecast until about 30 minutes before they occur, it is also difficult to take preemptive safety measures before the rain starts. Thus, train dispatchers are forced to determine and order avoidance measures of these hazards at extremely short notice immediately after a short burst of heavy rain that can generate a sudden hazard is forecasted along a railway line. This means that there is a huge burden on train dispatchers, and some kind of support to alleviate this responsibility is required.

To provide useful information for train dispatches when there is a downpour warning forecast, we developed a system that assists decisions to stop trains and evacuate passengers to avoid these hazards. The system has the main three functions: a database function, a calculation function, and a display function. A database function is the function for storing various data used for calculation and stored data can be updated freely. Therefore, the system can handle various types of railway line. A calculation function is the function that calculates stop points of trains to minimize risks of unexpected flooding due to short bursts of heavy rain and evacuation routes of passengers when an unexpected situation which forces passengers to evacuate occurs. Calculations are performed automatically based on the calculation algorithm, so train dispatchers can obtain information quickly. A display function is the function that displays calculation results and various data in the database on a monitor. The function helps train dispatchers get information intuitively.

In order to confirm the validity and accuracy of calculation results by the system, we conducted simulations using the system for the real railway line in the Tokyo metropolitan area. Two different patterns of data, the virtual forecasted data of flooding which we created and the actual forecasted data of flooding, were used in the simulations. From the results of these simulations, we confirmed the validity and accuracy of calculation results by the system.

We will proceed with the following development plans for bringing the system into practical service:

• Accumulation of verification cases of the system by carrying out more simulations and long-term trial operation on real railway lines
• Synchronization of the system with real-time train location information and real-time vehicle load information to accurately reflect the situation of trains at each time
• Improvement of the calculation algorithm to enable application to single-track or quadruple-track railway lines and consideration of facilities such as storage lines and vehicle bases which are ignored in current calculations

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