Heavy Rainfall-induced Disaster-mitigation System for Railways Based on Precipitation Forecast Data

Takuya URAKOSHI
Tunnel Engineering Laboratory, Structures Technology Division

Takeshi KAWAGOE
Geology Laboratory, Tunnel Engineering Laboratory, Structures Technology Division

Satoshi WATANABE
Geo-hazard and Risk Mitigation Laboratory, Disaster Prevention Technology Division

Naoya OZAKI
Transport Planning and Marketing Laboratory, Signalling and Transport Information Technology Division

A system to mitigate disasters due to localized heavy rain has been newly developed to improve railway operational safety. The developed system contains five components: (1) downloading of precipitation forecast data taking into consideration weather radar data, (2) runoff and inundation analysis, (3) large-scale landslide analysis, (4) train operation analysis to prevent trains from approaching inundated areas or areas affected by large-scale landslides, and (5) output mapping using a GIS. This system provides the railway engineers with a time-dependent hazard map and train operating information ahead of a disaster, and enables them to make a decision on when and where they should stop and resume train operations.

Keywords: localized heavy rain, disaster mitigation, inundation, large-scale landslide, train operation

1. Introduction

Localized heavy rain causes flooding and landslides, which threaten railway operations with disaster. To mitigate heavy rain related disasters, train companies in Japan usually operate trains in the light of rain amount measured by rain gauges installed along their railway lines. For example, if a measured value exceeds a regulation threshold value, the train company will decide to cease train operations. This type of operation control is quite effective, and severe incidents have drastically decreased. However, some outstanding issues remain to be solved to further improve safety. For example, a rain gauge may miss a localized cumulonimbus-induced heavy downpour because it covers a horizontal area of less than several kilometers [1] which is smaller than the intervals at which rain gauges are installed. In addition, the control system may not be effective in the case of debris flow triggered by a large-scale landslide that has occurred far away from the railway line, because the relevant rain gauges are only installed adjacent to tracks. Another possible scenario is that a train that has already been stopped at a station because of traffic control may subsequently be affected by flooding due to subsequent rain. One solution to avoid such situations is to stop trains at a station that is completely outside the potentially affected zone based on an issued flood hazard map, however, this does not solve the problem that in some cases there is simply not enough time to avoid flooding because the cumulonimbus develop too rapidly, or the rain is heavier than assumed in the issued hazard map.

It is hoped that mesh data for precipitation obtained by meteorological radar will enable railway engineers not to miss a localized downpour (Fig. 1). Real-time disaster prediction, based on precipitation forecast data obtained by numerical weather simulation, makes it possible to stop a train outside a hazardous area before a disaster occurs. Then, predictions indicating that the hazard has subsided after the heavy rain has stopped, makes it possible to decide when and where inspections should be carried out to enable train operations to resume, which shortens the time of the disruption.

A new system was therefore developed, entitled the heavy rainfall-induced disaster-mitigation system [2]. The developed system analyzes runoff and flooding, and large-scale landslide in the light of precipitation forecast data provided by a third party, and then analyzes train operations to prevent trains from entering areas affected by flooding and large-scale landslides. This system was designed for railway companies to be able to use in future.

Fig. 1 A future vision of train operations based on meteorological radar data
2. Configuration of the heavy rain-induced disaster-mitigation system

2.1 Process flow

The process flow of the heavy rainfall-induced disaster-mitigation system is shown in Fig. 2. Firstly, the precipitation forecast data is downloaded from a third party. Secondly, a runoff and inundation analysis is made using the precipitation forecast data, which gives an inundation depth. Areas given an inundation depth in excess of a threshold value are defined as the area affected by flooding.

In parallel, rain indices, such as hourly precipitation and continuous precipitation, are calculated from the precipitation forecast data. If the rain indices exceed given thresholds, then a large-scale landslide is judged to occur, and the surrounding area is defined as the area affected by the large-scale landslide.

Finally, an analysis of train operations is conducted in order to identify recommended stopping stations for all the trains, to avoid them entering the affected area. These outputs are mapped on a geographic information system (GIS), and viewed via user terminals.

Fig. 2 The process flow of the heavy rainfall-induced disaster-mitigation system

2.2 Forecast precipitation data

The precipitation forecast data for this research was provided by the National Research Institute for Earth Science and Disaster Resilience (NIED), Japan. Forecasts were obtained by blending high-resolution precipitation nowcasts from the Japan Meteorological Agency [3] and the calculated results of numerical weather simulations which the observed weather radar data assimilated to [4].

The spatial resolution of precipitation forecast data by NIED was 0.007 deg. in both latitudinal and longitudinal directions, corresponding to 630 m along the latitude and 780 m along the longitude in Tokyo, Japan.

The temporal resolution was one minute. For example, the forecast precipitation at 10:03 was the rain that fell in one minute from 10:02 to 10:03. Data was updated approximately every 10 minutes.

Forecasts were made for the following two hours. Although the behavior of cumulonimbus that have already appeared can be predicted with some degree of accuracy, predicting where and when cumulonimbi are likely to appear before they have formed, is still being researched. Furthermore, the lifespan of a cumulonimbus is generally considered to be approximately one hour. As such, rainfall volumes can only be predicted accurately for up to a maximum of one hour.

Nevertheless, the purpose of this research was to build a system with improved forecasting technology, and therefore two hours of data were provided by NIED.

In the new system, the precipitation forecast data was downloaded with user certification from the data server administrated by NIED every 10 minutes corresponding to the update period.

2.3 Runoff and flooding analysis

Runoff and flooding around tracks were analyzed in the light of the precipitation forecast data. In this study, a runoff and flooding analysis method [5] was applied to a watershed in Tokyo, Japan: the distribution model was applied to the surface runoff of rain into a river, and the unsteady flow analysis was applied to the river flow and the surface flow of the flood water [5].

The spatial resolution of the runoff and flooding analysis was 0.75 sec. in the latitudinal direction and 1.125 sec. in the longitudinal direction, corresponding to about 25 m in both the latitudinal and longitudinal direction in Tokyo, Japan, with a temporal resolution of 10 minutes. Generally, the finer the spatial resolution, the longer the calculation time. The flooding area obtained through analysis can reproduce the flooding hazard map published by the local government, on condition that the spatial resolution is below 25 m. Therefore, in order to reduce the calculation time, spatial resolution was set to around 25 m.

If the calculated inundation depth of the mesh is deeper than the threshold value, the mesh is classified as part of the area affected by flooding. Meshes corresponding to viaducts or embankments are excluded from the affected area however, because flooding over tracks on these structures would not occur. From the results of this analysis, the position of the affected area and time of flooding can be obtained.

2.4 Rain indices calculation

Rain indices for large-scale landslide analyses were calculated from the precipitation forecast data (Fig. 3). The same spatial resolutions were used for the rain indices as for the precipitation forecast data.

Hourly precipitation was defined as the cumulative precipitation based on forecast data for the previous hour. For example, the hourly precipitation at 10:40 would be...
the sum of forecast precipitation data from 9:41 to 10:40. Continuous precipitation was defined as cumulative forecast precipitation data since rainfall began. Therefore, if the precipitation forecast data is zero for the period \( T \), continuous precipitation is reset to zero. The period \( T \) was set to the same value used in the large-scale landslide analysis in the following section.

### 2.5 Large-scale landslide analysis

Large-scale landslide analyses are carried out in two steps: pre-analysis and system operation.

In the pre-analysis step, first, potential large-scale landslide locations are extracted by interpreting the terrain from a fine resolution 1:5,000-scale map using a one-meter mesh digital elevation model [6] and by ground survey (Fig. 4). Secondly, the potential landslide mass volume is estimated from the relation between the landslide mass volume and its area obtained from a synthetic analysis of past large-scale landslide cases [7]. Thirdly, the potential reach of a debris flow is analyzed by particle method [8] into which the potential area and estimated volume have been entered (Fig. 4). The results are registered into the database.

In the system operation step, the rain indices are compared to the thresholds set by the railway companies reflecting the position of their tracks. Then, the following past records can be referred to: hourly precipitation \( R_h \) and continuous precipitation \( R_c \) of past large-scale landslide cases reported as

\[
R_h \geq 50 \text{ mm} \quad \text{or} \quad R_c \geq 400 \text{ mm} \quad (1)
\]

or

\[
R_c \geq 500 \text{ mm} \quad (2)
\]

where the period \( T \) for calculation of \( R_c \) is 24 hours [7]. If the rain indices exceed the thresholds, the potential reach area of the debris flow is read from the database and is regarded as the area affected by the large-scale landslide. This analysis therefore makes it possible to predict the time of and the area likely to be affected by the large-scale landslide.

### 2.6 Train operation analysis

Train operation analyses to prevent train from entering areas potentially affected by flooding or large-scale landslides are carried out on the basis of predictions described in sections 2.3 and 2.5. If the prediction shows that a train can pass through a potentially affected area before the landslide or flooding occurs, it is permitted to enter the predicted affected area. Railway companies can decide on the optimal position to stop their trains based on the following three scenarios (Fig. 5) [9]:

I. Trains stop in sequence at stations before the affected area.

II. If the affected area appears likely to widen beyond the initial prediction, trains can be stopped at stations even further away from the affected area.

III. In order to maintain the same headway between trains after service resumes, trains can be stopped at stations spaced at suitable intervals.

Should all station platforms already be occupied by other trains, the system then searches level crossings between as a back-up stopping position to facilitate passenger evacuation to safety by road, acknowledging that doing this may block road traffic.

The mesh size of the train operation analysis is either one, four, eight, 16 or 24 times larger than that for the run-off and flooding analysis. If the new mesh includes at least one affected mesh from the original resolution data it is classified as part of the affected area (Fig. 6).

### 2.7 Display of results

The output from the system is viewed by the user via a user terminal over internet. There are two windows: one

![Fig. 4](image1)  An example of area identified during pre-analysis as being potentially affected by a large-scale landslide and potential reach of the debris flow

![Fig. 5](image2)  Strategies to find optimal position for stopping trains [9]

![Fig. 6](image3)  Reduction of mesh resolution of the affected area
showing the position of the stopped trains, the other showing precipitation data.

2.7.1 Window showing position of stopped trains

A screen shot of the window showing the position of stopped trains is shown in Fig. 7. Normally, the actual position of trains is mapped by GIS. If flooding or a large-scale landslide are predicted, the map also shows time remaining to the predicted event, the affected area, and the proposed stopping positions. The map also shows evacuation routes for passengers.

2.7.2 Precipitation data window

The predicted precipitation data provided by NIED: hourly precipitation, continuous precipitation, inundation depth, and information about large-scale landslides, are all mapped according to the user settings (Fig. 8(A)). In addition, graphical representations can be generated to show the relationship between hourly precipitation and continuous precipitation, and between time and the rain indices (Fig. 8(B)).

For large-scale landslides, the map shows the area potentially affected, the potential reach of debris flow and the affected area.

2.7.3 Time required for calculation

The time to process one cycle of the heavy rainfall-induced disaster-mitigation system was adjusted to be within 10 minutes as shown in Fig. 9, to coincide with the NIED update interval for predicted precipitation data. The time consumed for each process in the system was as follows (Fig. 9):

Download, less than one minute
Runoff and flooding analysis, less than three minutes
Calculation of rain indices, less than one minute
Analysis of large-scale landslide, less than one minute
Train operation analysis, less than two minutes

The total time from when prediction of precipitation commences until the calculation process of the heavy rainfall-induced disaster-mitigation system is complete is under 20 minutes: under 10 minutes to predict precipitation using the latest observed data from the meteorological radar, and under 10 minutes for one operating cycle of the system. Given that the target prediction period for forecasting precipitation was the following two hours, a user would obtain a forecast for the next one hour and forty minutes.

3. Test run of the heavy rainfall-induced disaster-mitigation system on flooding forecasts

3.1 Conditions of the test run

A test run of the developed system was conducted to forecast flooding for a railway line in Tokyo, Japan. The test ran between June, 2017 and March, 2018.

The study area for runoff and flooding analysis was a
catchment area of a river crossing the railway. Rain data was inputted for a total of four hours: two hours prior to the reference start time, and two after. This was because according to prior runoff and flooding analyses, surface water took two hours to flow out of the target area.

The mesh size of the train operation analysis was set to 100 m, i.e. four times larger than the mesh for the runoff and inundation analysis. Option one was selected for train operation (I), as shown in Fig. 5.

3.2 Results of the test run

3.2.1 Overview of the result

The system completed its cycle successfully within the expected time shown in Fig. 9. The time required for the system to produce an output was on average 15 minutes from when the NIED precipitation prediction began. However, the analysis output time depended on the actual rainfall.

3.2.2 An example of the test run: heavy downpour on August 19th, 2017

On August 19th, 2017, Tokyo was struck with a violent downpour which led to flooding and slope failure [10]. According to the precipitation analyzed by the Japan Meteorological Agency radar AMeDAS [10], 70 mm of rain fell between 16:00 and 17:00. Meteorological Agency issued a heavy rain alert (inundation) at 16:28 and a flood alert at 16:55 for some areas in Tokyo, which were maintained until 22:13 [10]. This rain brought inundation above the floor level.

The new system successfully predicted the flooding: At 16:42, the forecast precipitation data from 16:30 to 18:30 was downloaded from NIED. The system completed the analysis of this data by 16:45. This result predicted flooding of a depth of 40cm would occur at 17:00. The position of the predicted inundation was at the outlet of a river tunnel under the road where the road crossed the river. The time from the prediction to the event, i.e. the lead time in this case, was 15 minutes. After then, the system carried out an analysis every ten minutes, and finally predicted that the inundation would occur between 17:00 and 20:30.

No detailed comparison was made between the predicted and actual recorded time and location of flooding because of a lack of observed data. Ability to evaluate the accuracy of the developed system is therefore something that still requires further work. However, there were no reports of damage to tracks reported by the railway company.

3.2.3 Reproduce run for the heavy downpour on August 19th, 2017

A second test to reproduce the results was conducted on August 19th 2017, because the developed system overwrites its output rather than saves it.

The input data was predicted precipitation data from 16:40 to 18:40 provided by NIED (Fig. 10 (A)). The forecast flooding depth after analysis using the developed system is shown in Fig. 10 (B). Flooding was predicted along the river. When looking only at flooding that would affect the railways, potential inundations were predicted in two positions along the line. One was at the foot of a railway embankment, where flooding was predicted due to the accumulation of excess water from the river. The other was near a pond, where flooding was predicted to occur because of the rising water level in the pond.

The result of the train operation analysis is shown in Fig. 10 (C). The predicted inundation area at the bottom of the embankment was not counted within the affected area because water was not expected to submerge the track. The area near the pond however was classified in area likely to be affected by flooding. As the result of the train operation analysis, the train running from Station D to Station A was instructed to stop at Station D to avoid entering the affected area.

4. Conclusion

A system to mitigate the disasters due to localized heavy rain has been developed to improve railway safety. The system works by downloading forecast precipitation data from a third party, and then carrying out runoff and flooding analyses, large-scale landslide analyses, and train operation analyses to prevent trains from entering affected areas. During the test runs, the system successfully provided information to inform train operations with a one and 2/3 hours lead, updated every 10 minutes. Future work will concentrate on evaluation and improving the accuracy of the system’s output.

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Authors

Takuya URAKOSHI
Senior Researcher, Tunnel Engineering, Structures Technology Division  
Research Areas: Ground Water, Engineering Geology

Takeshi KAWAGOE, Ph.D.
Senior Chief Researcher, Head of Geology Laboratory, Disaster Prevention Technology Division  
Research Areas: Civil Engineering Geology, Hydrogeology, Track Ballast

Satoshi WATANABE
Senior Researcher, Geo-hazard and Risk Mitigation Laboratory, Disaster Prevention Technology Division  
Research Areas: Rainfall Disaster

Naoya OZAKI, Ph.D.
Senior Researcher, Transport Planning and Marketing Laboratory, Signalling and Transport Information Technology Division  
Research Areas: Transport Behavior Analysis, Operations Research