Problems Related to and Approaches for Developing Countermeasures against Natural Disasters

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It is generally said that climate change is influencing the activity range and intensity of rain. Accordingly, engineers in charge of disaster prevention must plan measures in consideration of future weather conditions. This paper is based on one of the scenarios presented in the 5th AR of the IPCC and compares current data for hourly rainfall with predicted figures. The comparison between current and predicted weather conditions confirms the need to develop disaster prevention technologies as a countermeasure to future extreme weather conditions. R.T.R.I. is therefore developing a dynamic hazard mapping system. This system maps floods, large-scale slope collapse and tornados, and displays the risk of their occurrence over time on a monitor. The map also indicates the best places for trains to stop based on hazard simulation, and routes to shelter for passengers.

Keywords: natural hazard, climate change, localized downpour, flooding, slope collapse, tornado, hazard map.

1. Introduction

Japan is located in a mid-latitude region and is thus very vulnerable to monsoons. Japan is also located on the edge of four tectonic plates, exposing it to a range of natural hazards including typhoons, earthquakes and volcanic eruptions. Factors for potential disasters have begun to change over recent years. For example, rainfall patterns have changed due to climate change. The number of localized downpours with unprecedented hourly precipitation volumes has increased, causing landslide disasters on a massive scale. As for earthquakes, the 2011 off the Pacific coast of Tohoku Earthquake highlighted the need to review the extent of expected damage caused by major earthquakes that are expected to occur in the near future, such as another Nankai earthquake and an earthquake centered directly under the Tokyo region, and to enhance the resilience of urban infrastructures given the likelihood that conventional design limits will be exceeded by future external forces.

This paper attempts to clarify issues that must be tackled when developing countermeasures against intensifying natural forces especially rainfall and gusts of wind, and presents some of the related efforts being made at RTRI.

2. Expected rainfall in the future

The design process for civil engineering structures involves verification of their ability to withstand external forces they are expected to face. This also applies to the development of countermeasures against natural hazards. Countermeasures must be evaluated for their effectiveness against anticipated natural forces. With the above background in mind, attempts were made to predict rainfall at the end of the 21st century using existing analytical data.

The prediction was based on analytical results of the RCP (Representative Concentration Pathway) 8.5 scenario from the regional climate model (MRI-NHRCM20) stored in the Inter-disciplinary Program on Data Integration and Analysis System (DIAS) [1]. Of the scenarios presented in the Fifth Assessment Report (AR5) produced by the Intergovernmental Panel on Climate Change (IPCC) [2], RCP 8.5 uses the highest greenhouse gas emissions forecast for the year 2100, regarded as the most extreme global warming forecast. The analytical results were corrected using data measured during a 20-year period from 1984 through 2004 and put through bias correction to predict rainfall over a 20-year period from 2080 through 2100 for each point on a 1 km grid. Fig. 1 is an example which compares the distribution of maximum hourly rainfall in a 100 km radius of Tokyo for the two 20-year periods considered, i.e. 1984-2004 and 2080-2100. While a relatively high number of points have a maximum hourly rainfall of around 35 mm/h to 50 mm/h in the past 20-year period considered, most of the region is shown with a maximum hourly rainfall of 50 mm/h to 80 mm/h over the future 20-year span. The predicted scenario also shows that the area with a rainfall exceeding 100 mm/h is likely to expand to the mountains in the north.

Figure 2 shows time series of maximum hourly rainfall predicted for the future 20-year period in Fig. 1. A rain event starting at around 23:00 on August 31, 2094 is
predicted to reach a maximum hourly rainfall of 180 mm/h at 01:00 on September 1 leading to a cumulative rainfall of 953 mm by the end of September 2. Among the massive disasters in recent years caused by record-breaking downpours was the heavy-rain disaster in northern Kyushu in 2012. In that event, AMeDAS data for Aso Otohime, where the heaviest rain was observed, shows the maximum hourly rainfall reached 106 mm/h and cumulative rainfall was 507.5 mm. That together with these predictions indicates that both short-time intensive rainfall and cumulative rainfall around the end of this century may double, compared with values recorded in the heavy rain disaster in northern Kyushu.

As mentioned earlier, the results of the prediction shown above are based on a worst case scenario from the IPCC. The possibility of such rainfall occurring in the future is expected to be reasonably reduced by ongoing global efforts to tackle global warming. That said, these predictions deserve to be included in anticipated rainfall scenarios, as part of rain disaster prevention for the future.

3. Disaster prevention based on future predicted climate

The type of disaster expected to result from extremely heavy rain as mentioned above includes overflowing of rivers and channels primarily in urban areas and resultant flooding. Current railway drainage is designed on the basis of past rainfall data. Ordinary railway drainage is designed to evacuate heavy rainfall with an occurrence probability of once in five years, even if it continues for ten minutes. Current drainage systems are therefore very likely to overflow in the type of heavy rain shown in Fig. 2. Road drainage is often designed for heavy rain with an occurrence probability of once in three years, making it equally likely to overflow in the type of heavy rain predicted in the future. Rivers can also overflow depending on the duration of the rain shower. All this indicates that the overflow from roads and rivers could end up flowing onto railways and adjoining facilities.

Earth and rock avalanches are another form of disaster arising from localized downpours. The massive damage caused by an avalanche in Hiroshima in August 2014 is still fresh in our memory. This disaster was just one of several that were triggered by localized downpours from a linear precipitation zone, and belongs to a large-scale disaster mode that can be predicted from localized downpours. Weather conditions that bring this kind of heavy rain can also cause wind gusts and tornadoes.

Given that these disasters are caused by rapidly changing weather conditions, it is difficult to predict when and where they will occur. In addition, the external forces underlying such disasters are too great to be controlled by physical countermeasures. These are two major challenges faced by any prevention effort. In other words, preventing these disasters completely with today’s technology would be difficult, and if at all possible would involve tremendous cost. As such, if total prevention is not possible, then should such an event occur it is crucial to at least minimize damage. Efforts are thus being made to develop real-time hazard mapping as an effective means to achieve this goal.

4. Real-time hazard mapping

Meeting the challenge described above requires a technology capable of predicting rapidly changing weather conditions and another technology to evaluate resulting damage based on the prediction. This section discusses the development of a real-time dynamic hazard mapping technology aimed at overflowing rivers, flooding, large-scale slope collapse and wind gusts.

4.1 Overflow and flood hazards

Many railway systems in Japan are designed to actively intervene in railway operations in case of heavy rain events. When potentially hazardous rainfall levels are observed, train services are suspended as part of this active intervention. In the case of sudden unprecedented heavy rain as described earlier, it is important to select an appropriate place to take refuge. In emergencies where stations are inundated, trains must be guided to an appropriate location to allow passengers to find shelter. Conventional flood hazard maps can be used for this. Many flood hazard maps, mainly for urban areas, already exist and are publicly available. These maps generally show areas vulnerable to flooding and the maximum water depths based on past data. These “static” hazard maps are an effective tool for identifying areas susceptible to heavy rain events so that appropriate action can be taken, but are not useful in a rapidly changing environment with sudden unprecedented downpours. In addition, conventional hazard maps do not reflect open cut or elevated railway structures. With those characteristics described above, conventional maps do not provide a clear picture of elements that could affect the early resumption of train operations, such as whether vehicles are submerged or not. In addition, conventional hazard maps do not reflect the capacity of drainage facilities and the actual extent of flooding which can be worse than shown. For that reason, these maps cannot be used as they currently are to ensure reliable transport.

Given the above, a method is being developed to accurately and successively assess flood hazards near permanent ways by using outsourced weather forecasts.

Figure 3 shows an example of assessment results. The
red line running from left to right is a watercourse. A track runs parallel to the watercourse. A portion of the track and some streets are shown inundated with overflow from the watercourse. From the analytical results, it is possible to know the extent of the flooding and the different depths of overflow shown with corresponding shades. An optimized analytical model is being developed to provide 2-hour head time rain forecasts at 10-minute intervals. This work also clarifies the relationship between the mesh size required for the analysis and the accuracy of the analysis.

According to plan, a prototypal system was developed by the end of FY 2016 and was tested in FY 2017 for accuracy and any practical or functional issues. To improve the accuracy of the system, assessment is underway for possible coordination with research partners who are working on a method for successively analyzing the inundation of road facilities.

4.2 Large-scale slope collapse hazards

A large-scale avalanche of earth and rocks similar to the one in Hiroshima could cause damage spreading over an extensive area. As with flooding, it is crucial to be able to identify appropriate places of refuge. With that in mind, work is being carried out to identify areas susceptible to large-scale slope collapse, thresholds for rainfall that could trigger a collapse and to develop hazard mapping technology that shows the entire areas that would be stricken as a result of rainfall exceeding the threshold.

In developing a method for selecting areas susceptible to large-scale slope collapse, topographical features of specific locations and areas surrounding past slope collapses were defined and topographical and geological details collected in field surveys were added to this data to identify the topographical conditions common to those sites and areas. Figure 4 shows examples of the topographical conditions identified for detecting susceptible areas. Using numerical topographic and other data, areas meeting those conditions were extracted to identify susceptible areas. Past large-scale slope collapses were examined, and Fig. 5 summarizes the relationship between the area of the slope that collapsed and the volume of earth displaced in the flow. Currently, a method is being developed to determine the expected extent of a large-scale slope collapse based on the topographical features of the area, the volume of earth displaced in the flow using Figure 5, to determine the area that would be ultimately covered by the flow using a particle method and assess risk to railway lines. At the same time, the mechanisms leading to large-scale slope collapse are being clarified to improve the accuracy of hazard mapping.

4.3 Wind gust hazards

Wind gusts and tornadoes are weather phenomena that hit highly localized areas and evolve rapidly. They are therefore by definition difficult to define and predict, and if they are extreme, can cause extensive damage. As such, technologies are being developed that are capable of detecting emerging wind gusts and tornadoes to assess their impact on railways.

Ground-based weather radars are now widely used to determine the status of rainfall. Weather radar antennae emit radio waves to rain clouds and measure the time for waves to return after bouncing off cloud droplets along with the strength of the radio waves on their return in order to determine the distance to the clouds and the intensity of the rain. More often than not, there is no rainfall on the ground when gusts are generated. While it is considered difficult to detect gusts of wind not accompanied by rain using radars, it appears possible to detect a rapidly developing cumulonimbus, which tends to be accompanied by gusts, using a radar. Based on the above, to be able to detect gusts that are generated near the ground using radars, it is necessary to clarify the relationship between meteorological conditions at high altitudes that are detectable by radars and the weather conditions near the ground that can directly cause damage. To clarify that relationship, numerical simulation is being made to establish three-
dimensional analysis of meteorological fields that generate gusts. Figure 6 shows an analytical example of meteorological conditions at median altitudes between the ground and higher altitudes being observed by radars for emerging tornadoes. The analysis shows vortices of clouds at upper levels moving while developing, although several kilometers off an area on the ground in which resultant damage was confirmed. Studies of these analyses will be pursued to ultimately develop a radar-based wind gust detection method.

4.4 Passenger evacuation based on assessment of hazards

By collecting and utilizing the results of flood, large-scale slope collapse and wind gust hazard assessments similar to those described above, appropriate actions can be taken to deal with rapid changes in weather and thereby help reduce the extent of resultant damage. Attempts are underway to develop a system for using the results of such assessments solely for the purpose of mitigating damage to railways.

Figure 7 shows an example of screenshots that would be displayed by this new system. The figure shows a possible flooding scenario. Based on the input of information including time-series hazard data, geographical data including refuges near tracks and road information to reach these evacuation spots, track information including points where trains can stop and train schedules including freight and deadhead trains, the system determines train stopping points and evacuation routes and delivers analytical results similar to the those shown on the screen in Fig. 7. To compute and come up with results, the system uses mathematical optimization technology. Under a number of expected constraints such as the position and direction of travel of trains at different points in time relative to the location of stricken areas, the system aims to compute optimum solutions to two objective functions, namely, minimization of traffic disruption and maximization of total distance between the affected trains and the hazard location. Once this analysis complete, the system can be used to show optimum places of refuge.

5. Conclusion

This paper outlined RTRI’s efforts to develop real-time hazard mapping technology to help prevent damage from intensifying rainfall and wind gusts in the context of the ongoing climate change. R&D work is also underway at RTRI to minimize the extent of damage from earthquakes and facilitate restoration. Once completed, these technologies will be proposed as countermeasures against possible damage from earthquakes, heavy rain events and gusts to help improve the resilience of railway facilities to natural hazards. Going forward, the technologies being developed will be validated followed by further work to adapt them for practical implementation.

Note: Some of the activities covered in this paper are being conducted under the SIP (Cross-Ministerial Strategic Innovation Promotion Program) “Disaster prevention and mitigation technology for improved resilience” (managed by JST) initiatives, organized by the Council for Science, Technology and Innovation.

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