DEVELOPMENT AND DEPLOYMENT OF EARLY WARNING SYSTEM FOR HIGHWAY SAFETY UNDER EXTREME NATURAL

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ABSTRACT**:** Recently, highway safety control under extreme natural hazards in Taiwan has faced critical challenges because of latest extreme climates. In an effort to develop an efficient early warning system for highway safety, the authors have developed an early warning method based on disastrous rainfall indices and rainfall patterns. Fundamental concept of such a methodology is to reform risk prediction and risk management from passive mode to active mode to acquire more time for mitigation mobilization and safety evacuation. The threshold rainfall indices are used to characterize triggering mechanisms of rainfall-induced natural hazards and further applied as the early warning criteria for highway safety control. In this paper, development of such early warning system for highway safety control is introduced in detail. Deployments of the proposed rainfall pattern analysis model in real storm events are also presented to verify feasibility of the developed system as well as sharing Taiwan’s experience in hazard mitigation. Progress of this study is hoped to improve hazard prevention and safety control for highway facilities during critical natural hazards.

KEYWORDS: rain fall pattern analysis, early warning, risk management, highway safety control

1. INTRODUCTION

Recently, highway safety control under extreme natural hazards in Taiwan has faced critical challenges because of latest extreme climates. Since 2009, Typhoon Morakot and many other storms afterward that invaded Taiwan had caused severe disasters such as landslides, debris flows, and floods. These disasters had damaged transportation infrastructures seriously and caused influential interruptions of emergency communications and injury relieves. The overwhelming rainfall amounts and intensities brought by these critical events have been recognized as the major triggering factors to these natural disasters. How to develop an efficient early warning system for highway safety has become the most important task of the highway authority (Lee and Towhata, 2010).

In an effort to fulfill such a task, the authors have developed an early warning method based on disastrous rainfall indices and rainfall patterns. Fundamental concept of such a methodology is to reform risk prediction and risk management from passive mode to active mode to acquire more time for mitigation mobilization and safety evacuation. In this study, the authors have collected detailed rainfall information at representative catchments from major hazard events in past ten years. Historical damage data of highway facilities was also collected from engineering reports. Pattern recognition analysis was first conducted to identify high risk precipitation indices- threshold rainfall intensities and rainfall amounts, that would cause slope failures and related debris flows. Combinations of these threshold rainfall indices could then be adapted to characterize triggering mechanisms of rainfall-induced natural hazards. They could possibly provide an efficient and accurate early warning framework by combining advanced real time weather prediction.

In this paper, development of such early warning system for highway safety control is introduced in detail. Deployments of the proposed early warning system in real storm events are also presented to verify feasibility of the developed system as well as sharing Taiwan's experience in hazard mitigation. Progress of this study is hoped to improve hazard prevention and safety control for highway facilities during critical natural hazards.

2. DEVELOPMENT OF EARLY WARNING SYSTEM

2.1 Watershed Management for Highway Bridges

The "Watershed Management" concept was developed by lessons learned from previous extreme rainfall induced hazards including the famous Typhoon Morakot. Principles of such a management method are to take advantages of spatial capacity of watershed from upstream to downstream. Instead of monitoring rainfall and flow condition at the bridge site, rainfall conditions at the selected control points in the upstream watersheds of the controlled bridges are systematically monitored. Critical rainfall indices of these control points defined based on historical hazard events including landslides, debris flows, and others are adapted for responding protocols. Active responding actions could be then mobilized in earlier stages according to mitigation preparations. The mitigation preparation program is divided into three levels- early warning, warning, and action. Threshold rainfall indices which outline the three mitigation preparation stages could be extrapolated based on the critical rainfall indices and characteristics of the watershed accordingly. The proposed watershed management method had been applied to 64 important bridge sites throughout major highways in Taiwan

2.2 Active Risk Management for Mountain Highways

Risk could be defined as the probabilities of failure and consequences caused by the failure of the protected objects under hazards. Concept of active risk management is to identify the potential risks and to monitor as well as equip high risk mountain highway sections. In an effort to install an active risk management system for mountain highway safety, following works had been taken:

1. High landslide potential sections of mountain highways were first identified by using historical hazard records,
2. Historical precipitation data were also analyzed to assess localized hazard triggering rainfall pattern, and,
3. Historical engineering data and retrofit cost were analyzed to evaluate possible consequences of mountain highway failure caused by landslides.

Threshold precipitation indices of rainfall induced hazards could be determined by summarizing analysis results of items 2 and 3 described above. With such risk identification process, active risk management could be applied to these high risk potential locations of mountain highways. Active responding actions could be mobilized in a much more efficient manner. Protocol of responding program is divided into early warning, warning, and action three levels, with according threshold rainfall indices.

Directorate General of Highways, DGH, has set up hazard control points according to the high risk potential locations with engineering and emergency recuse resources. In case of critical hazard events, emergency evacuation and responding retrofit could be quickly deployed. Such an active risk management process is aimed to have prompt mobilization for rescuing and restoring efforts.

2.3 Early Warning Scheme for Highway Hazard Mitigation

By combining the operation of both watershed management and active risk management, DGH have further improved its early warning scheme for highway hazard mitigation since 2010. Figure 1 shows the illustration example of active risk management based on accumulative rainfall. Figure 2 shows the schematic drawing of execution procedures of the improved early warning operation protocol. As defined in figures 1 and 2, precaution of the coming hazard would start 2 days before the forecasted attacking day (D-day) of the tropical storms or typhoons.

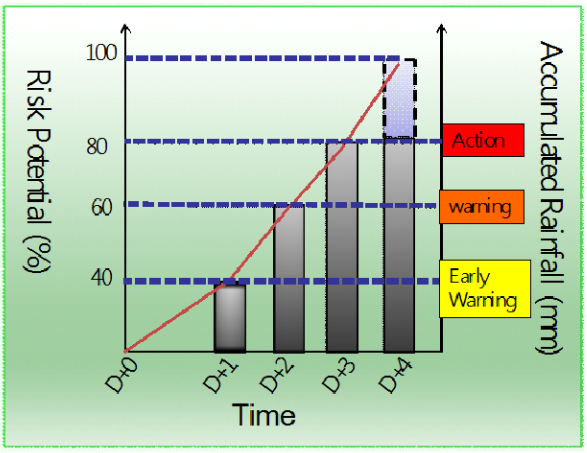


Figure 1 Example of active risk management based on accumulative rainfall.

Forecasted hazard scales, historical hazard information including rainfall and flood records, and damage data are firstly analyzed to determine early warning criteria. Hazard responding scheme could be then planned based on the analysis result including evacuation operation, control point installation, and deployment of joint forces including engineering resources, local government, police, and emergency medical resources. Preparation works would be carried on up to 4 hours prior to the attack of the hazard, with rising levels of preparation and mobilization efforts. At the same time, early warning information would be sent out via various medias including Local Broadcasting System, LBS, highway Changeable Message Signs, CMS, and forced mobile text messages to drivers and residents within or near the high risk potential highway sections.

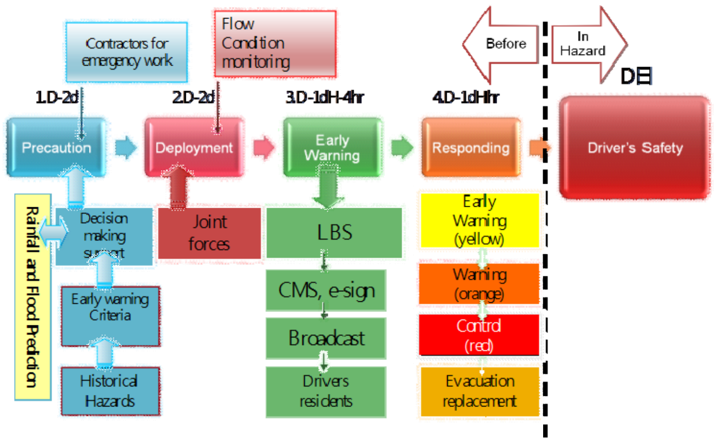


Figure 2 Execution flow chart of improved early warning operation protocol.

Once the hazard invaded, responding protocol described previously would then be executed to different levels of hazard situations accordingly. All stages of responding are judged based on the preset rainfall indices including 10min close watch ones. When the hazard condition reaches action level, traffic control including traffic closures would be activated and on-site vehicles would be guided to temporary shelters as well.

For short term weather forecast, the Center Weather Bureau under Ministry of Transportation and Communications has also set up the extreme weather simulating system, namely QPESUMS, in order to predict the critical weather condition within an hour to one minute time scale. The QPESUMS has great help to the improvement of the DGH early warning scheme.

3. RISK MANAGEMENT USING RAINFALL PATTERN ANALYSIS

3.1 Rainfall Pattern Analysis

In the first stage of the development of DGH early warning system, only accumulated rainfall was used as the hazard index to set up responding actions. However, it was found that both short term rainfall intensities and accumulated precipitation are very important rainfall indices to describe rainfall induced multi-hazards, including landslides, debris flows, and floods. The bi-axial rainfall pattern analysis was then introduced in an effort to further improve the early warning system. The bi-axial rainfall pattern analysis is to plot traces of short term rainfall intensities versus accumulated rainfalls. Figure 3 shows an example of converting timeline rainfall intensity and accumulated precipitation data, the hyetograph, into the bi-axial rainfall path. Such a path was also called “Snake Line.” As shown in Figure 3, this type of analysis would allow engineer to access characteristics of regional rainfall pattern and their correlation to rainfall induced hazards (Lee, 2011). For example, upstream catchment area would generally start with high rainfall intensities to cause landslides to occur. As the rainfall intensity stayed high enough to produce more landslides, increasing amount of the accumulated rainfall would then trigger the debris flows roaming down the watershed from upstream to downstream. In the case of extreme rainfall event, combination of debris piling up the riverbed and over scale accumulated precipitation would finally result in floods in the downstream area.

3.2 Use of Historical Hazard Data

DGH has collected extensive hazard data of highways in Taiwan since 1985 Typhoon Hebe. Such data include hazard types, scale of the failure, emergency mitigation efforts, and retrofit cost. Central Weather Bureau has also kept completed rainfall records since Typhoon Hebe. Extensive research efforts have been made by the authors to summarize historical hazard data and historical rainfall data based on the bi-axial rainfall pattern analyses for those high risk potential highway sections selected. Analysis result of such extensive data mining would provide important information on triggering mechanisms of rainfall induced hazard of the studied highway sections. Moreover, the proposed rainfall pattern analysis method is also capable of evaluating post-event hazards, i.e. landslides or debris flows occurred after rainfall stops under the condition when such hazard data is available.

4. CASE STUDY AND VERIFICATION

4.1 Lao-Nong River

Lao-Nong River was the most damaged area during Typhoon Morakot in 2009. Data of total 10 rainfall stations during Typhoon Morakot was collected to excise the proposed rainfall pattern analysis method. Table 1 summarizes basic information of the collected rainfall station including area of sub catchment area and area of landslides during Typhoon Morakot. Figure 4 shows the locations of the rainfall stations mapping with sub-watershed and landslides occurred during Typhoon Morakot. As shown in the figure, each rainfall station situates within a sub catchment of Ko-Ping River. Rainfall data including hourly intensities and accumulated rainfall was recorded during Typhoon Morakot (Lee, Wang, and Ishihara, 2011).

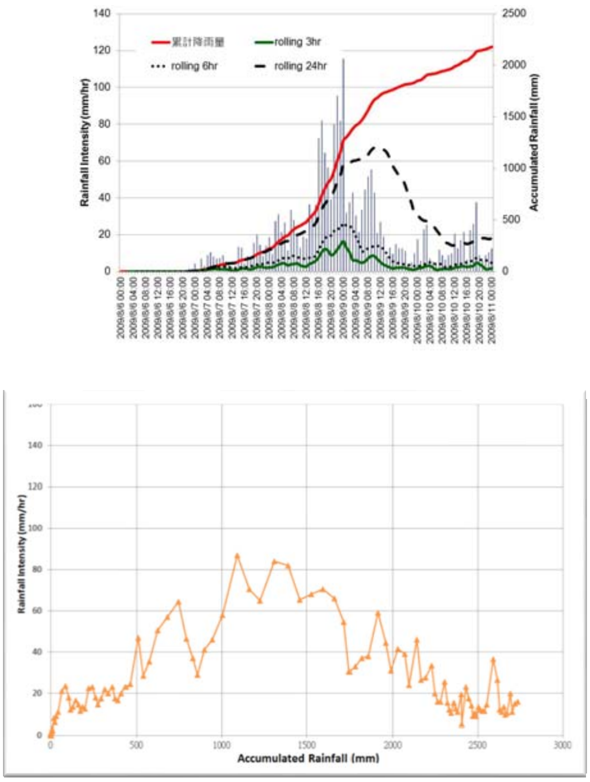


Figure 3 Example of bi-axial rainfall pattern analysis.

Table 1 Information of collected rainfall stations situated in Lao-Nong River catchment.

Station	No.	Stream Location	Catchment Area (m2)	Landslide Area (m2)
南天池	C1V190	ridge	7,387,043	448,620
梅山	C1V200	upstream	20,962,788	1,041,672
復興	C1V210	upstream	36,294,280	1,697,425
小關山	C1V220	upstream	18,034,990	983,301
高中	C1V230	upstream	30,419,845	3,568,920
新發	C1V240	upstream	50,933,628	3,731,716
溪南	C1V270	midstream	23,501,702	5,982,074
御油山	C1V300	midstream	25,376,376	967,403
吉東	C1V320	mainstream	--	--
大津	C1V340	mainstream	--	--

Figure 5 shows the Snake Line paths of three feature rainfall stations during Typhoon Morakot along Lao-Nong River from ridge CIV190 (天池), to upstream CIV230 (高中), and to downstream CIV340 (大津). As shown in the figure, downstream rainfall station, CIV340, first recorded peak rainfall intensity in the early stage of Typhoon Morakot; upstream rainfall stations quickly picked up the rainfall intensities and had accumulated dramatic precipitation. As described in previous paragraph, occurrences of large landslides or debris flows were also marked on the figure to identify possible incidence time of hazard events. As depicted in the figure, rainfall induced hazards started in under the conditions when rainfall intensity ran over 50mm/hr as well as accumulated rainfall reached 500mm, and had carried on throughout the event to cause serious damages to Lao-Nong River region. An exponential curve as indicated in the figure could then be drawn to define triggering threshold values of rainfall induced hazards of the studied area. This critical curve has trend from high intensity and low accumulated rainfall to low intensity and large accumulated rainfall. This trend agrees well to field observation that landslides first started when rainfall intensities reach the threshold values, and then further spread to wider area forming into debris flows while precipitation accumulated. The selected rainfall indices are proved to be able to cover development of multi-hazards during an extreme weather event as Typhoon Morakot.

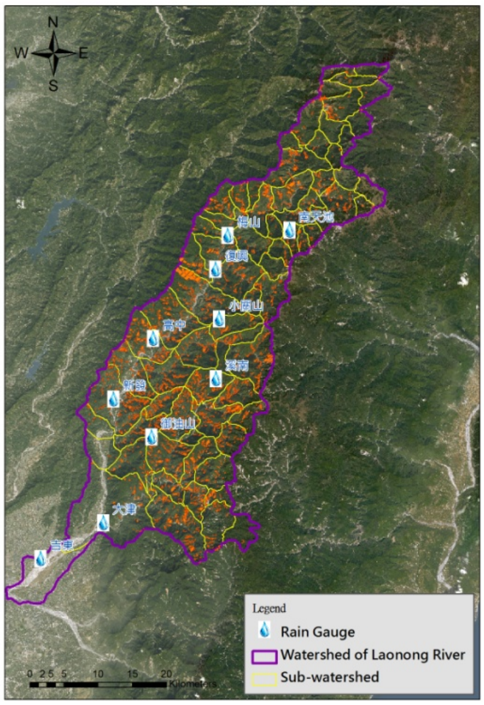


Figure 4 Locations and catchments of Lao-Nong River.

4.2 SuHwa Highway

SuHwa highway is the major passage connecting north to east coast of Taiwan. Due to the progressive geological activities occurred in the region, SuHwa highway has been suffering from natural hazards including landslides, rock falls, and debris flows, caused by heavy rainfalls and earthquakes (Figure 6).

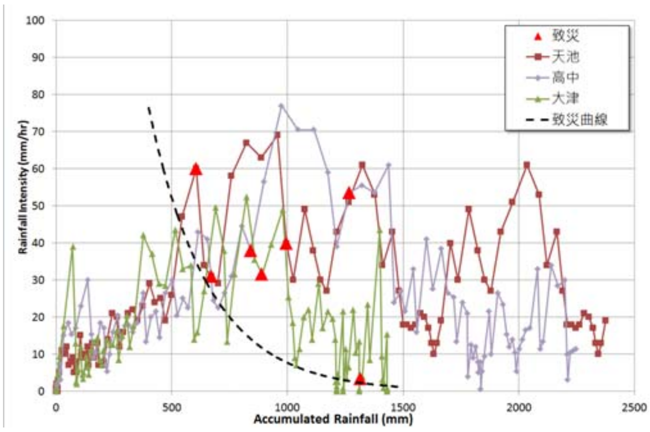


Figure 5 Rainfall pattern analysis of Lao-Nong River.

Figure 6 SuHwa highway damages caused by Typhoon Nalgae in 2011.

Rainfall and hazard data of five heavy rainfall events during the period in between 2010 to 2012 was collected for conducting verification case study of the proposed rainfall pattern analysis method. Figure 7 shows the analyzed section of SuHwa highway and the rainfall station location where rainfall data were recorded. In an effort to examine the triggering mechanism of the post event hazards, 3 hours rolling rainfall intensities, 6 hours rolling rainfall intensities, 12 hours rainfall rolling intensities, and 24 hours rainfall rolling intensities were calculated and analyzed as the short term rainfall intensities of the “Snake Line” analysis model. This type of analyses would allow us to investigate the time lag effects on landslides triggered by groundwater intrusion. Figure 8 shows the analysis results based on different time rolling rainfall intensities. As shown in Figure 8, 6 hours rolling rainfall intensities were identified as the best indices to describe triggering mechanism of landslide hazards occurred on SuHwa highway. Most of the recorded hazards were initiated at the peaks of 6 hours rolling rainfall intensities versus according accumulated precipitations. It was also observed in the 24 hours rolling intensities analysis that, for rainfall event with low rainfall intensities yet long duration, landslides could occur with time lag as long as 24 hours after the event. This information became very important for safety watch of traffic opened after the rainfall events.

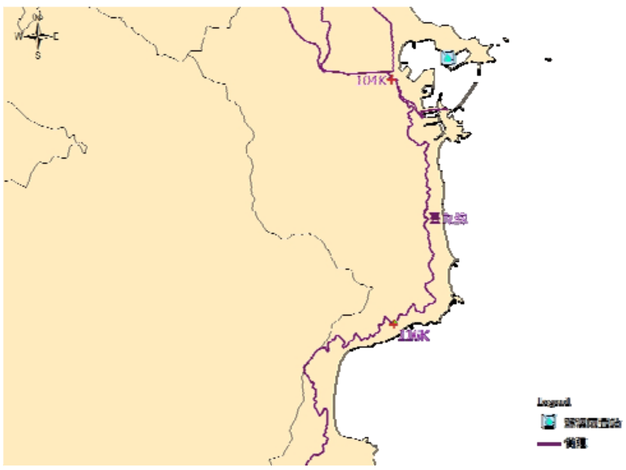
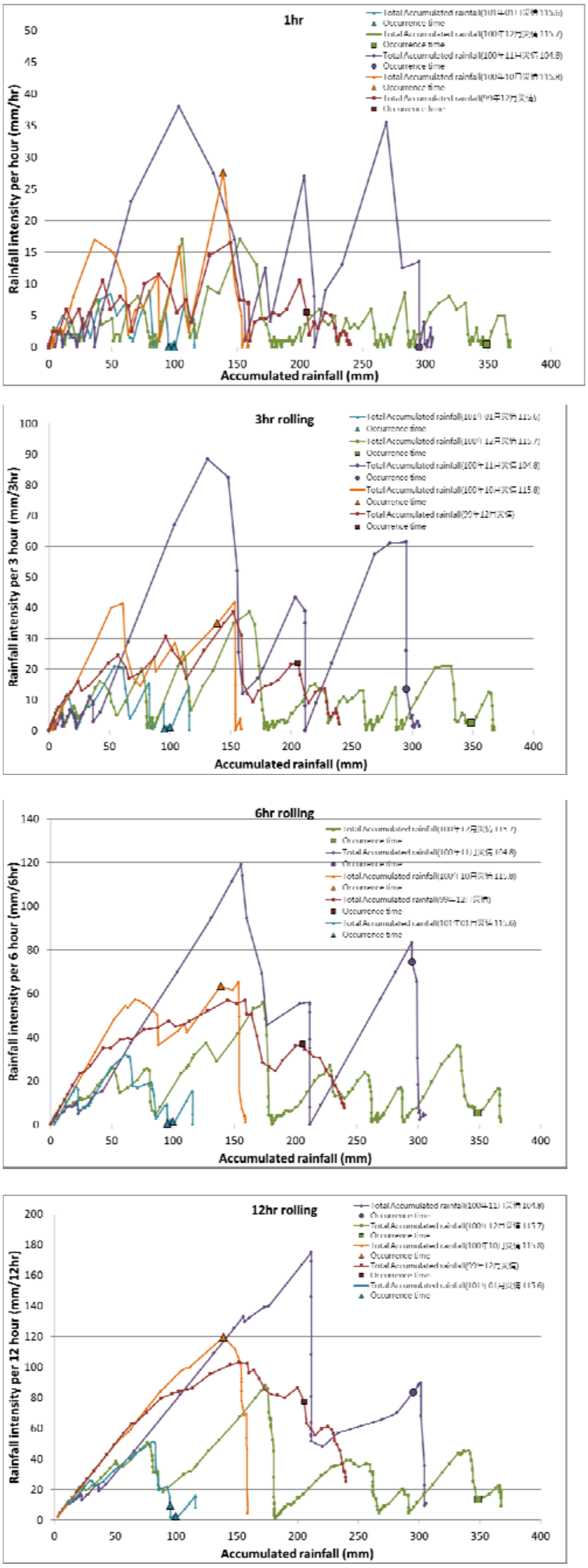


Figure 7 Analyzed section of SuHwa highway and location of rainfall station.



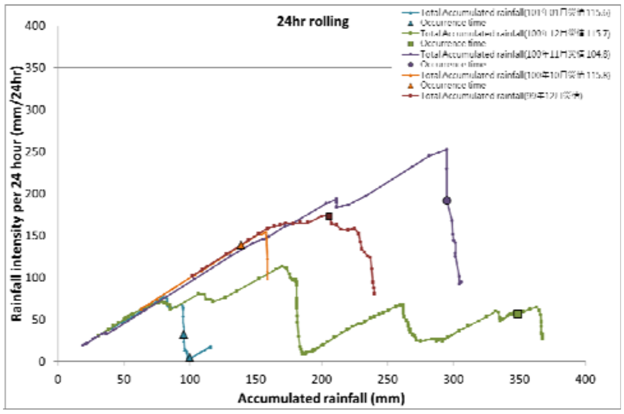


Figure 8 Analysis results of "Snake Line" model based on different time rolling rainfall intensities

5. PRACTICES AND CONCLUSIONS

In 2011, there were 5 extreme heavy rainfall events attacking Taiwan including Typhoon Sanda in May , Typhoon Ma-on in July , Typhoon Nanmadol in August（Accumulated rainfall closed to 1100mm）, Typhoon Nalgae in October（Accumulated rainfall exceed 1600mm）and heavy rainfall event in May this year. The proposed method has been successfully adapted in these Typhoon events. As a result of such watershed management and risk management acts, there were no causality occurred on highways. The DGH had executed 79 road closures for warning in advance by applying QPESUMS and organizing weather information; and there were total 27 hazards occurred after road closures. Although the highway traffic was interrupted due to serious landslide and debris flow damages, however, evacuation and preparation of shelter stations including food, medical supplies were in place in time to relieve the hazard influences to a minimum state.

Feasibility and applications of the proposed rainfall pattern analysis were verified through the extreme weather event such as Typhoon Morakot and recent hazards occurred on SuHwa highway. It would be further upgraded and applied to integrate the DGH hazard responding protocol to improve the reliability and efficiency.

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