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Towards Resilient Roads to Storm-Surge Flooding: Case Study of Bangladesh

Abstract

Operating roads are critical during emergency operations at a disaster area. Prolonged inundation of pavements accelerates rapid deterioration of pavements and increases maintenance cost. The upgrade of vulnerable pavements with a raised subgrade and gabion-walls is proposed as the mean to increase the resiliency of strategic roads vital during the emergency attention in the aftermath of a cyclone. Hence, optimal pavement management can be used to allocate upgrade and maintenance and rehabilitation (M&R) operations to reduce the damage and mitigate the geo-physical risk and community vulnerability before the disaster even occurs. A case study is presented for regional highways, arterial and collector roads of Barguna district in Bangladesh that is frequently affected by cyclones and storm surges. The geo-physical risk and vulnerability (GEOPHRIV) index of each road segments is estimated by integrating the geo-physical risk; community, structure and infrastructure vulnerabilities; and damage indices. Dynamic linear programming is applied to optimize M&R strategies and the conversion of strategic roads into resilient perpetual pavements. The same budget required to optimize roads condition is also used to guide the conversion of roads into perpetual pavements, therefore increasing the overall network resiliency. As expected, the results show that most of the annual budget is equally expended into the conversion or the resurfacing of pavements. The decision making approach herein proposed is very useful to roads agencies around the world, because it provides them with the ability to increase the resiliency of their strategic network ex-ante any flooding disaster.

Keywords:

Resiliency; pavements maintenance; geo-physical risk; vulnerability; storm surge; optimization.

Introduction

Road infrastructure supports the accessibility of emergency resources, evacuation of vulnerable people, and reconstruction and recovery of communities in a disaster-affected area (Faturechi and Miller-Hooks 2015). Natural disasters that have an adverse impact on the vulnerable people can make large portion of road network inaccessible. The inaccessibility of road network in disaster-prone areas makes the evacuation of people and logistic support challenging. Evacuation activities reduce the exposure of vulnerable people to natural hazards and ensure the lifeline to the survivors in the disaster-affected areas by providing logistics support (Yi and Kumar 2007). Both of these operations require the active operation of major roads connecting the affected areas to major supply centers, shelters and hospitals.

The coastal areas of Bangladesh are vulnerable to cyclones and storm surges and historically devastated by severe cyclones and suffered the losses of human lives, livestock and economy. The 1970 Great Bhola Cyclone caused massive destruction of coastal areas of Bangladesh, 500,000 human lives and billion dollar of property damage. Another deadliest cyclone 2B killed at least 138,000 people, left 10 million people homeless and caused two billion dollar of property damage in the coastal areas of Bangladesh on April 1991. Barguna district is the hardest hit of cyclones and storm surges among the coastal areas of Bangladesh. Since 1887, this district was hit by approximately 35 cyclones and storms. The 2007 cyclone SIDR that caused up to 9.5 meters height of storm surge killed 1335 people, annihilated 1119.89 sq. km. area (61.15 percent of total area), destroyed 60-70 percent of crop, and fully and partially damaged 95,412 houses (36.89 percent of total houses) in the Barguna district (Tamima 2009). Poor road condition and flooded roads in Barguna district disrupted the evacuation, rescue and relief operations before and after the cyclones and storm surges (Figure 1). The deteriorated and submerged major roads of Barguna district aggravated the emergency circumstances and increased the human and economic losses. In addition, the prolonged inundation of pavements from flooding caused the entrance of moisture in pavements that accelerates rutting and cracking. Increased damage in pavements from flooding results in rapid deterioration of pavements, reduction in pavement lives, and increased maintenance cost (Mallick *et al*. 2014). A well-structured pavement management system (PMS) can help to identify deteriorated pavement sections, maintain the pavement systematically to prevent or minimize damage before flooding, and increase strategic roads resiliency in preparation for future emergencies.

[Figure 1]

Literature Review

This study reviews the literature on natural disaster and road infrastructure and categorizes the studies into two broader themes such as: (1) physical damage of road infrastructure and its impact on transport mobility, and (2) social impact and rehabilitation strategies against natural disasters. Chang and Nojima (2001) measured the post-disaster accessibility and network coverage of urban rail and highway transportation systems in San Francisco Bay area (United States, USA), Los Angeles (USA) and Kobe (Japan) that were devastated by the 1989 Loma Prieta, 1994 Northridge and 1995 Hyogoken-Nanbu earthquakes, respectively. Chang and Nojima (2001) identified the predominant damage of these earthquakes were highway bridges although the extent of damage, level of system disruption and restoration timeframes were different. Chang and Nojima (2001) found a significant spatial disparity in the recovery of accessibility throughout the restoration process because of the different urban settings of the disaster-affected regions. For example, the overall post-disaster highway system performance was better in Northridge and Loma Prieta than in Kobe. Kim *et al*. (2002) developed the integrated commodity flow model to optimize network flows considering the partial or complete damages of road segments aftermath of natural disaster. Kim *et al*. (2002) compared the transportation cost with and without disaster scenario. Cho *et al*. (2000) estimated the transportation and economic cost of a hypothetical magnitude 7.1 earthquake at the Elysian Park blind thrust fault in Los Angeles by combining bridge and other structure performance model, transportation network model, spatial allocation model, and inter-industry model. For example, Cho *et al*. (2000) estimated the post-earthquake network equilibrium transportation costs (due to reduced production and network capacity) and bridge repair costs would be 1.5 billion and 93.5 billion US dollars, respectively. Sohn (2006) argued that the distance and distance-traffic volume as the two criteria of accessibility required to determine the potential impact of flood damage on the state transportation system in Maryland. Sohn (2006) further identified the greater accessibility loss at the county level considering the distance-traffic flow criterion in the case of disrupted links without an alternative solution. Sohn (2006) only used the highway networks ignoring the local streets that could be the alternative route of the disrupted highway links. Rowan *et al*. (2013) evaluated the threshold level of sensitivity of transportation assets to a given level of exposure to changes in climate or natural hazards. Rowan *et al*. (2013) developed a sensitivity matrix to present the relationship between four climate variables (sea waves, storm, precipitation and temperature) with transportation modes in the Mobile, Alabama, USA. However, Rowan *et al*. (2013) focused on the key elements of damage functions without characterizing the entire function.

Very few studies evaluate the pavement performance and maintenance and rehabilitation (M&R)costs in disaster affected areas. Some studies (Gaspard *et al*. 2006, Helali *et al*. 2008, Zhang *et al*. 2008, Vennapusa *et al*. 2013) show that transportation agencies perform small sample of visual inspections and field tests particularly non-destructive tests to determine the impact of natural hazards on pavement performance. Pantha *et al*. (2010) calculated the maintenance priority index (rating from 1 to 3) by integrating International Roughness Index (*IRI*) and slope stability condition in Nepal mountains. Pantha *et al*. (2010) claimed that a road segment with high score would get higher priority for M&R operations without detailing types and cost of these operations. Mallick *et al*. (2014) estimated the long-term impact of climate change on pavement performance and maintenance cost for a grid cell located in Massachusetts, USA. Mallick *et al*. (2014) estimated that the climate change could significantly reduce the structural strength of both subgrade and hot mix asphalt (HMA) layers of a grid cell located in Massachusetts. Mallick *et al*. (2014) also estimated that the average pavement life would decrease from 16 to 4 years over the span of 100 years and the maintenance cost could increase up to 160 percent. However, Mallick *et al*. (2014) considered the asphalt mix overlay as the only maintenance activity and didn’t calculate the effect of increased maintenance costs. Mallick *et al*. (2015) evaluated the contribution of pavement materials, climate and construction quality on the pavement’s vulnerability to flooding. Mallick *et al*. (2015) recommended different methods of providing additional strength to pavements that lie in flood prone areas such as aging resistant asphalt binder, greater thickness, low permeability and low voids in the HMA layer. However, Mallick *et al*. (2015) applied aging-related equations that have limited ability to evaluate the pavement performance.

Methodology

This study has been executed in three main steps: first the estimation of geo-physical risk and vulnerability (*GEOPHRIV*) index of each road segment through the geo-physical risk and vulnerability indices of the community and the structure and infrastructure, second the estimation of pavement performance in terms of *IRI* and third the optimization of long term budget allocation and scheduling of interventions (Figure 2).

[Figure 2]

Geophysical risk and vulnerability (GEOPHRIV) index of roads

Geophysical risk of a hazard is defined by the probability of occurrence and extent of resulting consequences aftermath of the hazard. The ‘Multipurpose Cyclone Shelter Program (MCSP)’ and ‘National Survey on Current Status on Shelters and Developing and Operational CYSMIS’ defined the geophysical risk zones of cyclones and tropical storms in coastal areas of Bangladesh (Tamima 2009). MCSP demarcates the risk zones based on the level of inundation under the surge water (Tamima 2009). Tamima (2009) collected data on inundation levels at each rural community of the Barguna district after the cyclone SIDR and identified the height of storm surge was within the range of 0.91 to 9.15 meters. The most devastated rural communities were Kakchira, Kalmegha, Patharghata, Baliatali, Naltona and Pancha Koralia (Tamima 2009). This study categorizes the geo-physical risk zones as very high, high, medium and low by combining the results of MCSP and Tamima (2009).

The vulnerability index of a community in Barguna district susceptible to cyclone and storm surge was determined using the Equation 1.

$$\text{Vulnerability index} = (D)^{(COMV+STRINFV)} \qquad (1)$$

Where D is damage index, and *COMV* and *STRINFV* are the community and the structure/infrastructure vulnerability indices, respectively. A principal component analysis (PCA) was applied to estimate the *D*, *COMV* and *STRINFV* indices. The value of each index was calculated by multiplying the standardized value of the corresponding attributes (Figure 2), the proportion of variance explained by each attribute and the proportion of variance explained by each factor (under which that particular attribute is loaded) (Amin and Tamima 2015). Standardized values for each attribute were estimated to remove the differences in measurement units of each attribute.

The power function of Equation 1 is continuous and differentiable at all points of its domain, except at the point $D = 0$ when $0 < (COMV + INFRAV) < 1$. Different degrees of *COMV* and *INFRAV* indices can extend the severity of damages. The integer of the vulnerability index was defined by Cavalieri's quadrature formula (Equation 2) to include all points of the domain of Equation 1.

$$\text{Vulnerability index} = \int_0^{D_n} \left[(D)^{(COMV+STRINFRV)}\right] dD = \frac{{D_n}^{(COMV+STRINFRV+1)}}{(COMV+STRINFRV)+1} \qquad (2)$$

The $GEOPHRIV_c$ index of each rural community (c) was calculated by integrating geophysical risk and vulnerability index (Equation 3). The values of $GEOPHRIV_c$ were defined within the circumference of 0 to 10.

$$GEOPHRIV_c = \frac{R!}{(R-1)!}\frac{{D_n}^{(COMV+STRINFRV+1)}}{(COMV+STRINFRV)+1} = R\,\frac{{D_n}^{COMV+STRINFV+1}}{COMV+STRINFV+1} \tag{3}$$

Where *R* defines geophysical risk zones of each rural community, that were categorized as 1, 2, 3 and 4 representing low, medium, high and very high geophysical risk zones, respectively. The $GEOPHRIV_i$ value of each road link (*i)* was estimated by summing up the $GEOPHRIV_c$ value of all rural communities within a 3 km buffer zone of the corresponding road link because Tamima (2015) observed that local people used to travel on an average 3-km distance to reach a cyclone shelter after receiving the cyclone warning.

A back-calculation procedure was used to obtain the contribution of each road to the overall $GEOPHRIV_i$ index. This came from the need to update the $GEOPHRIV_i$ within the dynamic optimization algorithm, after a road was reconstructed as a perpetual pavement. Three of the components of the $GEOPHRIV_i$ were not affected by the decision to upgrade a road; they are the risk zone (*R*), the community vulnerability (*COMV*) and the structure-infrastructure vulnerability (*STRINFV*) indices. However, the summation over the 3-km buffer zones, represented a loss of tractability to these values, hence their contribution to the overall $GEOPHRIV_i$ of each road needed to be re-established. Equation 3 was used once again to guide the back-calculation.

The contribution of the combined: community and structure/infrastructure (*COMV+STRINFV*) vulnerabilities were estimated from the storm surge height multiplied by the number of people affected. The obtained values were normalized on a zero to one scale which represented the power term *COMV+STRINFV* within Equation 3. The value of *R* was obtained by spatial proximity of each road segment to the risk zones and mapped again to 1, 2 or 3. The value of D_{ni} was back-calculated from the known $GEOPHRIV_i$ and the newly estimated *R* and the *COMV+STRINFV*. The obtained values of Damage for each road were mapped to a 1 to 1.77 interval; the value of 1 was deemed as no damage contribution of the road, because in this case the power function (Equation 3) results on no scaled impact of the road damage to the vulnerability of the community or other structures/infrastructure.

Pavement performance modeling

Road pavements in Bangladesh are built with HMA with unbound aggregate base underneath the HMA layer. Moisture in HMA and granular base layers damages the HMA pavements (Little and Jones 2003). This study applied the basic design equation of the 1993 American Association of State Highway and Transportation Officials (AASHTO) guide to estimate the present serviceability index (*PSI*) of flexible pavements in coastal region at a time *t* (Equation 4).

$$PSI_t = PSI_{t-1} - 2.7 \times 10^{a} \tag{4}$$

$$a = \left[0.40 + \frac{1094}{(SN+1)^{5.19}}\right] [\log_{10}(ESALs_t) - (Z_R \times S_0) - 9.36 \log_{10}(SN+1) - 2.32 \log_{10}(M_R) + 8.27]$$

Where PSI_{t-1} is the *PSI* at time (*t*-1), *ESALs*$_t$ is the 80 KN equivalent single axle load at time *t*, Z_R is the standard normal deviate that considers the design uncertainties, S_0 is the combined standard error of traffic prediction and performance prediction, *SN* is the structural number or structural strength of the pavement, and M_R is the subgrade resilient modulus (AASHTO 1993). The *SN* was calculated from the thickness of layers and their corresponding layer coefficients and drainage coefficients (AASHTO 1993). Drainage coefficients of different layers of pavement are determined based on the time of standing water and saturated condition. After the storm surge, water stagnation prolonged more than one month causing the very poor drainage quality in the study area that is defined by the drainage coefficients within the range of 0.75-0.40 (AASHTO 1993). This study considered the reliability level and corresponding Z_R value as 95 percent and -1.645 for the roads of Barguna district, respectively (AASHTO 1993). The value range of S_0 for flexible pavements was considered as 0.40 to 0.50 (AASHTO, 1993). The M_R was calculated based on the California Bearing Ratio (*CBR*) method. Heukelom and Klomp (1962) related M_R and *CBR* using Equation 5. Alam and Zakaria (2002) collected the samples from Katchpur area along Dhaka-Chittagong highway and from Aminbazar area along Dhaka-Aricha highway and kept in water for 4, 7, 30 and 45 days. Alam and Zakaria (2002) estimated that the average *CBR* values with medium compaction efforts were 2.7, 2.5, 2.2 and 1.9 keeping the samples in water for 4, 7, 30 and 45 days, respectively.

$$M_R = 1500 \times CBR \tag{5}$$

The ESALs for different categories of vehicles on the roads of Barguna district for the period *t* were calculated applying Equation 6 that was proposed by Bangladesh Road Materials and

Standard Study (BRMSS) report (Roads and Highways Department 1996). Where *r* represents the traffic growth rate, $AADT_i$ represents annual average daily traffic of *i* vehicle type, and EF_i is equivalent load factor of *i* vehicle type.

$$ESALs_t = \sum_i^n 365 \times AADT_i \times EF_i \times \frac{\left(1+\frac{r}{100}\right)^t - 1}{\frac{r}{100}} \qquad (6)$$

This study converted the *PSI* to *IRI* for each road segment following the Equation 7 since the transportation authorities in Bangladesh assess the performance of flexible pavements in terms of roughness progression. Sayers *et al*. (1986) developed Equation 7 during the International Road Roughness Experiment conducted in Brazil in 1982 that was validated by several studies (Paterson *et al*. 1992, Haas *et al*. 1994, Prozzi 2001).

$$IRI = 5.5 \ln \frac{5.0}{PSI} \qquad (7)$$

The *IRI* values were categorized as $0 \leq IRI \leq 2$, $2 \leq IRI \leq 4$, $4 \leq IRI \leq 6$ and $6 \leq IRI \leq 10$ for excellent, good, fair and poor conditions of roads, respectively. The road design standard for a rural road of Local Government Engineering Department (LGED) in Bangladesh defined the pavement design life as 10 years. Tamima (2009) estimated that the probabilities of returning severe (wind speed 89-118 km/hr), very severe (wind speed 119-221 km/hr), and super cyclones (wind speed 222 km/hr and above) at 10 years intervals were 0.187, 0.187 and 0.1339, respectively. Hence, this study considers a reduced pavement design life of 10 years. Roads will require the reconstruction with earth-filling every 10 years because they are expected to be washed away by storm surges that are considered to be recurrent every 10-years. The operational window of pavement M&R operations is presented in Table 1.

[Table 1]

Lifecycle optimization of road maintenance

Lifecycle optimization to achieve and sustain good pavement condition (decreasing $\overline{IRI}$) at a minimum cost was used to find required levels of annual M&R budget (Equation 8 and 9). The minimization of roughness progression (*IRI*) and *GEOPHRIV* values under such a budget was then used to find optimal strategic results for pavement management (Equation 10 and 11). This formulation relied on a transfer function that connects recursively all periods of time (Equation 12). Each road segment carried eight indexed characteristics: (1) type of road with two possible values AC-pavement or perpetual pavement, (2) functional classification of the road, (3) geophysical risk group, (4) level of Damage (*D*), (5) *GEOPHRIV*, (6) *COMV* + *STRINFV*, (7) Value of R (1 = low, 2 = medium, 3 = high) and (8) last intervention received to limit the number of interventions and to control the effectiveness of the intervention by switching to a new performance curve.

$$MINIMIZE \quad \mathrm{Z} = \sum_{t=1}^{\mathrm{T}} \sum_{i=1}^{a} \sum_{j=1}^{o} C_{tj} X_{tij} L_i \tag{8}$$

$$\text{Subject to}: \sum_{t=1}^{T} \sum_{i=1}^{a} L_i IRI_{t,i} \leq 0.9 \left(IRI_{t-1,i} \right) \sum_{i=1}^{a} L_i \tag{9}$$

$$\text{MINIMIZE} \sum_{t=1}^{T} \sum_{i=1}^{a} (W_{1t} * L_i IRI_{t,i} + W_{2t} * GEOPHRIV_{it}), \; IRI_{t,i} \text{ defined by Equation 12} \tag{10}$$

$$\text{Subject to:} \quad \sum_{t=1}^{\mathrm{T}}\sum_{i=1}^{a}\sum_{j=1}^{k} C_{t,j}\, x_{t,i,j}\, L_i \le \mathrm{B_t} \tag{11}$$

$\sum_{j \in J_{t,i}} x_{t,i,j} \in [0 \text{ or } 1]$, binary decision variable for road segment *i*

$$IRI_{tij} = X_{tij}\,(IRI_{(t\text{-}1)ij} - E_{ij}) + (1 - X_{tij})\,(IRI_{(t\text{-}1)ij} + D_{it}) \tag{12}$$

Where X_{tij} is 1 if treatment *j* is applied on road segment *i* at year *t*, zero otherwise; IRI_{ti} is condition Index for road segment *i* at year *t*; IRI_{tij} *is* condition index of road segment *i* at year *t* for intervention *j*; $IRI_{(t\text{-}1)ij}$ is condition Index of road segment *i* at year (*t*-1) for intervention *j*; C_{tj} is cost ($) of intervention *j* at year *t*; L_i is length of road (km) for road segment *i*; E_{ij} is improvement in terms of IRI reduction on road segment *i* from intervention *j*, D_{it} is deterioration on road segment *i* at time *t*, B_t is budget at year *t*, $GEOPHRIV_{,it}$ is the *GEOPHRIV* value for road *i* at time *t*, and W_1 and W_2 are the weights of the *IRI* and *GEOPHRIV* indices, respectively. For simplicity the Damage indicator D_{ni} was used instead of the $GEOPHRIV_{it}$ within the optimization codes.

Results and Discussion

Geo-physical Risk and Vulnerability Analysis

The PCA was applied to estimate the *D*, *COMV* and *STRINFV* indices for each community. The first step for performing a PCA was to assess the data suitability. The pattern of relationships among variables was identified from the correlation matrix, determinant of correlation, total variance (before and after rotation) and the component matrix (before and after rotation). The 'Eigenvalues' associated with linear components (factor) before extraction, after extraction and after rotation were evaluated. The 'Eigenvalues' represent the variance explained by the linear component. If the total variance of each test is unity, the 'Eigenvalues' of the first factors have the theoretical maximum equal to the number of tests (Kinnear & Gray 2009). The first factors have the greatest sums and thus account for the greatest part of the total variance. Table 2 illustrates that the first seven factors, six factors and first factor explain 80.46 percent, 78.12 percent and 82.05 percent variance of *D*, *STRINFV* and *COMV* indices and have eigenvalues greater than 1, respectively. This study considers the proportion of variances explained by each factor and variables from the rotated sum of squared loading. The rotated sum of squared loading, representing the effects of optimising the factor structure, was examined to equalise the relative importance of the most significant factors (Table 2).

[Table 2]

The communality of each variable, the total proportion of variance accounted for the extracted factors, was calculated by the squared multiple correlations among the test and the factors emerging from the PCA. The relationship between the variables and extracted factors was identified by the rotation component matrix of PCA (Table 3). The rotations were performed by the Varimax with Kaiser Normalization process and the convergence of rotation was obtained after 7 iterations.

[Table 3]

The values of *D*, *COMV* and *STRINFV* indices for each rural community were calculated by multiplying the standardized value of corresponding attributes, the proportion of variance explained by each attribute and the proportion of variance explained by each factor. The value of *GEOPHRIV* index for each rural community was estimated following Equation 3. The *GEOPHRIV* value of each road link was estimated by summing up the *GEOPHRIV* value of all rural communities within the 3 km buffer zone of the corresponding road link.

Optimization of Pavement M&R Operations

Firstly, the minimum required budget was estimated by minimizing total cost while reducing IRI 10% per year (Equations 8 and 9). It was found that USD 2,848,920 was the corresponding annual budget that ensures very good average roads condition (Figure 3). The budget was rounded to USD 3 million per year for the remaining analysis.

[Figure 3]

Secondly, the prioritization of maintenance operations for the rural road network was determined by minimizing the weighted values of IRI_i and $GEOPHRIV_i$ for each link (Equations 10 and 11) within the given annual budget constraint. As time periods passed by, more and more roads were converted to perpetual pavements (Figure 4) and the overall network condition improved to almost eliminate all roads in poor and fair condition by 20 years.

[Figure 4]

The split of the budget reveals that the priority is given first to convert roads into perpetual pavements (Figure 5a), and then into overlays and resurfacing of roads to sustain them in good levels of IRI condition (Figure 5b).

[Figure 5]

Figure 6 shows how the storm surge rise zoning is only one of many factors for the geophysical risk which produces a more integral picture of the concentration of population and vulnerability. Figure 6 also shows pavements upgraded to perpetual after 20 years of interventions.

[Figure 6]

Conclusions

Cyclone and storm surge have an adverse impact on the pavement condition of road network in the disaster-prone areas resulting in the disruption of evacuation, rescue and relief operations during the emergency period. The deteriorated and submerged roads aggravate the emergency circumstances and increased the human and economic losses. In addition, the prolonged inundation of pavements from storm surge causes the entrance of moisture in pavements that accelerates rapid deterioration and increases maintenance cost. This study estimates the geo-physical risk and vulnerability (*GEOPHRIV*) index of each road segment of Barguna district in Bangladesh integrating geo-physical risk, social and physical vulnerabilities of the communities, and damages from the cyclone SIDR. The optimization of pavement M&R operations for road network of Barguna district is achieved by minimizing the *GEOPHRIV* index and pavement roughness progression within the annual budget constraint.

The principal component analysis (PCA) of multivariate analysis techniques was applied to estimate the value of each index multiplying the standardized value of variables, the proportion of variance explained by each variable and the proportion of variance explained by each factor. The 1993 AASHTO guide was applied to estimate the deterioration of flexible pavements. Linear programming was applied to develop M&R strategies ensuring the good pavement condition of roads at a minimum maintenance budget.

Lifecycle optimization of M&R operations estimated that almost USD 3 million is the minimum annual budget that ensures good road condition in Barguna district. Most of the annual M&R budget will be allocated for the conversion and maintenance of the roads with the high and medium *GEOPHRIV* values. This reveals that the roads located at the high and medium geo-physical risk and vulnerability regions are given priority in the proposed PMS. The majority of the M&R budget will be invested for overlay followed by resealing.

This model helps the transportation authorities to identify deteriorated pavement sections, maintain the pavement systematically to prevent or minimize damage before flooding, route choice for emergency or evacuation traffic, and allocate resources for post-disaster M&R operations.

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