ODOT Library
555 13th Street NE
Salem, OR 97301
(971) 701-0709
ODOTLibrary@odot.oregon.gov

LITERATURE SEARCH
Climate Change Resilience Transportation Design Resources

Prepared by: Amanda J. Carter
August 07, 2025

Overview of Search Process and Results:
The initial literature search results presented here were retrieved from TRID which is an integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database; ROSA-P, the National Transportation Library's *Repository and Open Science Access Portal*; and the ASCE Library. The search query used to identify publications is or is some close variation of: [resilience AND climate AND (hydraulic OR pavement OR geotechnical OR bridge OR highway)]. Selected results were limited to within a ten-year timeframe (i.e. since 2015) and were filtered to case studies, new strategies or methodologies, and reports of completed projects. Results not included were research-in-progress or materials focused on funding, railroads, waterways, and aerospace.

It is recommended that all results, including those below, be vetted by a subject matter expert to ensure they are applicable to the goals and intention of ODOT's Resilience Resource Library. These results can then be used to further refine a more applicable search, to set up and maintain push notifications, or both. Maintaining an updated list of resources is possible with limited setup as both TRID and ASCE Library allow for RSS feeds which can provide push notifications of new publications on this topic. Additionally, ASCE Library enables the search to be saved with an option to alert to new results on a daily, weekly, or monthly basis.

Annotated Bibliography:
Arranged to reflect the existing structure of the Resilience Resource Library, five or more sources are listed for each topic area. Links or DOI and abstracts are listed with the citations. Links or DOIs open to full-text documents, pages that allow PDF downloads, or abstract pages. Articles and papers not openly available in full can be obtained through interlibrary loans.

Hydraulics:

Akhtar, A. A., Esquivel, A., Sharma, M., & Tandon, V. (2018). *Understanding Climate Change Impact on Highway Hydraulic Design Procedures*. Southern Plains Transportation Center, University of Oklahoma. https://rosap.ntl.bts.gov/view/dot/64728

The significant change in climate is evident from the records of increased temperature, changed precipitation pattern, increased frequency of extreme weather events like storms, floods, and so forth. Like other infrastructure highway infrastructures also suffer the consequences of these climate change. Since the hydraulic design of these infrastructures is performed using historical climate data, the designs may not be able to provide services because designs are not considering climate change influence especially in terms of precipitation intensity. This study aims at identifying the most accurate source of climate database that predicts future climate change with less uncertainty and links them into

the evaluation of vulnerability and risk of the bridges so that the impact of future climate can be incorporated into the design of new infrastructures. In this study, the NARCCAP database has been used to extract the future climate data for different cities of SPTC representing states. Climate models have predicted as high as 10.2% increase in precipitation for Houston, Texas, which leads to an increase in the intensity of streamflow in that region. A hydraulic model has been established using HEC-RAS for streamflow modeling. Overtopping depth and scour depth have been estimated as the primary vulnerability stressors of the bridge. This study has estimated the range of the return periods of the floods for which bridge may fail under the predicted future climate scenarios. The annual economic loss has been calculated for the bridges, and possible adaptation strategies have been suggested using HYRISK software

Board, T. R., National Academies of Sciences, E., & Medicine. (2025). *Practices to Enhance Resiliency of Existing Roadway and Embankment Culverts*. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/29134

State departments of transportation (DOTs) recognize that management and maintenance practices for existing roadway and embankment culverts fundamentally influence culvert performance and have subsequent impacts on adjacent assets and overall transportation system performance. State DOTs actively research and implement methods to reduce costs, identify and reduce risk, minimize maintenance, improve performance, and ultimately increase the longevity of culverts. The needs of state DOTs to reduce culvert degradation impacts and improve resilience are common, yet the approaches may be diverse. Variability in climate, climate events, seismic susceptibility, slope and embankment stability, watershed characteristics, and urban development and land uses create system challenges. Although the demands that state DOTs face vary significantly, commonalities exist, and practices used to enhance the resiliency of culverts can be broadly employed. This synthesis will provide awareness of management and maintenance practices used by other state DOTs to address and improve the performance and resiliency of their existing culverts. Culverts were frequently identified and assessed as vulnerable components to extreme events and climate change during a 2013-2015 pilot study (FHWA-HEP-16-079). Documenting practices and remedial measures for culvert management and maintenance is an important step in planning for improved system operations, performance, and resilience. The objective of this synthesis is to document management and maintenance practices used by state DOTs to enhance resiliency of existing roadway and embankment culverts.

Gómez, A., Maerz, J., Kinney, V., Bauer, S., & Bledsoe, B. P. (2023). *Bridge and Culvert Designs for Reduced Wildlife-Vehicle Conflicts and Improved Climate Resiliency: Phase I*. Georgia Department of Transportation, Office of Performance-Based Management and Research. https://rosap.ntl.bts.gov/view/dot/72620

This report describes the first phase of a comprehensive project to address the critical issue of Wildlife Vehicle Conflicts (WVCs), which average over 14,000 crashes and cost more than $850M per year in Georgia. With a focus on integrating hydraulic design principles with wildlife passage, this Phase I study conducted a preliminary and systematic literature review, extracting key insights into the ecological and structural variables that underpin best practices for reducing WVCs while facilitating wildlife movement. Notable findings include the enduring relevance of certain core ecological variables and a convergence of best practices for two groups of animals: medium / large-bodied mammals, and herpetofauna / small mammals. Results of the preliminary literature review suggest that there is sufficient knowledge to move forward with developing design guidelines for multi-objective hydraulic structures that better convey floods, reduce WVCs, and improve aquatic connectivity. Design modifications for flood and sediment conveyance under climate change are in accordance with several modifications that also reduce WVCs and promote aquatic connectivity. Building upon these insights, Phase II of the project is poised to enhance road safety, ecosystem connectivity, and infrastructure resilience through development of hydraulic design standards, integration of climate change considerations, spatial prioritization of structure enhancements and replacements, and recommendations tailored for the Georgia Department of Transportation (GDOT). By merging ecological knowledge with innovative engineering of wildlife friendly, climate-ready structures, this project aspires to forge a path toward safer and more sustainable transportation infrastructure in Georgia.

Krolak, J., Girard, L. G., Leon, S., Sourek, C., Dillin, M., & Sharar-Salgado, D. (2022). *Infrastructure Resilience to Extreme Events & Climate Change: Federal Lands Case Studies*. US Department of Transportation, Federal Highway Administration, Office of Infrastructure. https://rosap.ntl.bts.gov/view/dot/64313

The FHWA has provided technical resources such as HEC-17 Highways in the River Environment, to help analyze the vulnerability of transportation infrastructure in relation to extreme events and climate change. Following this philosophy, this document collects a series of Case Studies that examine the resilience of infrastructure against different extreme events representing potential climate change scenarios. The location of these Case Studies was within four National Parks. The rationale for focusing on National Parks was an attempt to disaggregate direct changes in precipitation or streamflow characteristics from those associated with land use or urbanization. The research investigated the sensitivity of extreme events (i.e., extreme weather events and climate changes), manifested by precipitation and streamflow, upon the resilience of transportation infrastructure hydraulic appurtenances (e.g., roadside drainage, storm drains, culverts, or bridges).

Pluimer, M. L. (2022). Holistic Approach to Evaluating the Sustainability and Resiliency of Buried Drainage Structures Relative to Climate Change. *Transportation Research Record, 2677(5)*, 925-933. DOI: 10.1177/03611981221138512

A research project was conducted in 2020 to assess the sustainability and resiliency of various buried drainage structures relative to the impacts of climate change and extreme weather events. As a result of this project, a risk assessment and rating system was proposed that calculates the risks that various extreme weather events, natural disasters, and other threats pose to buried drainage structures. One thing that differentiates this proposed risk assessment methodology from others is its holistic approach to sustainability and resiliency. The basis for this holistic approach is that the use of less sustainable materials contributes more to climate change, which in turn exacerbates the magnitudes and frequencies of extreme weather events, thereby increasing the importance of resiliency in buried drainage structures. Because of this relationship, the proposed risk index calculations and vulnerability ratings take into account factors assessing both the sustainability and resiliency of buried drainage structures.

Thomas, W. O., Newell, D., Bernzott, E., Szekeres, D., Harris, J., Tabb, C., & Siddiquee, F. (2020). *Development of Site-Specific Hydrologic and Hydraulic Analyses for Assessing Transportation Infrastructure Vulnerability & Risks to Climate Change*. US Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/58570

This pilot study supports PennDOT's continued efforts to develop processes and procedures to assess potential flooding vulnerabilities and risks related to transportation infrastructure. The study builds upon PennDOT's Extreme Weather Vulnerability Study and existing hydrologic and hydraulic (H&H) assessments that are typically conducted as part of the design process and used to obtain Pennsylvania Department of Environmental Protection (DEP) and U.S. Army Corps of Engineers environmental permits. The existing H&H assessments follow the procedures and requirements in PennDOT's Design Manuals. The pilot study includes three site-specific H&H assessments that have been expanded (as compared to current PennDOT procedures) to address the impacts of more intense and frequent precipitation events under future climate scenarios. The analyses and procedures conducted for the pilot study highlight the extraction and interpretation of global climate model precipitation data, the application of that data to the H&H process, and methods to evaluate adaptation strategies to improve infrastructure resiliency.

Vincent, A., & Sushama, L. (2024). City-scale modelling of road thermal and hydrologic characteristics and failure mechanisms: Case study of Montreal. *Sustainable Cities and Society, 108*, 105484. DOI: https://doi.org/10.1016/j.scs.2024.105484

This study focuses on understanding and quantifying projected changes to road thermal and hydrologic characteristics that are associated with road failure, for the City of Montreal, Canada. To this end, city-scale modelling using a land surface model with realistic representation of urban regions, including roads, enabled by the super-resolution of 250 m, for the current 2001–2020 and future 2041–2060 periods are used. Analysis for the cold season suggests potential reduction in failures associated with thermal characteristics such as daily freeze-thaw and partial thaws, with a projected decrease of 12.5% and 2 %, respectively. Higher potential for hydrologic characteristics-related failures are likely, given projected increases in road/surface runoff in the 12–15% range. For the warm season, projected increases in thermal characteristics such as daily maximum and minimum temperatures (4–4.5 °C), and hydrological characteristics (25 %), suggest increased potential for road failure from rutting and drainage issues. Analysis performed separately for the highways and local roads reveal important spatial variability of the considered characteristics and associated failures, which can be helpful in prioritizing road sections for detailed analysis and in the development of sustainable adaptation strategies for the Montreal road network and enhancing the city's resilience to future climate change.

Pavement:

Alshboul, O., Shehadeh, A., & Tamimi, M. (2025). Sustainability-Focused Pavement Management under Climate Variability. *Journal of Construction Engineering and Management, 151(7)*, 04025076. DOI: 10.1061/JCEMD4.COENG-15829

This paper explores transformative strategies in urban pavement management by integrating automated technologies and climate-adaptive innovations, specifically under the challenging conditions posed by climate change (CC). The research focuses on implementing advanced asphalt binders coupled with automated construction processes. We employ a dual approach, using machine learning (ML) algorithms and predictive analytics to optimize the environmental impact assessments, particularly targeting CO2 emissions throughout the pavement life cycle. Our findings reveal that incorporating climate-resilient innovations can significantly decrease maintenance frequencies by approximately 20% and extend the pavement lifespan by up to 15 years, aligning closely with climate projections from 2023 to 2060. A detailed life cycle cost analysis (LCCA) suggests potential fiscal savings of up to $500 million

in national highway maintenance over the next four decades. Moreover, our automated predictive model boasts accuracy with a coefficient of determination (R2) of 0.85, enhancing the precision and timeliness of maintenance interventions. This paper underscores the imperative of merging automated technologies with climate-adaptive innovations to bolster the sustainability and resilience of urban infrastructures, thereby advancing economically and environmentally sustainable urban development practices. This aligns with the Sustainable Development Goals, emphasizing the urgent need for sustainable cities and communities.

Banerjee, A., & Ghosh, D. (2024). *Enhancing the Resiliency of Pavement Infrastructure Built on Sulfate-Rich Expansive Soil Subjected to Climate Change*. Mountains-Plains Consortium. https://rosap.ntl.bts.gov/view/dot/82423

The study aimed to understand the impacts of extreme climatic conditions such as prolonged droughts and intense precipitation due to climate change on the resilience of civil infrastructures like embankments. The knowledge of unsaturated soil mechanics and soil chemistry is integrated to determine the impact of climate change on the stability of embankment slopes built with sulfate-rich expansive soils based on various emission predictions and climate models. An advanced suction-controlled triaxial setup that can determine the shear strength under varying moisture conditions and the resilient modulus of soils, was installed and calibrated. This setup is essential to study the impact of climate change. A series of suction-controlled triaxial tests were performed to demonstrate the behavior of clayey soil from the region with varying suction levels. The stability of an embankment was analyzed based on low to moderate emissions and high emissions till the end of the century. It was observed that for the high emissions scenario, the stability of embankment slopes decreased significantly, which demonstrated the need for resilience of embankments to address the stresses caused by climate change. An alternative treatment method using biopolymers and cement was identified as a potential candidate for the treatment of sulfate-rich expansive soils.

Halcomb, R. P., & Abaza, O. (2024). Alaskan Pavement Resilience: Navigating Climate Change in Cold Regions. *Cold Regions Engineering 2024: Sustainable and Resilient Engineering Solutions for Changing Cold Regions,* 438-449. DOI: https://doi.org/10.1061/9780784485460.041

The global phenomenon of climate change has led to significant environmental transformations, particularly affecting cold regions due to their extreme temperature dynamics. Among the critical elements facing the consequences of climate change in these regions are pavement structures, essential components of roadway, and airport infrastructure. This study explores the repercussions of climate change on pavement structures within cold regions, focusing specifically on shifts in temperature patterns and, subsequently, frost depth. Through the analysis of temperature records, this research investigates the annual average temperatures, emphasizing trends spanning multiple decades. Complementary to this, freezing degree day data are utilized to compute frost penetration depths and establish average trends over the same extended timeframe. By comparing three prominent Alaskan regions in terms of both temperature variations and frost penetration, the study aims to discern the direct implications of climate change. The regression analysis reveals noteworthy statistical changes in frost penetration depths across all studied locations. Projecting from current trends, future estimates for frost penetration indicate potential variations of around 15 cm over a 40-year period, contingent on the region. This study not only investigates if tangible effects of climate change on pavement structures exist but also offers valuable insights into potential long-term consequences for infrastructure in cold regions.

Jiang, Y., Ullah, S., Zapata, C., & Yu, X. (2025). Assessment of the impacts of climate change on cold region pavement design and operation. *Journal of Infrastructure Preservation and Resilience, 6(1)*, 20. DOI: 10.1186/s43065-025-00126-2

Cold region pavements are subjected to climate impacts, as frost heave and thaw settlement can significantly deteriorate the pavement surface conditions and reduce its service life. Due to the freezing/thawing behaviors, the smoothness of the flexible pavement surface usually shows seasonal fluctuations, i.e., an increases or decreases of international roughness index (IRI) during freezing season or thawing season, respectively. However, few existing models capture such season-dependent mode of IRI variations. In this study, calibrated models for flexible pavement are proposed for evaluating the IRI on seasonal scales through both global and local calibrations. The globally calibrated model successfully links the freezing–thawing processes to flexible pavement performance. The performance of both the global and local calibrations are verified by field measurements at selected road sections and Mechanistic Empirical Pavement Design Guide (MEPDG) model predictions. The proposed model connects climatic factors with pavement performance, and therefore offering a tool to assess the pavement IRI response to future climate changes. Based on the globally calibrated model, a series of analyses were conducted to forecast the impacts of climate change on IRI at sites located in different cold climate zones. The effects of climate change on pavement construction and operation are investigated. From this, the impacts of climate change on pavement design adaptation as well as the environmental footprint of vehicle operations are estimated.

Jiang, Y., & Yu, X. (2023). Holistic multiphysics simulation of climatic responses of cold region pavements. *Journal of Infrastructure Preservation and Resilience, 4(1*), 24. DOI: 10.1186/s43065-023-00090-9

In cold regions, the environment dynamics lead to variations of soil temperature, water content, and deformation, which are characterized by highly coupled physical interplay. The hydraulic and thermal properties of unsaturated soils are highly nonlinear, which is further complicated when subjected to freezing. This paper presents a comprehensive multiphysics coupling model to evaluate these complex processes. The model considers the behaviors of unsaturated frozen soils. It accounts for the influences of meteorological, geothermal, and hydrological factors. The model is validated through two pavement case studies using Long-Term Pavement Performance (LTPP) road section data. The first case analysis is performed for a pavement section in Vermont, and the simulation lasted for 30 days during a non-freezing season on an hourly basis. The results validated the performance of the model considering unsaturated soil behaviors. The second case study is based on a daily analysis of a pavement section in South Dakota over a freezing–thawing cycle over 194 days. The results validated the model in considering the frozen unsaturated soil behaviors. Both case studies demonstrate the performance of this comprehensive model in quantifying the spatial and temporal variations of soil temperature and water content in response to environmental stressors. The capability of the model in accurately predicting the responses of pavement to the meteorological factors unleashes the potential of this model to assess the effects of climate and climate change on cold region pavement, as well as other types of geo-structures.

Jibon, M., Abdullah All Sourav, M., Mahedi, M., Kim, S., Ceylan, H., & Velasquez, R. (2024). Heavy rainfall and moisture susceptibility of pavement foundation: A case study coupling finite element method and MnROAD moisture monitoring data. *Transportation Geotechnics, 48*, 101312. DOI: https://doi.org/10.1016/j.trgeo.2024.101312

The Midwest region, including Minnesota, has been experiencing increased heavy precipitation events due to climate change, and the Minnesota Department of Transportation (MnDOT) is currently investigating the effect of climate change on pavement foundation and other transportation assets. As part of this effort, a study was conducted to investigate the impact of heavy rainfall on pavement foundation performance by focusing on moisture dynamics and resilient modulus changes in the pavement base layer. This study is aimed at understanding the adverse effects of heavy rainfall on moisture fluxes within pavement foundation and corresponding stiffness of the base aggregate layer. A two-step approach was adopted for predicting changes in saturation when estimating corresponding resilient modulus values using the resilient modulus prediction equation employed in AASHTOWare Pavement Mechanistic-Empirical (ME) Design. PLAXIS 3D, a finite-element analysis tool, was utilized to simulate the movement of moisture within the pavement layers under varying heavy rainfall scenarios. By incorporating predicted saturation from PLAXIS 3D simulations into the Pavement ME equation, corresponding resilient modulus values were estimated for the base layer. To ensure its accuracy and reliability, the model was validated using field sensor data from the MnROAD facility. Multiple linear regression models were developed to provide a means for estimating resilient modulus changes due to heavy rainfall. This study highlights the importance of considering moisture effects in pavement design and maintenance in regions prone to heavy rainfall events, and findings can be used by transportation agencies as part of their transportation/geotechnical asset management programs.

Kim, K., Riley, S., Yamashita, E., Marasco, D., & Webster, L. (2023). Promoting Porosity: Adaptation of Urban Roadways for Flooding and Climate Change. *Transportation Research Record, 2678(7)*, 549-562. DOI: 10.1177/03611981231208188

Using environmental and transportation data from a dense urban watershed in Honolulu, Hawaii, the use of porous pavement is investigated as a strategy for mitigation and adaptation to flooding events and increasing resilience to climate change. The potential for water capture to abate pollution and recharge aquifers is also considered. This research is motivated by the increased likelihood of flooding and demands for improved transportation resilience. Based on the impacts from a 2004 flood in Honolulu, installation of permeable asphalt pavements on residential streets with low-to-moderate traffic volumes, and 2% to 5% slope, flooding would be significantly reduced. With the highest absorption rate (90%), 1.8 trillion gal/year could be diverted, while, with a lower absorption rate (50%), 691 billion gallons would be captured. The transformation of roadways, culverts, stormwater infrastructure, and existing drainage systems requires a different approach to planning, designing, construction, and paving (or not) roadways. Adoption of nature-based transportation solutions and integration with low impact development standards by local governments are needed to reduce flood risk and improve environmental quality. Design criteria are reviewed in the context of a specific watershed but also for development and application of methods in other locations. Improved communications and collaboration between researchers, land use planners, and practitioners will further advance resilience through innovation and adaptation to climate change. Porosity is also a factor and requires appreciation for nature and understanding of the seepage and conveyance of new ideas.

King, D., & Taylor, P. (2023). Concrete Overlay Strategies for Improving Pavement Resilience. *Transportation Research Record, 2677(8)*, 259-269. DOI: 10.1177/03611981231156570

Increases in flooding events and rising groundwater levels caused by climate change threaten to weaken pavement foundations, which can have a major impact on flexible pavement service life. Rigid pavements are not as sensitive to the strength of underlying layers, so one potential method to improve the resilience of existing asphalt pavements is to construct concrete overlays. In this analysis, typical asphalt pavement sections on collector and arterial streets under Iowa climatic and soil conditions are identified and evaluated under a variety of theoretical flooding scenarios to determine the impact of inundation on service life. Three types of concrete overlay designs are developed for these typical asphalt pavement sections under the same conditions. A life cycle cost analysis (LCCA) is performed to compare the costs and performance of the concrete overlay strategies to a conventional flexible pavement rehabilitation strategy under the theoretical flooding scenarios. The results of the LCCA indicate that a variety of concrete overlay designs can provide more cost-effective performance when pavement foundation layers become inundated, depending on the roadway functional class and frequency of flooding. These findings indicate that concrete overlays can be a useful method for improving resilience of existing flexible pavements and mitigating the costs of flood damage.

Liu, Y., Chu, C., Zhang, R., Chen, S., Xu, C., Zhao, D., . . . Cao, Z. (2024). Impacts of high-albedo urban surfaces on outdoor thermal environment across morphological contexts: A case of Tianjin, China. *Sustainable Cities and Society, 100*, 105038. DOI: https://doi.org/10.1016/j.scs.2023.105038

The urban heat island (UHI) effect can exacerbate various environmental challenges related to high temperatures in urban areas. Increasing urban surface albedo is an effective strategy to mitigate UHI. However, the efficacy of high-albedo urban surfaces across varying urban contexts remains poorly understood. In this study, we leverage Urban Weather Generator to systematically simulate the effects of high-albedo roads, walls, and roofs on urban microclimate across Tianjin. Our simulation covers a typical meteorological year, representing typical weather conditions from January to December. Our results reveal that increasing road albedo is more effective in mitigating UHI in fringe areas, whereas increasing wall and roof albedo is more effective in mitigating UHI in central areas. Local climate zones with an urban aspect ratio of about 0.5 can obtain a maximum reduction of road surface temperature (-6 °C) and wall surface temperature (-3 °C). The temperature changes induced by albedo changes show evident seasonal characteristics: the road temperature decreases significantly in summer, while the wall temperature decreases significantly in spring and autumn. Our results could help guide UHI mitigation policies and urban planning in cities hoping to enhance urban surface albedo to balance urban growth and climate resilience.

Pham, S. V. H., Nguyen, K. V. T., Le, L. H., & Dang, N. T. N. (2024). Developing RTI IMS Software to Autonomously Manage Road Surface Quality, Adapting to Environmental Impacts. *IEEE Transactions on Intelligent Transportation Systems, 25(11)*, 18472-18484. DOI: 10.1109/TITS.2024.3442949

In the context of increasing negative environmental impacts driven by alarming climate change, extreme weather conditions will necessitate new ways to plan and manage the maintenance of road networks. This promotes the need to shift from reactive and predetermined maintenance methods to predictive and proactive maintenance. Predicting road damage has become a challenge and there is a need to build a more modern pavement quality assessment system in the future. Aimed at enhancing the resilience and sustainability of the road system against significant environmental impacts, this study develops software integrating advanced technology to intelligently manage road infrastructure quality. The software in this study applies machine learning technologies like Yolo, GPS positioning, and online Internet connectivity to automatically detect and locate road damage on the traffic network map. The study successfully developed software capable of automatically identifying road damage or signs of pavement quality degradation before they become more severe. The results of this study help support transportation management agencies by providing an overview of the health of each road within a road network and aiding in the efficient allocation of road maintenance funds. The software in this research not only achieves the goal of modernizing road patrol and maintenance activities but also opens avenues for exploring Industry 4.0 technologies in the development of intelligent traffic management systems.

Ren, D., Ishikawa, T., Si, J., & Tokoro, T. (2024). Effect of complex climatic and wheel load conditions on resilient modulus of unsaturated subgrade soil. *Transportation Geotechnics, 45*, 101186. DOI: https://doi.org/10.1016/j.trgeo.2024.101186

Resilient modulus (M_r) is a fundamental mechanical property vital for assessing the resistance of pavement structures to cyclic vertical loads. It has played a pivotal role in pavement design and has been instrumental in predicting pavement responses and fatigue life. The M_r of subgrade soil is affected by a multitude of factors, including stress, moisture, and temperature conditions, all of which interact to define the response of the soil. This research investigated the effect of complex climatic conditions on M_r with a particular focus on areas experiencing significant seasonal changes in snowy cold regions like Hokkaido, Japan. Previous studies have proposed predictive models for M_r, incorporating the concept of matric suction, to account for moisture conditions. However, these models have rarely considered suction hysteresis in the soil–water characteristic curve (SWCC) or the effects of wheel loading on frost-susceptible subgrade soil during different seasons. In this study, a series of M_r tests were conducted on two types of subgrade soil under various climatic and wheel loading conditions. The test results promise to enhance our understanding of the complex interplay of climatic and stress conditions on M_r of standard sand and frost susceptible subgrade soil along different drying and wetting paths, particularly in regions with significant seasonal variations.

Yao, L., Leng, Z., Ni, F., Lu, G., & Jiang, J. (2024). Adaptive maintenance strategies to mitigate climate change impacts on asphalt pavements. *Transportation Research Part D: Transport and Environment, 126*, 104026. DOI: https://doi.org/10.1016/j.trd.2023.104026

This study aims to explore the potential of optimization-based maintenance strategies in adapting asphalt pavements to future climate change. Based on a highway network in Jiangsu, China, the impacts of climate change, characterized by global warming and intensified precipitation, on pavement life cycle cost (LCC) and performance were quantitively assessed, and the benefits of maintenance optimization in mitigating climate change impacts were examined. The findings indicate that climate change may increase pavement rutting depth and reduce pavement roughness and skid resistance, while its effect on transverse cracking varies over time. Adjusting the maintenance schedules, but still following the threshold-based approach, would increase the LCC by about 15.5 %~19.1 %. The optimization-based maintenance decision-making model significantly mitigates climate change impacts, ultimately even saving 0.6 % of LCCs compared to the baseline. The outcomes will provide a quantitative understanding of the climate change impacts on asphalt pavements, as well as adaptive maintenance strategies to improve pavement resilience.

Zhang, C., Tan, Y., Gao, Y., Fu, Y., Li, J., Li, S., & Zhou, X. (2022). Resilience assessment of asphalt pavement rutting under climate change. *Transportation Research Part D: Transport and Environment, 109*, 103395. DOI: https://doi.org/10.1016/j.trd.2022.103395

The service performances of asphalt pavement, especially rutting, will be inevitably affected by climate change. However, existing studies have generally focused on the rutting depth and rutting life, and thus became insufficient for comprehensively evaluating the influence of climate change on rutting over the service life. A resilience assessment method for asphalt pavement rutting is developed to solve the above problem. First, the original resilience method is extended to fit the system whose performance level continues to decline. Then, the calculation formulas of rutting resilience are derived by combining the rutting prediction model and the level assessment model. Subsequently, the influence degrees of climate change in representative cities on rutting resilience are studied. The results suggest that neglecting climate change in rutting design of asphalt pavement will lead to insufficient resilience, especially in northern China. Furthermore, the predicted temperature under RCP8.5 should be employed for asphalt pavement design.

Geotechnical:

Argyroudis, S. A., Mitoulis, S. A., Winter, M. G., & Kaynia, A. M. (2019). Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. *Reliability Engineering & System Safety, 191*, 106567. DOI: https://doi.org/10.1016/j.ress.2019.106567

Vulnerability is a fundamental component of risk and its understanding is important for characterising the reliability of infrastructure assets and systems and for mitigating risks. The vulnerability analysis of infrastructure exposed to natural hazards has become a key area of research due to the critical role that infrastructure plays for society and this topic has been the subject of significant advances from new data and insights following recent disasters. Transport systems, in particular, are highly vulnerable to natural hazards, and the physical damage of transport assets may cause significant disruption and socioeconomic impact. More importantly, infrastructure assets comprise Systems of Assets (SoA), i.e. a combination of interdependent assets exposed not to one, but to multiple hazards, depending on the environment within which these reside. Thus, it is of paramount importance for their reliability and safety to enable fragility analysis of SoA subjected to a sequence of hazards. In this context, and after understanding the absence of a relevant study, the aim of this paper is to review the recent advances on fragility assessment of critical transport infrastructure subject to diverse geotechnical and climatic hazards. The effects of these hazards on the main transport assets are summarised and common damage modes are described. Frequently in practice, individual fragility functions for each transport asset are employed as part of a quantitative risk analysis (QRA) of the infrastructure. A comprehensive review of the available fragility functions is provided for different hazards. Engineering advances in the development of numerical fragility functions for individual assets are discussed including soil-structure interaction, deterioration, and multiple hazard effects. The concept of SoA in diverse ecosystems is introduced, where infrastructure is classified based on (i) the road capacity and speed limits and (ii) the geomorphological and topographical conditions. A methodological framework for the development of numerical fragility functions of SoA under multiple hazards is proposed and demonstrated. The paper concludes by detailing the opportunities for future developments in the fragility analysis of transport SoA under multiple hazards, which is of paramount importance in decision-making processes around adaptation, mitigation, and recovery planning in respect of geotechnical and climatic hazards.

Kim, K., Chun, J., & Yamashita, E. (2022). Building Back Better: Transportation Recovery Challenges From the 2018 Kaua`i Flooding Disaster. *Transportation Research Record, 2677(2)*, 1238-1251. DOI: 10.1177/03611981221111150

This study describes and analyzes the recovery of transportation systems damaged by flooding and landslides in 2018 on the island of Kaua'i, Hawai'i. Following describing the record-setting rainfall and massive landslides that closed the major highway connecting the North Shore communities with the rest of the island, the challenges of "building back better" are investigated. While there was an urgency to finish the roadway repairs as quickly as possible, there was also a need to reduce future risks from flooding and landslides. Strong leadership, coordination, communications, and resource sharing helped improve pre-existing traffic, congestion, parking, and accessibility concerns for residents and tourists. There are important lessons learned concerning the need for timely, accurate data and information. Mitigation and adaptation projects that go beyond simply replacing and repairing assets before the storm are also analyzed. Opportunities to utilize greener, nature-based, and context-sensitive design, engineering, and planning solutions to mitigate and adapt highways to climate-induced extreme events remain challenging even in a community known for scenic beauty, pristine natural areas, and rich cultural heritage. While the community-led efforts to implement improvements to the State park at the end of the road were exemplary, there are still ongoing challenges of increased climate threats and inflexible, limited systems for funding—not just in disaster recovery but also investments in community resilience

Meyer, M., & Dorney, C. (2023). *Climate Resilience Risk Assessment Tool and Guide: Literature Review, Technology Scan, and Interviews Report*. US Department of Transportation, Federal Highway Administration, Office of Operations. https://rosap.ntl.bts.gov/view/dot/73518

The purpose of this report is to identify current and emerging data collection, infrastructure surveillance and monitoring technologies, and similar approaches for monitoring changing environmental and weather conditions. In addition, the report examines the use of risk-based analysis tools to identify road locations potentially vulnerable to such changing conditions. The primary audiences for this report include transportation agency operations and maintenance managers and staff, transportation officials interested in strategies to minimize the impacts of extreme weather events, and those interested in the application of sensing and data collection technologies to manage better transportation system performance. The report is based on a literature review, technology scan, and on staff interviews from 10 transportation agencies. Most of the technology and practices identified in this report focused on flood monitoring and winter maintenance operations. From a technological perspective, research suggests that many of the challenges of advancing road weather management systems can be overcome with the application of current database management technologies and practices. Piggybacking on current and understood practices in State DOTs seems to be the major focus of many States. The use of nontraditional technologies as data collection platforms is another notable characteristic of the literature, e.g., use of unmanned aerial vehicles and automated/connected vehicles. There are very few examples of quantitative, risk-based approaches or practices in support of transportation decision making. This is particularly true for traffic and system operations. Most of the literature relating to extreme weather, climate change, and transportation system resiliency, especially the earliest citations, provide general descriptions of potential threats and of possible strategies to minimize the threats. In general, the literature review and interviews suggest that there is still a lack of understanding of risk-based planning and analysis.

Salunke, R., Khan, S., & Khan Md, F. (2023). Incorporating Advanced Imaging Techniques for Climate-Resilient Geotechnical Asset Management. *ASCE Inspire 2023,* 230-238. DOI: https://doi.org/10.1061/9780784485163.02

Geotechnical asset management (GAM) is in the early stages of adoption within transportation agencies, especially in Mississippi (MS). Geotechnical assets in central Mississippi are vulnerable to excessive deformation due to the high volume changing Yazoo clay, further impacted by the high amount of rainfall and seasonal variations. In a changing climate, high-intensity rainfall events add excessive loads on the geotechnical and transportation infrastructure assets causing catastrophic failures. Therefore a GAM program that addresses resiliency and climate adaptiveness is much needed. Infrastructure climate resilient design is geared toward recovering quickly from shocks from adverse effects due to natural hazards fueled by ever-increasing significant climate events. Geotechnical infrastructure assets should be built and maintained such that they are not only resilient but also adaptive to evolving climatological conditions. Highway authorities have attempted to incorporate resilience into their asset management programs in terms of uninterrupted performance under shifting conditions. However, there is a need to identify the damage and loss metrics for geotechnical assets and include them in the GAM. Furthermore, evaluation of climate-resilient geotechnical assets requires a precise examination of the effects of new extreme patterns on short- and long-term behavior. This is particularly accurate for geotechnical assets such as highway slopes built on high-volume changing clay whose performance and strength are impacted by long-term and short-term precipitation and temperature fluctuation. Without proper monitoring, the geotechnical assets are susceptible to failures causing significant social and economic impact. Integrating technologies to implement advanced monitoring and assessment techniques are much needed for a climate-resilient GAM. To this end, this study focuses on incorporating advanced imaging technologies such as electrical resistivity imaging (ERI) and uncrewed aerial vehicles (UAVs) with optical and thermal imaging sensors into geotechnical asset performance assessment. Furthermore, this study presents a methodology for using advanced imaging technologies in implementing a decision support structure to test and investigate the resilience and adaptiveness of geotechnical assets such as highway slopes in central Mississippi. The findings will benefit the decision-makers to implement robust geotechnical asset management solutions in light of the increased intensity and frequency of significant climate events.

Wolf, R. E., Bouali, E. H., Oommen, T., Dobson, R. J., Vitton, S., Brooks, C., & Lautala, P. (2015). *Sustainable Geotechnical Asset Management Along the Transportation Infrastructure Environment Using Remote Sensing: Final Report*. Michigan Technological University. https://rosap.ntl.bts.gov/view/dot/38809

This report summarizes the work and results obtained from USDOT Cooperative Agreement No. RITARS-14-H-MTU, on remote sensing applications for geotechnical asset management. Considering the context of transportation asset management, a framework for the application or remote sensing tools is developed, particularly for monitoring geotechnical asset surface displacement, as part of the monitoring necessary for geotechnical asset management. A review of the transportation asset management paradigm is given in chapter 1, and the requirements for remote sensing based geotechnical asset management are explored in chapter 2. A survey on current practices, perceived needs and limitations gives an overview of the perspective of transportation agencies on this topic. Appropriate technologies are identified and selected for the tasks most relevant to geotechnical asset management, as explained in chapter 3. Field verification and evaluation of the remote sensing technologies is reported in chapter 4, always within the context of geotechnical asset monitoring. The monitoring of geotechnical assets has the goal of continuously or frequently assess the assets' performance, according to the transportation management needs. Chapter 5 discusses asset performance definition and monitoring. Using the geotechnical asset condition information obtained from the monitoring requires some framework for decision making, the decision support system discussed in chapter 6 presents a web framework that contribute to this goal. Any implementation of new technology or methods requires and evaluation of its benefits, weighted against the costs of adopting such technologies, chapter 7 explores the costs of implementing remote sensing methods, and the value of the information that can be obtained from them. For transportation agencies to adopt the new technologies and implementation framework is necessary. Chapter 8 discusses the implementation framework for the remote sensing technologies tested in the project, giving also hypothetical examples on two of the field sites included in the project. The outreach components of the project are summarized in chapter 9, including the development of an outreach video and the multiple conference presentations and papers that were generated during the duration of the project.

Bridge:

Al Hawarneh, A., & Alam, M. S. (2025). Novel time-dependent seismic fragility assessment tool for existing RC highway bridges in a multi-hazard environment considering regular maintenance. *Engineering Structures, 330*, 119868. DOI: https://doi.org/10.1016/j.engstruct.2025.119868

In environments where bridges are subjected to multiple hazards over their lifetime, assessing the fragility of bridges solely under earthquake loading would not provide proper insights into the actual performance of bridges. Moreover, existing time-based fragility tools in the literature fail to accurately represent bridge behavior, as they depict corrosion as an ongoing process that continuously deteriorates the bridge until its end. This study addresses the necessity of employing realistic, time-dependent fragility tools that consider the impact of routine maintenance activities, such as concrete patching and grouting, in bolstering the future resilience of bridges. The performance-based assessment in this study is conducted on existing bridges that have already suffered from past corrosion. In this research, climate change scenarios are first investigated based on future forecast models to anticipate the temperature and relative humidity changes up to the year of 2100. Subsequently, corrosion is quantified in concrete and steel using the proposed climate change scenarios. Then, nonlinear static pushover analysis is conducted to assess the drift ratio at various limit states of the bridge. Based on the pushover curves, time-based fragility analysis is conducted to assess the performance of reinforced concrete bridge columns in various environments under different corrosion levels using multiple climate change scenarios. Accordingly, maintenance-adjusted fragility tools are developed using different maintenance strategies at various intervals. The proposed temporal fragility tools serve as a benchmark for bridge engineers to evaluate the seismic performance of existing bridges in multi-hazard environments.

Chirdeep, N. R., Gangwar, M., Shekhar, S., & Bahurudeen, A. (2025). Seismic resilience of deteriorating bridges under changing climatic conditions. *Engineering Structures, 324*, 119355. DOI: https://doi.org/10.1016/j.engstruct.2024.119355

This study underscores the critical need to integrate changing climatic conditions into corrosion models for civil engineering infrastructures, particularly highway bridges, given the potential reduction in structural performance post-seismic events. The paper introduces a novel framework for assessing the seismic resilience of deteriorated highway bridges in the context of changing climatic conditions. The framework is demonstrated on a non-seismically designed simply supported highway bridge situated near the sea in a seismically active region of Gujarat, India. An improved corrosion deterioration model is used that considers the impact of climate change and non-uniform pitting corrosion for evaluating the deterioration of RC bridge components. A detailed three-dimensional finite-element model of the

case-study bridge is developed that can accurately simulate various failure modes of corroding bridge piers. Time-varying seismic fragility curves are developed using damage limit states and probabilistic seismic demand models while considering the influence of climate change. Bridge seismic resilience is estimated by aggregating the seismic vulnerability, losses, and recovery functions. Results show that incorporation of changing climatic factors will considerably reduce the seismic resilience of the 75-year corroded bridge up to 56 %. Finally, a comparison of seismic fragility and resilience is carried out using the proposed and conventional corrosion deterioration model to evaluate the significance of considering the effects of climate change in the seismic resilience assessment framework.

Dong, Y., & Frangopol Dan, M. (2016). Probabilistic Time-Dependent Multihazard Life-Cycle Assessment and Resilience of Bridges Considering Climate Change. *Journal of Performance of Constructed Facilities, 30(5)*, 04016034. DOI: 10.1061/(ASCE)CF.1943-5509.0000883

Climate change and an increase in the number of hazards and/or their intensities may increase the probability of failure associated with civil infrastructure systems. Understanding how natural hazards affect the life-cycle performance of highway bridges can lead to improved preparedness prior to extreme disasters and can ultimately benefit society. In this paper, a framework for time-variant loss and resilience assessment of highway bridges under time-dependent multiple hazards is presented. The effects of earthquakes and floods on bridges are both investigated. The life-cycle hazard losses with and without aging effects and climate change are computed. Additionally, the probabilistic changes in the hazard intensity and frequency resulting from climate change on the total life-cycle hazard loss are also investigated. The proposed framework is applied to a highway bridge located in California.

Kopiika, N., Robery, P., Ninic, J., & Mitoulis, S. A. (2025). Remaining Life of Ageing RC Infrastructure for Sustainable development—Deterioration Under Climate Change. *Case Studies in Construction Materials, 22*, e04757. DOI: https://doi.org/10.1016/j.cscm.2025.e04757

This paper assesses structural deterioration in ageing reinforced concrete (RC) infrastructure assets, emphasizing the need for climate adaptation to ensure long-term sustainability. By advancing empirical models to account for the accelerating effects of climate change on carbonation-induced corrosion, this paper for the first time in international literature leverages material vulnerabilities, observed long-term trends degradation trends, and future climate projections to facilitate structural assessment for service life prediction. The method is then applied in two real-world case studies: a dam which also functions as a bridge in Ukraine, constructed in the 1930s, and a long-span bridge in Greece constructed in the 1970s. The models developed quantify the acceleration of carbonation rates under varying environmental conditions due to climate change, revealing regional differences of up to 25 % in degradation rates between coastal and inland areas in different climates (temperate continental and mediterranean).The study also highlights the limitations of standard corrosion models in capturing stress concentrations, cracking, and seismic effects in cantilevered structures, introducing ‘Achilles heel’ points—critical vulnerabilities in low-redundancy structures. The proposed modelling is a robust framework for predicting degradation, offering an effective approach for the global assessment of various reinforced concrete structures and informing optimized design and maintenance strategies. The findings demonstrate the importance of developing tailored adaptation strategies that align with specific environmental conditions. They provide actionable insights for engineers and policymakers to enhance the resilience of RC structures amidst evolving climatic challenges.

Mitoulis, S.-A., Bompa, D. V., & Argyroudis, S. (2023). Sustainability and climate resilience metrics and trade-offs in transport infrastructure asset recovery. *Transportation Research Part D: Transport and Environment, 121*, 103800. DOI: https://doi.org/10.1016/j.trd.2023.103800

Climate change exacerbates natural hazards and continuously challenges the performance of critical infrastructure. Thus, climate resilience and sustainable adaptation of infrastructure are of paramount importance. This paper puts forward a novel framework and metrics for optimising *sustainability* (Greenhouse Gas emissions - GHG), *climate resilience* (restoration time), and *cost*. The framework aims to facilitate decision-making by operators and stakeholders and communicate actionable trade-offs between these principles. It describes approaches for quantifying ex-ante adaptation and ex-post recovery from the lenses of sustainability and resilience using relevant metrics. This paper concludes with an application of the framework on a bridge, where normalised metrics are integrated into one unique index (I_{SRC}), which can be used in the recovery prioritisation for portfolios of similar assets. The optimisation program includes a bridge recovery, while reducing GHG emissions. The impact of climate change on the sustainability and resilience indexes is examined and the results show how the optimum solutions are adversely affected by different climate projections. In all scenarios examined, more sustainable solutions leading to reduced GHG emissions (tCO2e) are the optimum solutions when weighing resilience and cost. Based on the case study analysed in this paper, the low carbon restoration strategy resulted in up to 50% higher I_{SRC}, which can justify investments for low GHG adaptation strategies in transport assets.

Xu, M., & Yang, C. (2024). Bridges in a changing climate: Fragility-based approach for evaluating the time-variant performance of bridges subjected to heavy vehicle collisions. *Engineering Structures, 305*, 117717. DOI: https://doi.org/10.1016/j.engstruct.2024.117717

Climate change exacerbates the structural deterioration of concrete highway bridges, posing a threat for them to resist vehicle collisions. However, the investigation into the safety of highway bridges under the joint effects of climate change, deterioration, and collisions caused by heavy vehicles is lacking. This paper presents a practical framework for assessing the lifetime fragility of concrete highway bridges exposed to both heavy vehicle collisions and climate change-accelerated corrosion. The main challenge of applying fragility-based approach in this framework lies in developing surrogate demand models, which traditionally requires extensive time-consuming simulations of vehicle-bridge collisions using finite element methods. To overcome this, an impact force time history model is proposed as an efficient alternative to represent collision demands on bridge piers by heavy vehicles. Implementation of this model has demonstrated a remarkable reduction of approximate 90% in computational time requirements compared to the collision analysis. The framework enables the generation of fragility surfaces at any given time throughout the bridge's service life. The effectiveness of the framework is demonstrated using an example highway bridge, and fragility surfaces are generated for various climate scenarios. The results indicate a rise in the probability of collapse, from 0.4% for a structurally sound bridge to 87.2% after 80 years of chloride exposure when subjected to a heavy vehicle collision with an impact velocity of 100 kph and a truck weight of 36 t. Additionally, the impact of climate change is evident, further increasing this probability to 97.4%. These findings underscore the significant roles that both corrosion and climate change play in influencing the vulnerability of concrete bridges to heavy vehicle collisions. Addressing these factors in collision design and lifetime assessment is essential for ensuring the structural resilience and safety of bridges over time.

Zhang, D., Xiong, W., Ma, X., & Cai, C. S. (2024). Fragility Evaluation of Bridge Pile Foundation Considering Scour Development under Floods. *Journal of Bridge Engineering, 29(8)*, 04024052. DOI: 10.1061/JBENF2.BEENG-6665

Flooding occurrences have become increasingly severe, posing a serious danger to end-user safety and bridge resilience. As flood fragility assessment is a valuable tool for promoting the resilience of bridges to climate change, it is of great importance to push the development of such methods. However, flood fragility has not received as much attention as seismic fragility despite the significant amount of damage and costs resulting from flood hazards. There has been little effort to estimate the flood fragility of bridges considering various flood-related factors and the corresponding failure modes. To this end, a fragility-based approach that can explicitly address the scour-hole geometry and flood-induced lateral load is presented. First, a three-dimensional finite-element model with pile foundations and surrounding soil was established to estimate the failure mode under various flood scenarios. The loadings on pile foundations were characterized by vertical loading from the superstructure, horizontal loading from the flood-induced lateral load, and the scour effect simulated through a time-history analysis. Then, all potential failure modes of bridge pile foundations in various flood scenarios were summarized. Based on extensive parameter investigations using the deterministic method, the dominant failure mode of penetration failure was determined, and a failure envelope was fitted to guide the design of the pile foundation. Upon establishing the failure mode, a probabilistic fragility analysis considering uncertainties in hydraulic, structural, and geological parameters was finally conducted using the Latin hypercube sampling (LHS) method. The results showed the effects of variation on the fragility of the pile foundation, highlighting that the deterministic analysis without considering the uncertainties in model parameters leads to underestimating the risk due to the penetration failure and the significant influence region.

Highway:

Byron, E., & Nelson, P. A. (2023). Probabilistic Modeling of Landslide Hazards to Improve the Resilience of Transportation Infrastructure. Mountain-Plains Consortium. https://rosap.ntl.bts.gov/view/dot/68407

Precipitation-induced landslides pose risks to humans through property damage, disruption of infrastructure, injury, and loss of life. These risks may be altered by climate change, as changes in vegetation cover and associated root cohesion might lead to a change in areas susceptible to landslides. We investigate this possibility through Monte Carlo simulations of slope stability in the Colorado Front Range, where climate change is expected to significantly change vegetation cover across the landscape. Climate change simulations predict an overall increase in the area susceptible to landslides and a shift to more instability on north-facing slopes. Our study suggests that vegetation changes due to climate change could result in major shifts in the people and infrastructure susceptible to landslides. We also apply a landslide runout model to a large spatial scale to determine whether simplified assumptions using easily accessible data can provide realistic estimates of landslide stopping locations. We consider stopping rules using slope, curvature, and travel distance and find that a combination of a critical angle and a distance the landslide must maintain beneath the critical angle best predicts stopping locations in our study area

Mohamed, K., & Shen, J.-D. (2024). Exploring the Potential for Incorporating Artificial Intelligence in Highway Resilience to Climate Change. *Transportation Research Record, 2679(1)*, 670-678. DOI: 10.1177/03611981241253610

Highway infrastructure needs to be able to withstand, recover quickly, and adapt to the extreme conditions and loads associated with climate change and other natural hazards. Investigation of new analysis methods of the different types of data for improving transportation resilience is critical. The highway owners are challenged with managing the highway geotechnical features and structures to achieve the adaptive capability. The optimization of the investment requires quantification of the changing hazards and correlation to infrastructure performance. The use of new and broader data sources and artificial intelligence (AI) and machine learning (ML) opens a door to more efficient development of necessary models with many potentially relevant variables and a more adaptive updating process. Climate tools developed by the Federal Highway Administration could be integrated with or enhanced using AI/ML modules trained using properly selected data. The improvement of infrastructure resilience also depends on adequate evaluation of the probability of various damage levels from extreme events. The application of AI/ML on a broader data source will enable data-driven probabilistic damage modeling approaches that are often not feasible using traditional regression processes. This paper discusses from a user's point of view several potential applications that could take advantage of AI/ML techniques and big data availability, including geotechnical asset management, geohazard programs, and probabilistic damage evaluation. Challenges in current practice are analyzed and connected to the need for a new approach. The anticipated applicable areas are offered to the AI/ML professionals to consider for further studies.

Nasrazadani, H., Adey Bryan, T., Moghtadernejad, S., Alipour, A., & Dorren, L. (2025). Simulation-Based Evaluation of Resilience-Enhancing Measures for Transportation Systems Subject to Hydrometeorological Hazard Events. *Journal of Infrastructure Systems, 31(1)*, 04024035. DOI: 10.1061/JITSE4.ISENG-2512

This paper identifies the essential requirements for simulation-based approaches such that these approaches serve as effective decision support tools for evaluating the effectiveness of climate-adaptation measures that enhance the resilience of transport systems against hydrometeorological events. These requirements include the ability to capture the effect of different types of measures, the spatial and temporal possibilities of their execution, their aggregate effect when executed together, and the effect of uncertainties in their evaluation. A novel simulation-based approach that meets the identified requirements is presented, and its application in a case study is showcased. The presented approach uses a set of interacting probabilistic models to generate numerous scenarios, each representing chains of cascading events from the occurrence of a possible hazard event, the impact on the assets and the network, restoration of the infrastructure, and the temporal evolution of its service. The models enable capturing the effect of resilience-enhancing measures on the intensity of hazard events and their ensuing consequences. The case study includes a road system in Switzerland comprising 605 km of roads and 121 bridges and subject to rainfall events leading to flooding and landslide. Twenty-one portfolios of measures combining four specific types are considered, and their effect on resilience was evaluated. Those include flood protection walls, stormwater retention basins, raising road embankments, and temporary flood barriers. The proposed approach enables infrastructure managers to engage in an appropriate quantitative evaluation to better devise and plan measures with the aim of cost efficiently improving resilience.

Proctor, G., Varma, S., & Smadi, O. (2023). *How Pavement and Bridge Conditions Affect Transportation System Performance*. US Department of Transportation, Federal Highway Administration, Office of Operations. https://rosap.ntl.bts.gov/view/dot/73519

This document takes an expansive view and considers how pavement and bridge conditions can contribute to system performance areas, such as highway safety, freight mobility, or reliability. The document also considers other impacts, such as how attributes such as pavement shoulders, pavement friction, or bridge conditions contribute to highway safety, freight movement, noise reduction, and transportation system resilience. This document also includes three fictional transportation asset management plan (TAMP) chapters illustrating how the TAMP could directly support multiple transportation performance objectives. Those chapters are the performance gap analysis, risk assessment, and investment strategies.

Rahman, F., Zohuruzzaman, A. Q. M., Khan, S., & Whyte, T.-N. (2025). Evaluation of Climate Resiliency of Highway Embankment Using LiDAR and Electrical Resistivity Imaging. *Geotechnical Frontiers 2025*, 89-99. DOI: https://doi.org/10.1061/9780784485996.0

Climate change has been playing a crucial role in altering the precipitation patterns in the southern USA. States like Mississippi, Louisiana, and Alabama have seen increased numbers of extreme events like hurricanes, storms, and heavy rainfall. Therefore, rainfall-induced landslides have been very common in recent years. In Mississippi, due to the prevalence of highly expansive clay soil, slope failure has brought about a huge financial burden for the authority. In order to create resiliency in highway embankments, regular monitoring and early detection of landslide risks are important. The objective of the current study is to evaluate the landslide behavior of highway slopes under changed climatic conditions. One highway slope near Grenada, Mississippi, was selected for the study. The slope has a history of shallow landslide. Remote sensing technology like Light Detection and Ranging (LiDAR) has been utilized to compare the topographical surfaces in different seasons. Electrical Resistivity Imaging (ERI) was performed, and seasonal variations in subsurface moisture contents were obtained from the ERI profiles. In addition, rainwater data of the site location from available open sources were collected. Perched water zones have been detected through the ERI images when there were events of extreme rainfall. A drone mounted with an advanced LiDAR scanning system has been utilized to detect any trend of slope movement in the study site. The LiDAR scan gathered dense point cloud data to construct 3D surfaces and produce topographic maps of the slope. The integration of ERI and LiDAR provides a comprehensive understanding of the climate resilience of highway slopes in the face of climate change.