Drainage Deficiencies and Flexible Pavement Deterioration with a Framework for Indian Highway Investigation

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Abstract — Drainage-related pavement deterioration is difficult to diagnose because moisture, traffic loading, construction quality and pre-existing distress can interact. A pavement survey that records potholes alongside blocked drains does not by itself establish which mechanism caused the damage. This focused narrative review examines official pavement guidance and selected experimental, forensic and modelling research on moisture entry, drainage performance and flexible pavement distress. It develops a proposed framework for investigating Indian highway sections through linked drainage, moisture and condition observations. The framework separates rainfall exposure from drainage function, treats existing cracking as a possible pathway for moisture entry, and recommends repeated measurements across seasons. A prospective matched-section design is presented with an explicit causal question, drainage-restoration intervention records and a statistical strategy for separating total and mediated effects. The synthesis supports mechanism-based investigation rather than a uniform assumption that adding drains will resolve every pavement failure. No Indian case-study dataset, measured deterioration rate or quantified maintenance benefit is reported. The paper provides a testable research design and a maintenance decision framework whose local performance remains to be established.

Keywords: Pavement Drainage; Moisture Damage; Flexible Pavements; Pavement Deterioration; Monsoon; Maintenance Prioritisation

I. Introduction

Pavement drainage is a functional system comprising entry control, internal water movement and discharge to a suitable outlet. Recording the presence of a roadside drain provides only partial information about that system. For research purposes, the relevant question is whether the pavement retains damaging moisture under the loading and environmental conditions it experiences. That question requires observations beyond the surface appearance of the drain.

The selected literature connects moisture with pavement material behaviour [1], investigates moisture entry through cracking [2], and reports field or model-based assessments of drainage arrangements [3, 4]. Forensic evidence also identifies interacting construction and drainage factors in early pavement failures [5]. Together these sources justify examining multiple causal pathways rather than assigning all wet-season damage to a single deficiency.

The objectives of this paper are to synthesise those pathways, define variables for an Indian highway investigation and propose a design capable of testing drainage-related deterioration. The scope is flexible pavement. Concrete pavement joint deterioration and hydraulic design of major waterways are outside the analysis. Indian highway relevance is prospective: no Indian field case is presented, and foreign performance values are not transferred as local estimates.

II. Review Method

A focused narrative search was conducted on 1 November 2026 using terms including “pavement drainage moisture deterioration FHWA research”, “Effectiveness of INDOT drainage 2019” and the titles of identified technical reports. Five directly relevant sources were selected from FHWA, Purdue University's research repository and the United States National Transportation Library. Selection favoured an identifiable publisher, a clear technical mechanism and an accessible account of methods or findings.

The review used the accessible reference-manual chapter [1], the official report description [2], repository abstracts [3, 4] and the official forensic-report summary [5]. It did not extract uninspected report tables or conduct a systematic database search. Results are discussed at the level supported by those accessible materials. No pooled estimates, quantified causal effects or claims about the prevalence of drainage defects in India are made. A targeted full-text expansion would be required for a comprehensive journal review.

III. Evidence on Mechanisms and Performance

A. Moisture Sources and Material Response

The FHWA geotechnical reference manual [1] describes moisture entry from groundwater, lateral movement, pavement edges and other pathways, and explains the relevance of drainage to pavement performance. Its treatment supports an important distinction: rainfall is an external exposure, while the moisture retained within a pavement depends on the structure and its surroundings. Groundwater-related problems may persist when a surface drain appears unobstructed. This guidance establishes a mechanism, not a locally calibrated deterioration relationship.

Masud and Haider's LTPP study [2] investigates moisture infiltration through surface cracking and its implications for pavement performance. The accessible report description supports treating cracking as a possible input to moisture damage rather than solely an outcome. This is a key problem for observational inference: severe distress and poor moisture conditions may develop together. The description alone is insufficient to reproduce the report's equations or estimate the reduction in life for another pavement.

B. Drainage Effectiveness and Structural Tradeoffs

Feng, Hua and White [3] monitored three Indiana test sections using environmental records, drainage observations and subsequent pavement testing. Their repository abstract reports that the drainage systems continued to function effectively and that the alternatives differed in drainage

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speed. The study is valuable because it considers both water removal and the stability of drainage layers. A successful hydraulic response should therefore be evaluated alongside mechanical performance, rather than assumed to guarantee it.

Ghavami et al. [4] used laboratory hydraulic properties and finite-element modelling to examine drainage layers, filters and edge drains under Indiana conditions. Their reported findings indicate benefits for subgrade moisture control and acknowledge material and construction tradeoffs. The results support conditional design assessment: an open-graded layer is one possible solution within a pavement system, not a universal retrofit prescription. Local materials, groundwater, outlet conditions and structural demands still require investigation.

C. Forensic Evidence and Causal Ambiguity

Scholz and Rajendran [5] investigated early failures following rehabilitation on five Oregon interstate projects. The official summary identifies likely interacting causes including tack-coat problems, permeable layers, inadequate drainage and possible compaction deficiencies. This evidence cautions against inferring cause from one visible feature. A blocked drain may coexist with an asphalt-layer problem, and cleaning that drain may not restore an already damaged structure.

The synthesis therefore supports a sequence of diagnosis, intervention and outcome monitoring. It does not support a general percentage improvement from drainage maintenance. The unresolved research question is how much drainage function explains subsequent distress after baseline condition, material properties, traffic loading and environmental exposure have been considered on Indian highway sections.

Source	Evidence contribution	Transfer limitation
FHWA manual [1]	Moisture pathways and design considerations	Guidance rather than an Indian performance model
LTPP study description [2]	Cracking as a moisture-entry pathway	Detailed estimates not extracted
Indiana monitoring [3]	Drainage and structural behaviour observed together	Small experimental setting and local materials
Indiana modelling [4]	Drainage alternatives and moisture response	Results depend on model inputs and boundaries
Oregon investigation [5]	Competing causes of premature distress	Selected failure cases do not establish prevalence

Table 1: compares the types of evidence used.

IV. Proposed Investigation Framework

A. Causal question and observation unit

The proposed primary question is whether restoring deficient drainage reduces the subsequent rate of pavement deterioration compared with otherwise similar sections that do not receive the same intervention during that period. This is narrower and more testable than asking whether wet pavements are generally worse. Intervention eligibility, maintenance timing and the outcome measure should be specified before analysis.

The observation unit should be a homogeneous pavement section with consistent layer structure, rehabilitation history, traffic conditions and drainage arrangement. Its length should be determined by those changes rather than imposed uniformly across every road. Both carriageway edges should be inspected where relevant. Repeated records must retain the same section boundaries so that changes in condition can be separated from changes in the sampling unit.

A proposed causal structure places rainfall and drainage condition upstream of retained moisture, which influences material response and distress. Traffic load, subgrade characteristics and pavement age may affect the observed relationship. Baseline cracking may both precede the intervention and increase moisture entry. Subsequent cracking can become part of a feedback process. The analysis should identify these temporal positions instead of combining all measurements into a single cross-sectional regression.

B. Measurement Plan

The proposed survey should measure drainage function, not simply asset presence. Records should cover obstruction, continuity, outlet condition, shoulder levels, water marks and observed ponding. Where safe and technically justified, measurements after rainfall should document water recession. Moisture sensors or targeted subsurface observations can provide more direct evidence than visual indicators, but their calibration and installation influence must be recorded.

Variable group	Suggested measurement	Analytical purpose
Drainage function	Obstruction, outlet continuity, recession time	Identify the deficiency and restoration achieved
Moisture state	Calibrated water content or saturation indicator	Test the proposed intermediate mechanism
Distress progression	Mapped cracking, rut depth, pothole area	Measure change using consistent definitions
Pavement and loading	Layer history, material data, axle-load information	Control important competing explanations
Environmental exposure	Event rainfall, antecedent rain, groundwater evidence	Separate weather exposure from drainage response
Interventions	Date, location, scope, associated resurfacing	Avoid assigning combined-work effects to drainage alone

Condition surveys should distinguish distress type, severity and extent. A single combined condition index can

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hide different responses: a rut may reflect structural deformation, whereas a pothole record may also depend on patching frequency. Photographs should use repeatable location references, and ambiguous cases should be independently reviewed. Missing observations during heavy rain should be recorded because they may omit the most informative events.

V. Proposed Empirical Methods

A. Design and sampling

A prospective panel should include candidate sections across contrasting terrain, drainage arrangements and soil conditions, with surveys before and after at least one wet season where feasible. Several survey rounds are preferable to a single before-and-after pair. The required duration should reflect the expected deterioration rate; a short study may measure moisture changes without being capable of detecting structural benefits.

Intervention sections should be matched to comparison sections on baseline distress, pavement age, structure, loading and environmental exposure. A pilot should estimate measurement variability and within-road correlation to inform sample size. It would be inappropriate to withhold urgent drainage work for research. Comparison selection should follow independently determined maintenance scheduling, and that selection process must be documented because it can introduce confounding by indication.

B. Statistical strategy

For a continuous distress outcome, a candidate repeated-measures model is $Y_{it} = \alpha_i + \lambda_t + \beta(\text{Treated}_i \times \text{Post}_t) + \gamma X_{it} + \varepsilon_{it}$. Here α_i represents section effects, λ_t represents common survey-period effects, and β is the intervention-associated change under the model assumptions. This difference-in-differences form requires a credible parallel-trends argument and absence of unaccounted differential interventions. It is not automatically causal because matching was performed.

Binary failures or counts require suitable alternative models, and maintenance that removes distress changes the meaning of the outcome. A new overlay must therefore be identified as an intervention rather than coded as spontaneous recovery. Standard errors should account for correlated observations within roads or intervention groups. Where there are few independent clusters, uncertainty methods and inferential limits should be explicitly discussed.

The primary model should estimate the total effect of restoration without automatically adjusting for post-restoration moisture, which may mediate that effect. A separate mechanism analysis can examine whether restoration changes moisture and whether that change precedes deterioration differences. This distinction avoids controlling away the process the study is attempting to investigate. Baseline moisture and baseline distress remain useful for design and adjustment where justified.

C. Quality Checks and Interpretation

Field instruments should be checked before repeated surveys, and a subset of sections should be assessed twice to estimate measurement repeatability. Rainfall data should be associated with a documented station or verified spatial product. A record that combines unrelated rainfall and distress periods cannot support event-level interpretation. Sensitivity tests should consider alternative section definitions; exclusion of combined drainage-and-overlay works and different assumptions about missing observations.

Results should be expressed as changes in the actual outcome units, with uncertainty intervals and baseline distributions. Relative percentages alone can exaggerate small baseline differences. Analyses should also report whether moisture response and distress response agree: an intervention may restore water discharge yet show no detectable surface improvement during the available follow-up. That outcome would not by itself prove that the drainage work was ineffective.

VI. Maintenance Decision Framework

The proposed decision sequence begins with identifying the likely water source and determining whether the discharge path functions. Surface maintenance may be appropriate for an obstructed functioning drain, but an unsuitable outlet or groundwater inflow requires a different investigation. Where subsurface material damage is suspected, targeted testing should precede an assumption that cleaning alone will restore serviceability. These are diagnostic recommendations, not verified treatment-effect estimates.

Economic evaluation should compare complete treatment alternatives over a common horizon, including inspection, recurrent cleaning, repair, user disruption and rehabilitation costs. Benefits attributed to drainage should come from locally observed or transparently modelled performance. Discount rates, cost dates and uncertainty ranges must be stated. A sensitivity analysis is especially important when the main benefit is a projected extension of pavement life rather than an observed reduction in repair expenditure.

VII. Limitations and Future Research

The review is geographically weighted toward United States research and uses accessible summaries for several reports. It cannot establish the adequacy of any Indian highway drainage arrangement or confirm that every relevant publication has been captured. No model has been fitted and no proposed variable has been validated. Future work should obtain full texts, add Indian longitudinal studies, and test whether the framework remains useful across different climates and construction practices.

VIII. Conclusion

The selected evidence supports investigating drainage within a coupled moisture, material and loading system. It also shows why observed drainage deficiencies should not be treated as conclusive proof of the cause of every pavement failure. The proposed repeated-section design links restoration, moisture response and distress progression while making competing explanations explicit. Its main contribution is a testable route from field diagnosis to performance evaluation, rather than a claimed universal drainage benefit.

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IX. DECLARATIONS

Data availability: No original field or laboratory dataset was generated. Research status: All equations and survey procedures are proposed; no Indian case study or numerical result is claimed. Author affiliations, funding and competing interests require completion by the submitting authors.

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