

Highway Drainage System: A Comprehensive Study on Design, Importance, and Maintenance

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Abstract:

A highway drainage system is one of the most important components of highway engineering because it protects roads from water-related damage and increases the life span of pavements (**Federal Highway Administration [FHWA], 1992**). Improper drainage leads to pavement deterioration, potholes, erosion, reduced driving safety, and increased maintenance costs (**Ahmed, White, & Bourdeau, 1993**). This research paper discusses the concept, objectives, types, components, design considerations, maintenance practices, and recent advancements in highway drainage systems. The study also highlights the importance of surface and subsurface drainage in maintaining pavement performance and traffic safety. Modern sustainable drainage practices and the use of geotextiles and permeable drainage layers are also discussed. The paper concludes that an efficient highway drainage system is essential for durable, safe, and economical transportation infrastructure.

Keywords — Highway drainage, surface drainage, subsurface drainage, pavement deterioration, stormwater management, highway engineering.

I. INTRODUCTION

Highways are exposed to rainfall, runoff, groundwater seepage, and flooding throughout their service life. Water is considered one of the most

harmful factors affecting pavement performance because it weakens the subgrade soil and reduces pavement strength (**Ahmed et al., 1993**). Therefore, an efficient highway drainage system is necessary to

remove excess water from the pavement surface and subsurface layers.

The primary purpose of highway drainage is to collect, convey, and dispose of water safely without causing damage to the roadway structure or surrounding environment. Proper drainage improves road safety, prevents hydroplaning, minimizes erosion, and reduces pavement maintenance costs (FHWA, 1994).

II. Objectives of Highway Drainage System

The major objectives of highway drainage systems are:

- 1) To remove rainwater quickly from the pavement surface.
- 2) To prevent water infiltration into pavement layers.
- 3) To protect embankments and side slopes from erosion.
- 4) To maintain pavement strength and durability.
- 5) To improve road safety and riding comfort.
- 6) To reduce maintenance and rehabilitation costs.

To prevent flooding and waterlogging on roads.

These objectives improve the overall efficiency and life span of highways (Hagen & Cochran, 1996).

III. Importance of Highway Drainage

Highway drainage plays a significant role in pavement performance and transportation safety. Water entering pavement layers causes weakening of the subgrade and formation of cracks and potholes. Efficient drainage systems help in maintaining structural stability and extending pavement life (Mallela, Titus-Glover, & Darter, 2000).

The importance of highway drainage includes:

- Prevention of pavement failures.
- Reduction in hydroplaning accidents.

- Improved skid resistance.
- Protection of pavement foundation.
- Increased service life of highways.
- Reduced repair and maintenance expenditure.

According to Wyatt and Macari (2000), highways with proper drainage systems show better structural performance and lower maintenance requirements compared to poorly drained pavements.

IV. Types of Highway Drainage

Highway drainage systems are mainly classified into two categories:

A. Surface Drainage:

Surface drainage removes water from the road surface before it infiltrates into pavement layers (FHWA, 1992).

Components of Surface Drainage:

- a) Camber or Cross Slope:
Camber provides a transverse slope to the pavement surface to facilitate water runoff toward the edge.
- b) Side Drains:
These are channels constructed along the roadway to carry runoff water safely away.
- c) Catch Water Drains
Constructed on hill roads to intercept runoff from higher ground.
- d) Kerbs and Gutters
Used in urban roads to collect and direct stormwater.
- e) Culverts
Structures provided under roads to allow natural water flow across highways.
- f) Storm Sewers
Underground pipelines used in urban highways to convey rainwater.

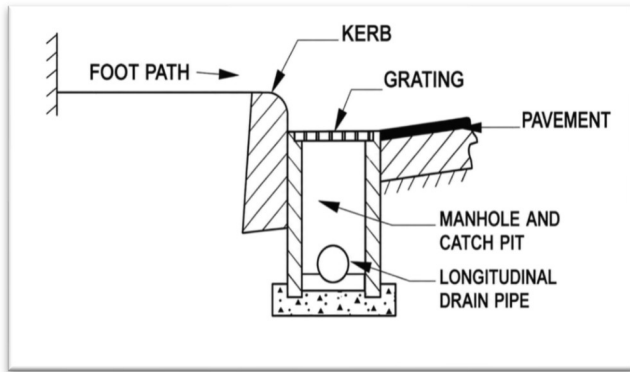


Figure 1. Surface Drainage System.

B. Subsurface Drainage

Subsurface drainage removes water that infiltrates into pavement layers and subgrade soil.

Components of Subsurface Drainage

- a) Longitudinal Drains
 Provided parallel to the roadway to remove infiltrated water.
- b) Edge Drains
 Installed along pavement edges to drain water from the base course.
- c) Drainage Layer
 A permeable layer placed below the pavement to facilitate quick water movement.
- d) Geotextiles
 Used as filter materials to prevent clogging of drainage systems.

Research by **Xu, Chen, and Wang (2022)** indicates that permeable drainage layers and geotextiles significantly improve pavement drainage efficiency and reduce moisture-related pavement distress.

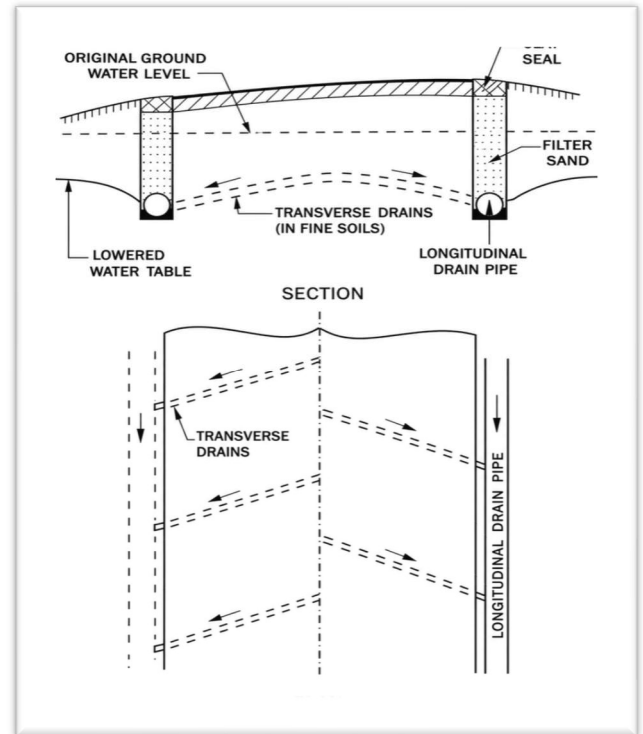


Figure 2. Subsurface Drainage System.

V. Design Considerations for Highway Drainage

The design of highway drainage systems depends on several factors:

- a) Rainfall Intensity
 Drainage structures must be designed according to local rainfall data and storm frequency.
- b) Topography
 Road alignment and surrounding terrain influence runoff flow patterns.
- c) Soil Characteristics
 Permeability and drainage properties of soil affect subsurface drainage design.
- d) Pavement Type
 Flexible and rigid pavements require different drainage considerations.
- e) Traffic Volume

High-traffic highways require stronger and more efficient drainage systems. increases maintenance expenditure (Wyatt & Macari, 2000).

- f) Environmental Conditions
Flood-prone and coastal regions need special drainage arrangements.

The Federal Highway Administration (1994) emphasizes that proper drainage design is essential for pavement durability and long-term highway performance.

VI. Causes of Drainage Failure

Highway drainage systems may fail due to:

- Poor design
- Insufficient slope
- Clogging of drains
- Sediment deposition
- Lack of maintenance
- Improper construction
- Heavy rainfall and flooding

Drainage failure results in waterlogging, pavement cracks, rutting, potholes, and erosion (Ahmed et al., 1993).

VII. Maintenance of Highway Drainage System

Regular maintenance is necessary for effective drainage performance.

Maintenance Activities

- 1) Cleaning of side drains and culverts
- 2) Removal of debris and vegetation
- 3) Inspection of drainage structures
- 4) Repair of damaged channels
- 5) Flushing of storm sewer systems
- 6) Maintenance of geotextile filters

Studies have shown that lack of drainage maintenance significantly reduces pavement life and

VIII. Modern Trends in Highway Drainage

Modern highway drainage systems focus on sustainability and climate resilience.

- a) Sustainable Drainage Systems (SuDS)
These systems reduce runoff and improve groundwater recharge through:
 - 1) Permeable pavements
 - 2) Bioswales
 - 3) Retention ponds
 - 4) Vegetated channels
- b) Use of Geotextiles
Geotextiles improve filtration and prevent clogging in drainage systems (Yeo, Araújo, & Maksimović, 2018).
- c) Smart Drainage Monitoring
Advanced sensors and AI-based monitoring systems help detect flooding and drainage blockages.
- d) Climate-Resilient Drainage Design
Modern drainage systems are designed considering extreme rainfall and flood events caused by climate change. Climate-resilient drainage designs help minimize flood-related pavement damage and improve infrastructure sustainability (Zhang & Mishra, 2019).

IX. Advantages of Proper Highway Drainage

- Increases pavement life
- Reduces maintenance cost
- Improves driving safety
- Prevents erosion and flooding
- Enhances riding quality
- Protects pavement foundation
- Reduces traffic disruption

Proper drainage also improves economic efficiency by reducing frequent repairs and rehabilitation costs (Hagen & Cochran, 1996).

X. Highways Design and Analysis

Effective drainage is a critical requirement for roads in hilly and mountainous regions, where intense rainfall, steep slopes, and surface runoff can rapidly weaken pavement layers and trigger slope instability. Proper surface and subsurface drainage systems, including side drains, catch water drains, cross-drainage structures, and adequate pavement drainage layers, are essential to prevent water infiltration, erosion, and moisture-related pavement distress. Improved drainage not only enhances pavement durability and structural stability but also reduces maintenance requirements and extends service life under challenging environmental conditions.

Road construction in hilly and mountainous regions faces significant challenges due to steep gradients, unstable slopes, heavy rainfall, drainage issues, and difficult terrain. These conditions accelerate pavement deterioration through moisture ingress, erosion, and slope instability, necessitating durable and sustainable construction materials. Previous studies by Ranadive and Tapase (2012, 2013, 2016) and Tapase and Ranadive (2016, 2017) demonstrated that pavement performance is strongly influenced by traffic loading, material properties, temperature, and environmental conditions, with finite element modeling serving as an effective tool for performance prediction.

In hilly regions, inadequate drainage and heavy rainfall are major contributors to premature pavement failures. Reviews by Chandak et al. (2017, 2018) and Sayyed et al. (2021) identified drainage, traffic loading, environmental factors, and material characteristics as critical performance parameters. Studies by Sayyed et al. (2019), Tapase et al. (2020), and Patil et al. (2021) further reported that overloading, poor drainage, and unsuitable construction practices are primary causes of pavement distress.

To improve sustainability and performance, researchers have explored the use of waste plastic, e-waste, crumb rubber, bagasse ash, and reclaimed

asphalt pavement (RAP), demonstrating enhanced engineering properties and reduced dependence on virgin materials (Chandak et al., 2019; Dombe et al., 2019; Sayyad et al., 2022; Tapase et al., 2022). Among alternative materials, steel slag has emerged as a promising aggregate due to its high strength, abrasion resistance, load-bearing capacity, and improved drainage characteristics, making it suitable for hilly road construction.

Although substantial progress has been made in pavement performance evaluation, sustainable materials, and subgrade stabilization, limited research has focused on the application of steel slag in hilly regions. Studies addressing the combined effects of steep gradients, drainage conditions, slope stability, and environmental exposure on steel slag-based pavements remain scarce. Therefore, further investigation is required to assess the suitability of steel slag for enhancing the durability, stability, and long-term performance of roads in mountainous areas.

XI. Conclusion

Highway drainage systems are essential for the safety, durability, and performance of roads. Water is one of the major causes of pavement deterioration; therefore, proper surface and subsurface drainage systems are necessary for efficient highway functioning (Ahmed et al., 1993). Modern drainage techniques such as permeable drainage layers, geotextiles, and sustainable drainage systems have significantly improved pavement performance (Xu et al., 2022). Regular inspection and maintenance are equally important to ensure the long-term effectiveness of drainage systems. Future highway projects should focus on sustainable and climate-resilient drainage designs to minimize flood damage and improve transportation infrastructure reliability.

XII. References

- 1) Ahmed, Z., White, T. D., & Bourdeau, P. L. (1993). *Pavement drainage and pavement-shoulder joint evaluation and rehabilitation*. Purdue University Research Repository.
- 2) Federal Highway Administration. (1992). *Drainable pavement systems (Participant Notebook)*. U.S. Department of Transportation.

- 3) Federal Highway Administration. (1994). *Drainable pavement systems (Instructor's Guide)*. U.S. Department of Transportation.
- 4) Hagen, M. G., & Cochran, G. R. (1996). Comparison of pavement drainage systems. *Transportation Research Record*, 1519(1), 1–10.
- 5) Mallela, J., Titus-Glover, L., & Darter, M. I. (2000). Considerations for providing subsurface drainage in jointed concrete pavements. *Transportation Research Record*, 1709(1), 1–9.
- 6) Wyatt, T. R., & Macari, E. J. (2000). Effectiveness analysis of subsurface drainage features based on design adequacy. *Transportation Research Record*, 1709(1), 70–78.
- 7) Xu, G., Chen, J., & Wang, T. (2022). Sustainable pavement drainage systems: Subgrade moisture, subsurface drainage methods and drainage effectiveness. *Construction and Building Materials*, 347, 129950.
- 8) Yeo, I., Araújo, M., & Maksimović, Č. (2018). Exploring the effects of geotextiles in the performance of highway filter drains. *Geotextiles and Geomembranes*, 46(5), 559–565.
- 9) Zhang, R., & Mishra, D. (2019). Design approach for drainage layer in pavement subsurface drainage system considering unsaturated characteristics. *Transportation Geotechnics*, 18, 57–71.
- 10) Chandak, P. G., Patil, R. P., Tapase, A., Attar, A. C., & Sayyed, S. S. (2018). Performance evaluation of low volume rural roads: A state-of-the-art review. In *Civil Infrastructures Confronting Severe Weathers and Climate Changes* (pp. 43–57). Springer. https://doi.org/10.1007/978-3-319-95750-0_4
- 11) Chandak, P. G., Sayyed, S. S., Tapase, A. B., Patil, O. D., & Kumbhar, S. S. (2025). Stabilizing the black cotton subgrade soil utilizing cow dung and sugarcane bagasse ash for design of rural roads. In *Proceedings of the International Conference on Construction, Real Estate, Infrastructure & Project Management* (pp. 144–158). Springer Nature. https://doi.org/10.1007/978-981-96-3357-4_10
- 12) Chandak, P. G., Tapase, A. B., Patil, R. P., Sayyed, S. S., & Attar, A. C. (2019). Utilizing different wastes in rural roads of Karad, District–Satara, India. *International Journal of Innovative Technology and Exploring Engineering*, 9(1), 3464–3469. <https://doi.org/10.35940/IJITEE.A4906.119119>
- 13) Chandak, P. G., Tapase, A. B., Patil, R. P., Sayyed, S. S., & Attar, A. C. (2021). Design charts for black cotton subgrade soil in Karad Taluka: A case study. *Innovative Infrastructure Solutions*, 6(1), Article 3. <https://doi.org/10.1007/s41062-020-00395-8>
- 14) Chandak, P. G., Tapase, A. B., Sayyed, S. S., & Attar, A. C. (2017). A state-of-the-art review of different conditions influencing the behavioral aspects of flexible pavement. In *Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology* (pp. 300–312). Springer. https://doi.org/10.1007/978-3-319-61902-6_25
- 15) Dombe, S., Tapase, A. B., Ghugal, Y. M., Konnur, B. A., & Patil, A. (2019). Investigation on the use of e-waste and waste plastic in road construction. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Sustainable civil infrastructures: Innovative infrastructure geotechnology* (pp. 85–99). Springer. https://doi.org/10.1007/978-3-319-95750-0_8
- 16) Gade, A., Kulkarni, S., Tapase, A., & Bonde, S. (2019). A cost-effective approach towards road construction—Kondave: A case study. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Civil infrastructures confronting severe weathers and climate changes* (pp. 98–106). Springer. https://doi.org/10.1007/978-3-319-96241-2_10
- 17) Patil, A. M., Tapase, A. B., Ghugal, Y. M., Konnur, B. A., & Dombe, S. (2019). Investigation on the use of crumb rubber and bagasse ash in road construction. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Sustainable civil infrastructures: Innovative infrastructure geotechnology* (pp. 121–134). Springer. https://doi.org/10.1007/978-3-319-95750-0_11
- 18) Patil, O. D., Chandak, P. G., Tapase, A. B., Patil, R. P., & Patil, N. E. (2021). Critical pavement response analysis under overloading for design of low volume rural roads. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Civil infrastructures confronting severe weathers and climate*

- changes (pp. 25–40). Springer. https://doi.org/10.1007/978-3-030-79641-9_3
- 19) Ranadive, M. S., & Tapase, A. B. (2013). Investigation of behavioral aspects of flexible pavement under various conditions by finite element method. In P. V. Lade, J. A. Yamamuro, & V. N. Kaliakin (Eds.), *Constitutive modeling of geomaterials* (pp. 765–770). Springer. https://doi.org/10.1007/978-3-642-32814-5_98
- 20) Ranadive, M. S., & Tapase, A. (2016). Pavement performance evaluation for different combinations of temperature conditions and bituminous mixes. *Innovative Infrastructure Solutions*, 1(1), Article 5. <https://doi.org/10.1007/s41062-016-0005-5>
- 21) Ranadive, M. S., & Tapase, A. B. (2016). Parameter sensitive analysis of flexible pavement. *International Journal of Pavement Research and Technology*, 9(6), 466–472. <https://doi.org/10.1016/j.ijprt.2016.10.002>
- 22) Sayyed, S. S., Patil, R. P., Tapase, A., Attar, A. C., & Chandak, P. G. (2021). Review and assessment of flexible pavement. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Civil infrastructures confronting severe weathers and climate changes* (pp. 139–149). Springer. https://doi.org/10.1007/978-3-030-79641-9_11
- 23) Sayyed, S. S., Tapase, A. B., Patil, R. P., Attar, A. C., & Chandak, P. G. (2019). Performance evaluation of flexible pavement for critical parameters causing premature failure. *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, 9(1). <https://doi.org/10.35940/IJITEE.A4950.119119>
- 24) Sayyad, S., Patil, R. P., & Tapase, A. B. (2022). Investigating the effect of RAP and crumb rubber in bituminous layer for pavement constructed in Satara District. *International Journal of Pavement Research and Technology*, 15(2), 333–348. <https://doi.org/10.1007/s42947-020-00069-5>
- 25) Tapase, A. (Ed.). (2021). *Infrastructure sustainability through new developments in material, design, construction, maintenance, and testing of pavements*. Springer. <https://doi.org/10.1007/978-3-030-79640-2>
- 26) Tapase, A. B., Chandak, P. G., Patil, R. P., Attar, A. C., & Sayyed, S. S. (2020). Evaluation and remedial measures on premature failure of roads in India. *Journal of Performance of Constructed Facilities*, 34(1), Article 04019112. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001384](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001384)
- 27) Tapase, A. B., & Ranadive, M. S. (2016). Performance evaluation of flexible pavement using the finite element method. In *Geo-China 2016: Material, design, construction, maintenance, and testing of pavement* (pp. 141–148). American Society of Civil Engineers. <https://doi.org/10.1061/9780784480082.014>
- 28) Tapase, A. B., & Ranadive, M. S. (2017). Predicting performance of flexible pavement using finite element method. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Sustainable civil infrastructures: Innovative infrastructure geotechnology* (pp. 137–146). Springer. https://doi.org/10.1007/978-3-319-61902-6_12
- 29) Tapase, A. B., Sayyed, S. S., Patil, N., Kadam, D., Shelar, A., & Patil, R. P. (2021). Conservation planning of road construction raw materials: Satara—A case study. In D.-H. Chen, S. Kim, & A. Tapase (Eds.), *Civil infrastructures confronting severe weathers and climate changes* (pp. 109–131). Springer. https://doi.org/10.1007/978-3-030-79641-9_9
- 30) Tapase, A. B., Sayyed, S. S., Patil, N., Kadam, D., Shelar, A., Patil, R. P., & Chandak, P. (2022). Analytical and laboratory investigation on the use of RAP and waste plastic for conservative planning of road construction raw materials. *Journal of Testing and Evaluation*, 50(6), 2820–2837. <https://doi.org/10.1520/JTE20210044>