A Node-Based Optimization Model with an Asymmetric Cost Function for Multi-Trolley Pose in Tunnel Lining to Minimize Concrete Consumption

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SUMMARY

Concrete consumption is a primary cost driver in tunnel secondary lining construction. The highly irregular as-built surfaces of excavated tunnels, combined with traditional trolley positioning methods aimed at guaranteeing minimum thickness specifications, frequently results in significant concrete over-consumption. This paper presents an automated, multi-trolley pose optimization method that leverages high-precision as-built point cloud data to determine an optimal sequence of trolley poses that minimizes total concrete usage. The methodology first involves rasterizing the tunnel point cloud data. Thin Plate Spline (TPS) interpolation is then employed to fill data voids, thereby generating a complete and seamless digital tunnel surface. Subsequently, a sequence of N trolleys, each modeled as a variable-radius frustum, is abstracted into a chain-like model connected by N+1 shared nodes. The state of each node is defined by its lateral offset (Y, Z) and its lining radius (R). This node-based model inherently ensures geometric continuity at the trolley joints. The optimization objective—to minimize the interstitial volume (i.e., the gap) between the tunnel surface and the trolley model—is formulated as a non-linear least-squares (NLS) problem and solved using the Ceres Solver library. A key innovation lies in the design of an Asymmetric Cost Function. This function applies a standard cost to concrete surplus (actual > design thickness), aligning with the primary goal of volume minimization. Conversely, it applies a high-weight penalty to any deficit (actual < design thickness). This strategy effectively transforms the rigid engineering constraint of minimum thickness into a robust, soft constraint within the optimization framework. The model flexibly accommodates various boundary conditions, including fixed-start, fixed-start-and-end, or fully adjustable node configurations. Experimental results demonstrate that the method converges rapidly to a set of globally optimized node parameters. A comparison of pre- and post-optimization concrete volumes, calculated precisely using a frustum-based model, confirms that the method achieves a significant reduction in concrete consumption (approx. 7.6%) while strictly adhering to all design specifications. This research provides a practical optimization

tool for digital and automated tunnel construction, offering direct application value in reducing project costs and enhancing quality control.