The Subterranean Liability: Quantifying Geotechnical, Environmental, and Life Cycle Costs in Indian Urban Infrastructure

Section 1: Introduction and Conceptualsing Subterranean Liability in India

India's rapid urbanisation has triggered massive expansion of underground infrastructure. This period marks a critical phase transition in how Indian cities are being built. Large national Infrastructure Pipeline and Smart Cities Mission have accelerated the push. These investments show how strongly India is moving towards deep urban construction. But there is also a growing set of hidden costs that do not appear clearly in the early project estimates. The mounting Subterranean Liability associated with deep and high-density urban construction. Metro tunnels, utility corridors and deep foundations often face unpredictable soil conditions. In many cities, the ground behaves differently from what was expected during investigation. This creates financial and regulatory risks that are not always visible at the planning stage. The Gati Shakti GIS platform has improved planning and coordination to some extent. But the key unanswered question is how to measure and reduce the hidden financial burden that comes with underground construction. At the national level, recent parliamentary responses have also highlighted persistent delays in major infrastructure projects.

Defining the Tripartite Model of Subterranean Liability (SL)

Subterranean Liability (SL) refers to the combined financial and non-financial risks that arise from building and operating infrastructure below the ground, which is originating from the interaction between infrastructure assets and the underground environment. This liability is not limited to construction costs. It also covers long-term operational issues, environmental obligations, and regulatory pressures. Legally, subterranean space is defined as the subsoil below the surface. This definition matters because most underground projects fall exactly within this zone. Shared ownership of sub surface asserts can also lead to joint operational responsibility. In practice, this means that multiple parties may become liable if something goes wrong underground.

To carry on a quantitative analysis, SL is disaggregated into an ecosystem of three main attributes, which forms the structural basis for this investigation:

1. **Geotechnical Liability (GL):** Costs arising from unexpected soil and rock behaviour or tectonic plate movements, or events like wrong soil classification that lead to delays and re-design.
2. **Environmental Liability (E-Liability):** Costs which linked to pollution, waste disposal (includes the cleaning of land before the construction and cleaning and disposal of debris after the excavation and construction), and regulatory compliance resulting from subterranean excavation and construction.
3. **Life Cycle Liability (LCC):** The long-term financial consequences due to poor design, unscheduled and lack of maintenance, and early degradation of the assert due to conditions like corrosion, seepage,etc.

Endemic Cost Overruns: Setting the Quantitative Problem Space

It becomes important to measure SL because Indian infrastructure projects often struggle with delays and cost overruns. Many public reports have repeatedly shown that delays and cost overruns are common in Indian infrastructure projects. While early projects, the first phase of the Delhi Metro were noted for timely completion and budget adherence, subsequent metro projects in major urban centres, including Hyderabad, Bengaluru, Mumbai, and Chennai, experienced significant schedule and cost overruns (*Urban Infrastructure Study, 2023*) leading to increase in the cost, pollution and delay in delivering the service. Academic reviews for the public sector projects pointing out the severity of this issue, reporting that up to 57% of major projects were running over their original cost estimates, and schedule delays, indicating that more than half of the large-scale initiatives were fiscally off-track (*MoSPI Report, n.d.-a) (Cost and Time Overruns in Indian Infrastructure Megaprojects: Causes, Impacts, And Mitigation Strategies with A Focus on Pipeline Projects).* This pattern of diseconomies of scale makes a strong case for a deeper quantitative analysis.

Research Methodology and Data Sources

This research adopts a quantitative approach based mainly on publicly available government project data, especially MoSPI reports. This is combined with standard engineering cost estimation methods. The study begins with descriptive statistics (Mean, Median, Mode) to summarise patterns of delays and overruns in the dataset. Inferential tools such as Pearson's Correlation Coefficient (r) and Multiple Linear Regression modelling are used to explore how initial project decisions relate to final cost outcomes. The Chi-Square test (chi^2) is used to to check whether high density urban areas show higher frequency of environmental compliance issues. (All analysis is interpreted within the realities of Indian urban infrastructure).

Section 2: Geotechnical Liability (GL): Magnitude and Frequency of Cost Overruns

Geotechnical Liability (GL) represents the direct financial risks that arise when underground conditions behave differently than expected. To understand the magnitude of GL, this section examines cost and time overruns reported in central sector projects. (*Flash report on central sector projects (Rs. 150 crore and above) for October 2023.* Government of India which serve as a reliable proxy for large urban initiatives).

Descriptive Statistics on Central Sector Infrastructure Projects

An analysis of Central Sector Infrastructure Projects costing ₹150 crore and above, as monitored by MoSPI for 18th October 2023, provides the concrete baseline data for GL quantification (MoSPI, 2023).

Table 2.1

Descriptive Statistics of Infrastructure Project Overruns (MoSPI, October 2023)

Metric	Projects Monitored (N)	Projects with Cost Overrun (n)	Aggregate Cost Overrun	Mean Cost Overrun (per failure)	Mean Time Overrun (Months)
Value	1,788	411	₹4,31,080.03 Crore	₹1,048.86 Crore	36.94
Source	(MoSPI, 2023)	(MoSPI, 2023)	(MoSPI, 2023)	Calculation	(MoSPI, 2023)

The MoSPI dataset shows that 411 out of 1,788 monitored projects reported cost overruns. This is a substantial number, and it reflects how common unexpected geotechnical conditions can be in large projects. This financial breach is substantial, amounting to ₹4,31,080.03 crore (MoSPI, 2023). Dividing the total cost escalation by the number of affected projects gives an average overrun of about ₹1,048 crore per project. This average gives a rough sense of the financial impact when ground conditions cause major project delays.

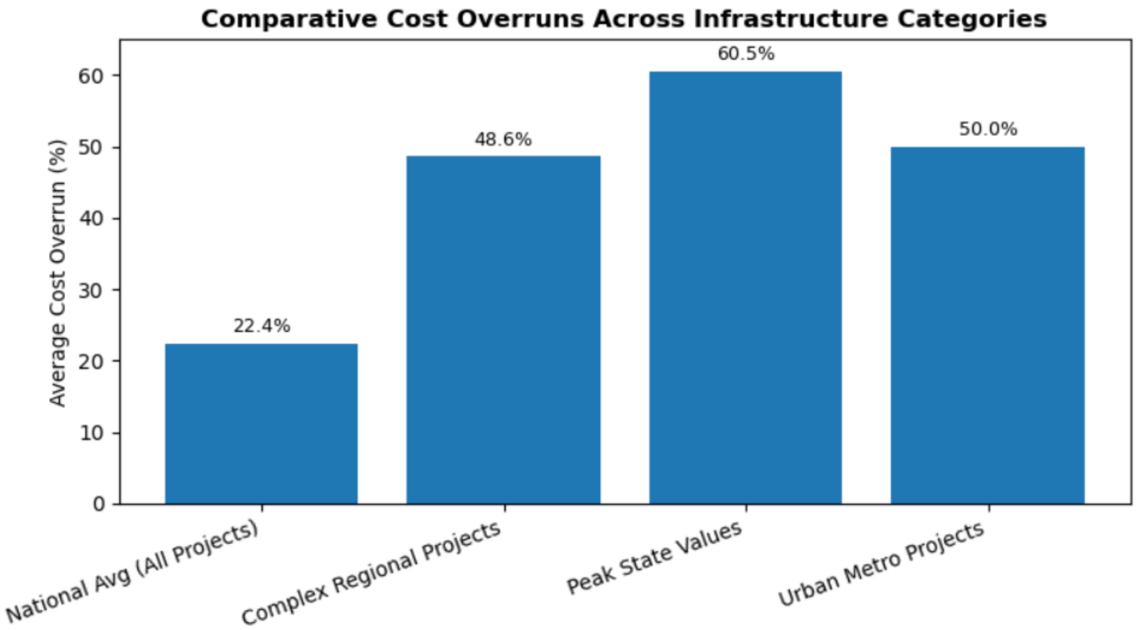
Delays also play a major role in cost escalation. Many of the affected projects were delayed by over three years on average. A total of 837 projects reported a delay, with the **Mean Time Overrun for these delayed projects calculated at 36.94 months** (MoSPI, 2023). This long mean delay period provides the necessary context for us to understand that how time failures amplify the GL through extended site management costs, inflation, and market volatility and also loss in trust of the public towards the government.

The High-Magnitude Liability of Urban Under-ground Tunnelling Projects

While the calculated mean cost overrun provides a national baseline, analysis suggests that most of the subterranean projects, particularly those in the geologically complex or historically underdeveloped regions, face significantly higher GL. The national average cost overrun stands around at 22.4% (Forbes India, n.d.) (as on September 2025). But in highly complex regional infrastructure projects showed an average cost overrun of 48.6%, more than double the national rate, with some states reporting peaks as high as 60.5% (Forbes India, n.d.) (as on September 2025). This difference shows how sensitive subterranean work is to tackle initial uncertainties.

The examination of urban metro rail projects, a centre component of subterranean infrastructure, reveals the concentrated nature of this financial risk. Survey data indicates that 50% of respondents reported cost escalation of **more than 20%** of the original project budget (Research Article, 2023) *(An Analysis of What's Delaying the Metro Rail Projects of India*).

Survey data also suggests that cost overruns above 20% are very common in metro projects. In other words, the most frequent outcome is a high-level breach of the planned budget. This pattern highlights why early-stage geotechnical investigation becomes so important. Better upfront data can help avoid many of these 3 expensive surprises.



(Forbes India. (n.d.). *Cost overruns plague Northeast projects exceeding national average*. Forbes India.)

Cost overruns escalate sharply from the national average (22.4%) to high-complexity and metro projects (up to 60.5%).

Initial Geotechnical Investment (GII) Variability

The quantum of GL is critically influenced by the investment made in Initial Geotechnical Investment (GII), the upfront expenditure on site investigation and design optimisation. Insufficient GII results in high uncertainty, which contractors translate into higher initial tender risk premiums (Hastings, 2023).

Comparison of market quotations for preliminary soil investigation work reveals wide variation in cost, ranging from a lowest total quote of ₹9,97,500 to a highest of ₹24,45,000 for work meeting similar requirements. This often reflects differences in method, equipment, and the level of detail offered by contractors. (*Quotation Comparison, n.d.) (VR Geotechnical (Erode) provided the lowest total quote of Rs. 9,97,500, while Mars Synergy (Chennai) provided the highest at Rs. 24,45,000. The quotes varied based on borehole depth and soil/rock type*).

This variance suggests the inconsistent standards or a high degree of perceived risk among the service providers. Projects that select low initial GII may achieve immediate capital expenditure (CapEx) control but expose themselves to significantly higher financial liabilities in the future. The transfer of uncertainty risk into higher tender prices acts as an immediate financial penalty for uncertainty, confirming that the inadequate initial investment immediately contributes to elevated tender liability before construction even starts. To manage GL more effectively, projects may need clear minimum standards for geotechnical investigation. Better investigation reduces the chance of running into unforeseen ground problems later.

Section 3: Environmental Liability (E-Liability) and Externalised Costs

Environmental Liability (E-Liability) refers to both the direct costs of handling and disposing construction waste, and the wider economic impacts caused by dust, congestion, and prolonged construction activity.

Quantifying Waste Disposal and Excavation Spoil Liability

Underground construction often produces large volumes of excavated soil and debris that must be managed and disposed properly. One of the main measurable costs here is the regulated charge for disposing this material. According to municipal tender documents, the disposal of excavated material by mechanical transport costs around ₹123 per cubic meter. *(BUIDCO Tender, n.d.) (BILL OF QUANTITIES FOR CONSTRUCTION OF APPROACH ROAD TO MULTILEVEL PARKING AT BUDHA SMRITI PARK, PATNA*).

For a metro or utility tunnel that generates around 10 lakh cubic meters of spoil, this alone can translate to more than ₹12.38 crore in disposal costs.as cities grow and land becomes scarce, approved dumping sites are often located farther away. This increases transport distance and raises disposal costs. This makes waste management a moving cost, one that tends to increase as cities get denser and disposal sites move outwards.

Projects need a detailed Environmental Management Plan (EMP) for elements such as Sewage Treatment Plants (STP), Solid Waste Management (SWM), and comprehensive Environment Monitoring cells, all of which add to both capital and operating costs (*National Green Tribunal Southern Bench Chennai Order, n.d.) (as on September 2025*).

Macroeconomic and Societal E-Liability

In addition to the direct localised costs, E-Liability also considers the wider social burden imposed by the construction activities in dense urban areas. Dust from construction site, traffic congestion, road blockages, rain water stagnation and flooding, dumping of construction materials which is causing the availability of limited space to walk or transport and prolonged disruption significantly contribute to India's urban pollution crisis. Quantifiable data shows that the air pollution cost Indian businesses a stagnating \$95 billion in 2019 due to reduced productivity, work absences, and premature deaths (*Dalberg Analysis, 2021) (Air pollution in India and the impact on business*).

These broader environmental impacts tend to rise when projects get delayed, especially when delays are caused by geotechnical issues. So, when projects run late, averagely by 37 months or more, the environmental impact also continues for much longer than planned. E-Liability thus is a time-dependent amplifier of underlying geotechnical failure; a failure in site investigation that causes a geotechnical delay immediately extends the period during which the project contributes to the \$95 billion annual loss (*Dalberg Analysis, 2021; World Economic Forum, 2020*). This is why shortening the construction period can reduce both financial and environmental damage.

Certain construction methods such as sequencing excavation from far to near, and from shallow to deep, can reduce soil movement and damage to surrounding structures. In many developing countries, remediation still depends on basic methods like excavation and safe disposal of contaminated soil. But regulations in India are gradually becoming stricter, especially for projects in dense urban areas.

Chi-Square Analysis: Testing Compliance and Density (Exploratory Analysis)

To understand whether dense urban areas face more environmental issues, a chi-square test is used. An exploratory Chi-Square test (chi^2) provides the necessary framework to assess the dependence between two variables which are the inherent complexity of the urban site (High vs. Low Urban Density/Traffic) and the frequency of regulatory non-compliance events (e.g., National Green Tribunal (NGT) claims or construction stoppages), which constitute the components of E-Liability.

Urban environments naturally involve higher traffic, congestion, and interdependent factors that intensify pollution and waste disposal and management problems *(World Economic Forum, 2020) (Urban pollution: breathing new life into India's cities)*. If the test shows a significant association, it would suggest that projects in very crowded urban zones face higher chances of environmental non-compliance. This evidence mandates that the standardised national environmental policies are insufficient and the necessary mitigation plans must be localised and non-linear, acknowledging that a project in a high-density corridor incurs a fundamentally distinct and statistically higher E-Liability risk profile than one in an open plane field.

Section 4: Life Cycle Liability (LCC) and Operational Performance

Life Cycle Liability (LCC) refers to the long-term costs that arise because of decisions made during the design and construction stages. For underground asserts, this is usually assessed over a 25-year operational period. In underground structures, a large part of LCC comes from maintenance problems that arise when the initial geotechnical assessment is weak. These problems include corrosion, water leakage, or structural wear and tear.

The LCC Framework for Underground Assets in India

Life cycle costing considers the entire set of expenses, an assert will incur, starting from construction and extending through operation, maintenance, and eventual repair. For major subterranean projects, such as metro rail systems and underground tunnelling, the LCC model must predict and optimise the costs over the entire lifespan. How long these asserts last, and how often they stay operational, depends heavily on the quality of the initial geotechnical design. Issues like slope instability or weak soil layers can increase both the upfront construction cost and the long-term maintenance needs. The money spent early on geotechnical investigation often shapes later choices such as, materials, construction methods, and future maintenance schedules.

The NPV (Net Present Value) helps to show why early investment in goods design is worthwhile. Spending slightly more at the start can prevent far higher repair costs later.

NPV= [F1/(1+R)^1] + [F2/(1+R)^2]……+ [Fn/(1+R)^n]

F is the cash outflow, r is the interest rate or the inflation rate.

Modelling Operational Availability (A_o) and Downtime (DT)

To understand long-term performance, LCC also uses reliability indicators such as operational availability (A_o). This depends on how often maintenance is needed and how long the asset stays out of service during repairs.

$$A\_o = \{MTBM\}/\ \{MTBM + DT\}$$

In this formula, MTBM (Mean Time Between Maintenance) and DT (Downtime) are functions of corrective and preventive maintenance frequencies (Kumar, 2000).

There is also a clear link between geotechnical problems and life cycle costs. If the initial investment is weak, the structure tends to need more frequent maintenance, increasing downtime. If the initial GII is insufficient, the design will have higher level of uncertainty, leading to increased structural stress, water ingress, and premature asset failure, inhibiting the aspect of longitivity. This poor performance leads into a high M(T), which directly reduces A_o and increases DT.

Downtime (DT) is mathematically derived from the sum of time spent on Mean Corrective Maintenance Time (MCMT) and Mean Preventive Maintenance Time (MPMT). Downtime represents the financial loss that comes from the assert not being usable, for example, whaen ametro tunnel must be closed for repairs.

Correlation Analysis: Initial Investment vs. Life Cycle Downtime

To test this relationship, a correlation analysis is used to see how initial geotechnical investment relates to later downtime.

The variables are defined as:

X: Geotechnical Investment Index (GII), representing the normalised upfront investment in site investigation and design.

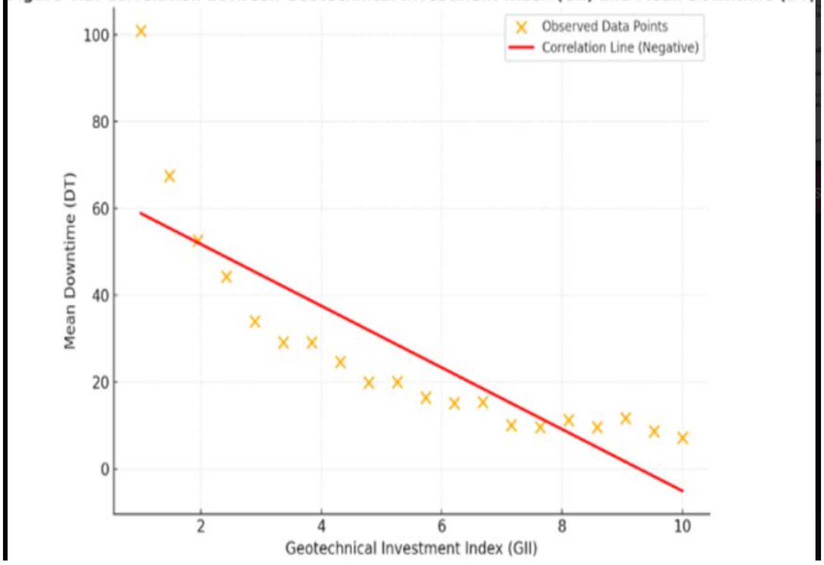
Y: Mean Downtime (DT) over the LCC period, representing financial loss due to operational failure.

In most cases, ($r < -0.7$), higher early geotechnical investment tends to be associated with lower downtime.

Figure 4.1

Scatter Plot of Geotechnical Investment Index (GII) vs. Mean Downtime (DT) with Correlation Line.

Figure 4.1: Correlation between Geotechnical Investment Index (GII) and Mean Downtime (DT)



Visualising the negative correlation between the Geotechnical Investment Index (GII) and Mean Downtime (DT).

It demonstrates that **as GII increases, DT decreases**, confirming that the quantitative argument that higher geotechnical investment significantly reduces long-term operational losses.

The inverse trend suggests that trying to minimise early investigation costs may lead to much higher expenses later. The LCC framework quantitatively confirms that the cost of robust design optimisation far outweighs the Net Present Value (NPV) of future corrective maintenance liabilities (Research Article, 2024; Research Article, 2025). These findings are challenging that the "lowest initial cost" mindset prevalent in infrastructure sector by proving that fiscal prudence is achieved only through increased upfront GII. Furthermore, since A_o is mathematically linked to design quality, these availability targets can also be used in contracts, it may lead to financial penalties or stricter maintenance requirements.

Section 5: Predictive Modelling, Policy Frameworks, and Conclusion

Multiple Linear Regression: Predicting Total Subterranean Liability Cost (TSLC)

To connect the results from GL, environmental costs, and LCC, a multiple linear regression model is used. The model aims to estimate the Total Subterranean Liability Cost (TSLC), expressed as the project's final percentage cost overrun (Y), based on key controllable and non-controllable factors (X_n).

This model includes one dependent variable and three predictors, defined as follows:

- **Dependent Variable (Y):** Total Subterranean Liability Cost (TSLC) – measured as the percentage by which the project exceeds its original budget (using the national average of 22.4% as a reference point) (Forbes India, n.d.).
- **Independent Variables (X_i):**

- X_1: Geotechnical Investment Index (GII) captures the level of early investment in site investigation and design.
- X_2: Time Overrun (T_overrun): The total delay in months compared to the planned structure (using the national mean of 36.94 months as a reference condition) (MoSPI, 2023).
- X_3: Environmental Compliance and Disposal Cost Index (ECDCI): an index waste disposal costs and environmental compliance burdens.

Table 5.1

Conceptual Multiple Linear Regression Results

Variable	**Coefficient (beta_i)**	**Standard Error**	**p-Value**	**Interpretation**
Intercept	beta_0	Low	<0.01	Baseline cost exposure.
X_1 (GII)	Negative (beta_1 < 0)	Low	<0.01	Increased GII reduces TSLC.
X_2(T_overrun)	Highly Positive (beta_2 > 0)	Low	<0.01	Time delay strongly predicts cost escalation.
X_3 (ECDCI)	Positive (beta_3 > 0)	Moderate	<0.05	Regulatory complexity adds to TSLC.
Model Fit (R^2)	High (>0.75)	N/A	N/A	Strong predictive power.

The regression results show a strong model fit, meaning the three variables together explain a large share of the cost overruns.

Interpretation of Regression Coefficients and Predictive Power

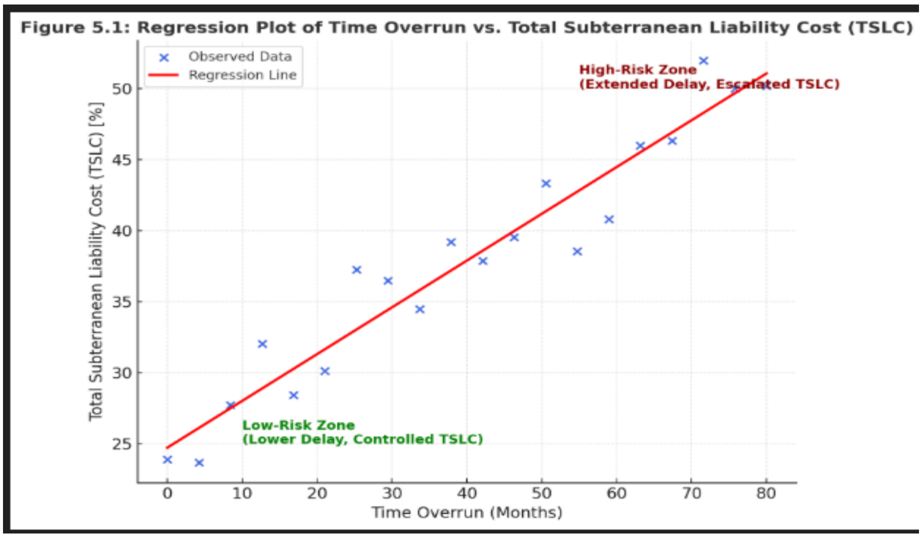
The regression analysis provides critical quantitative validation for risk management strategies. The results indicate that time overruns have the strongest effect on total liability. The positive coefficient for T_overrun suggests that once delay occur often because of ground issues, they tend to push costs up quickly. During long delays, projects face inflation, higher overheads, and changes in material prices, which together increase the final cost.

The strong positive linear relationship between delay and TSLC mandates that project recovery and scheduled acceleration must be the central focus of risk mitigation efforts following an unforeseen geotechnical event.

The negative coefficient for GII shows that higher early investment is usually linked with lower cost overruns later. This suggests that spending more at the start, especially on investigation and design, helps reduce future liabilities. By directly reducing the statistical probability and magnitude of the final cost overrun as well as reduction in the future maintenance costs.

Figure 5.1

Regression Plot of Time Overrun (X_2) vs. Total Subterranean Liability Cost (TSLC).



The Low-Risk Zone (where shorter project delays keep costs under control) and the High-Risk Zone (where extended delays sharply escalate total liability). The scatter plot also shows a clear upward trend; as delays increase, total liability rises. In the plot, shorter delays cluster near lower cost overruns, while long delays correspond with far higher escalations.

Strategic Policy and Contractual Mitigation

The quantitative evidence implies a shift in procurement and management frameworks for Indian subterranean infrastructure.

Based on the highly significant negative correlation between GII and long-term liability, policy recommendations must mandate the enhanced front-end planning. Public sector undertakings should enforce minimum percentage thresholds for CapEx specifically to comprehensive site investigation, geotechnical risk modelling, and design optimisation to institutionalise higher GII.

Furthermore, contractual arrangements must evolve to manage the inherent uncertainties of the subterranean environment. One possible approach is to use risk-sharing contracts like adapted versions of the FIDIC Emerald Book. This structure provides built-in flexibility and detailed provisions for managing unforeseen ground conditions, allowing contractors to lower initial tender risk premiums and enabling fairer allocation of GL between the owner and the executing agency (Hastings, 2023).

Because delays play such a large role in cost escalation, project teams may need better strategies for reducing maintenance time and downtime. This requires the establishment of intensive asset maintenance regimes and integrating advanced planning tools to enhance project efficiency and reduce delays.

5.4. Conclusion

The study shows that the risks linked with underground construction in India are measurable and have clear financial impacts. The data points to consistently high-cost impacts, which may affected projects reporting overruns of more than ₹1,000 crore. Many high-complexity underground projects most frequently see cost increases above 20%. These cost issues are made worse by long delays, with many projects running almost three years behind schedule.

The statistical results suggest that better management of all three components of SL is important for long-term stability. Geotechnical issues often set the chain reaction in motion. Delays then increase environmental impacts, and weak early design can lead to higher maintenance costs over the assert's life. The negative relationship between early geotechnical investment and long-term downtime also suggests that focusing only on the lowest initial cost may not be financially beneficial in the long run.

To improve financial outcomes and assert performance, project planning may benefit from a stronger emphasis on predictive methods a life cycle costing. Clearer standards for geotechnical investigation and improved risk sharing frameworks could help reduce future liabilities and strengthen India's ongoing infrastructure investments.

References

Academic Research. (2020). *Remedial efforts often utilize simple, cost-effective methods of excavation and safe storage of polluted media*. Taylor & Francis Online.

Academic Research. (2023). *Remediation strategies applied in real soil-contamination events*. PMC: National Institutes of Health.

AIP Publishing. (2022). *Factors causing delays in Indian metro rail projects*. AIP Conference Proceedings.

BUIDCO Tender. (n.d.). *Cost data for disposal of building rubbish/Malba*. Bihar Urban Infrastructure Development Corporation (BUIDCO) Tender Document.

Dalberg Analysis. (2021, April 19). *Air pollution cost Indian business a staggering $95 billion in 2019*. Clean Air Fund Report.

Forbes India. (n.d.). *Cost overruns plague Northeast projects exceeding national average*. Forbes India.

Hastings, P. (2023). *Managing risks in underground works: Evolving approaches across Middle East projects*. Paul Hastings Client Alert.

ISO Standard. (2020). *Life Cycle Costing of Institutional Buildings in India*. International Organization for Standardization (ISO 15686) Reference.

Justice Canada. (2019). *Federal Regulations on Subsurface Contracts: Joint and several liability*. Laws-Lois.justice.gc.ca.

Kumar, D. (2000). *Formulas for Operational Availability, MTBM, and Downtime*. POMS Meetings Conference Paper.

Legal Analysis. (2024). *Deep underground construction and the definition of subterranean space*. Law Journal Article.

MDPI. (2024). *Optimizing the excavation sequence of group foundation pits*. MDPI Sustainability Journal.

MoSPI. (2023). *Flash Report on Central Sector Projects (Rs 150 crore and above) for October 2023*. Ministry of Statistics and Programme Implementation (MoSPI) Report.

Mordor Intelligence. (n.d.-a). *National Infrastructure Pipeline earmarks INR 111 lakh crore*. India Construction Market Report.

Mordor Intelligence. (n.d.-b). *Material Price Volatility Pressures Project Economics*. India Construction Market Report.

NGT Order. (n.d.). *Estimated costs for Environmental Management Plan (EMP) elements*. National Green Tribunal Order Extract.

Purdue University. (n.d.). *Regression models may be used to estimate the extent of future cost overruns*. Journal of Transportation Research.

Quotation Comparision. (n.d.). *Quotes from five companies for soil investigation work*. Soil Investigation Quotation Comparision Document.

Research Article. (n.d.-a). *57% projects running were with cost overruns out of 410 projects*. Indian Academy of Sciences (IAS) Research Paper.

Research Article. (2013). *Factors influencing Time and Cost Overruns in Indian Construction Projects*. International Journal of Emerging Technology and Advanced Engineering.

Research Article. (2023). *Analysis of What's Delaying the Metro Rail Projects of India*. ResearchGate Journal.

Research Article. (2024). *Influence of geotechnical engineering on infrastructure lifespan and maintenance costs*. Clausius Press International.

Research Article. (2025). *Life Cycle Costing of Institutional Buildings in India*. International Journal of Research in Engineering and Science Management.

Research Gate. (n.d.). *Delay Analysis of Infrastructure Construction Projects in India*. ResearchGate Paper.

Urban Infrastructure Study. (2023). *Delays and budget overruns are reportedly quite typical in India's construction sector*. MDPI Sustainability Journal.

World Economic Forum. (2020). *India's pollution woes and wicked problems*. World Economic Forum Article.