Architectural Innovations in Underground Museum Design: Integrating Light, Ventilation, and Human Experience

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Abstract

Underground museum architecture has evolved as a critical frontier in the intersection of environmental engineering, human psychology, and spatial design. Once seen merely as functional or secretive infrastructure, subterranean museums now represent sophisticated experiments in climatic adaptation and cultural narrative.

Designing below the surface poses inherent challenges: scarcity of daylight, restricted air movement, complex waterproofing, and heightened psychological sensitivity to spatial confinement. Yet these very challenges drive innovation. Lighting strategies are now hybridized—combining skylights, reflective shafts, fiber optics, and indirect artificial lighting that emulate natural daylight. Ventilation methods have shifted from purely mechanical HVAC systems to hybrid passive approaches, such as earth-to-air heat exchangers, solar chimneys, and thermal stacks. Structural ingenuity manifests through the use of reinforced concrete shells, ferrocement domes, and post-tensioned slabs that balance load-bearing demands with spatial openness.

The research concludes that successful subterranean museums achieve equilibrium between environmental control and experiential liberation. They function not as hidden spaces but as extensions of the landscape, using light, air, and material tactility to maintain a dialogue between surface and depth. Key recommendations include integrating daylighting systems with reflective technology, employing thermally active materials to stabilize underground microclimates, and designing spatial hierarchies that respect human orientation and emotional comfort.

Ultimately, this paper argues that underground museums transcend their technical typology—they redefine how architecture can exist "beyond the surface," merging ecology, culture, and emotion into one continuous spatial experience.

Keywords

Underground Architecture; Museum Design; Lighting; Ventilation; User Experience; Sustainable Design; Spatial Psychology; Subterranean Structures

1. Introduction

Architecture below ground challenges the most fundamental parameters of perception—light, air, and scale. In traditional architecture, the surface defines the visible boundary of human activity. In contrast, underground architecture inverts this relationship, transforming the earth itself into both structure and envelope. The shift from surface architecture to subterranean design marks a significant moment in contemporary practice, wherein environmental consciousness and cultural preservation converge.

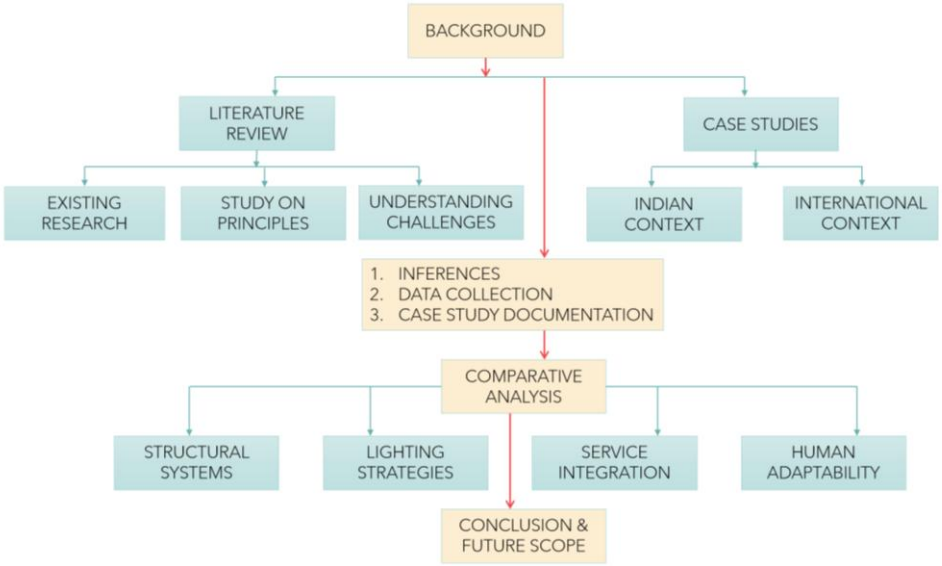
Underground museums are a particularly expressive typology within this field. They respond to three critical conditions of our time: (1) scarcity of urban land, (2) the need to protect heritage sites and fragile landscapes, and (3) the demand for immersive, controlled exhibition environments. These spaces allow cultural infrastructure to coexist invisibly with historic or ecological contexts—reducing visual intrusion while offering profound spatial experiences.

Historical precedents of subterranean design—from the Hypogeum of Ħal-Saflieni in Malta to India's rock-cut caves at Ajanta and Ellora—reveal that light, shadow, and enclosure have long been instruments of spiritual and emotional transformation. In modern times, architects such as B.V. Doshi, I.M. Pei, and Bjarke Ingels have extended this legacy by embedding museums beneath the earth's surface, translating ancient spatial wisdom into sustainable, technologically refined forms.

This paper interrogates how these spaces achieve balance between technical efficiency and human emotion, exploring how controlled environments can still feel alive, breathable, and awe-inspiring.

2. Methodology

The research adopts a qualitative analytical framework supported by case-based evidence, structured through four interlinked methodological phases. It begins with a comprehensive literature review examining global scholarship on underground architecture, with particular emphasis on environmental design strategies, museum typologies, and spatial psychology, drawing from seminal works by Sterling & Godard (1997), Yeang (2006), Banham (1981), and Carmody & Sterling (1993). This is followed by data collection through systematic documentation of selected case studies using authoritative architectural journals, museum archives, and verified building standards, including NBC India (2016), ASHRAE 62.1, ECBC (2017), and CIBSE LG08. The study then undertakes a comparative analysis, evaluating each case against four key parameters: lighting systems (natural and artificial), ventilation strategies (passive and mechanical), structural and construction techniques, and user experience in relation to spatial psychology. Finally, the research culminates in synthesis and recommendations, integrating quantitative environmental performance data—such as illuminance levels, humidity, and CO_2 concentration—with qualitative spatial observations to derive evidence-based design principles for underground museum architecture.



3. Literature Review

3.1 Evolution of Underground Architecture

From prehistoric caves to futuristic "earthscrapers," underground spaces have continuously mirrored humanity's relationship with nature and mortality. In ancient Egypt and India, the descent underground signified entry into the sacred. In medieval Europe, crypts and catacombs represented concealment and protection. Modern architects reinterpret these archetypes to serve civic and cultural functions.

Sterling and Godard (1997) identify two broad motivations for subterranean construction: environmental optimization and land-use efficiency. The stable temperature and acoustic insulation offered by soil make

underground environments inherently energy-efficient. Banham (1981) emphasized that the soil acts as a natural thermal moderator, providing passive insulation unmatched by above-ground envelopes.

3.2 Lighting and Human Psychology

Carmody and Sterling (1993) highlight that lighting is the defining psychological element in underground environments. Natural light not only guides orientation but also reduces anxiety associated with enclosed spaces. The Color Rendering Index (CRI) and correlated color temperature (CCT) significantly influence perception—warm white light (3000–3500K) evokes intimacy, while neutral white (4000K) enhances alertness and visibility.

3.3 Ventilation and Environmental Comfort

ASHRAE standards (62.1) specify that underground spaces require a minimum fresh air supply of 10 L/s per person, maintaining CO_2 levels below 1000 ppm and relative humidity between 45–55%. Hybrid ventilation systems—combining passive air shafts with variable-air-volume mechanical systems—represent best practice in balancing comfort and energy efficiency.

3.4 Structural and Construction Innovations

Advances in ferrocement, post-tensioned slabs, and diaphragm walls have enabled architects to sculpt vast underground spaces without intrusive columns. Waterproofing remains a critical technical concern; systems such as PVC geomembranes, bentonite panels, and drainage mats now ensure long-term durability even under high hydrostatic pressure.

3.5 Experiential and Cultural Dimensions

Yeang (2006) argues that underground architecture should not be seen merely as "earth-sheltered" sustainability but as experiential sustainability—spaces that reconnect users emotionally to the environment. In this sense, underground museums become instruments of introspection, inviting visitors to journey inward—physically and psychologically.

4. Case Studies

4.1 Husain–Doshi Gufa, Ahmedabad, India

The Husain–Doshi Gufa, popularly called *Amdavad ni Gufa*, stands as an architectural dialogue between art, nature, and technology. Conceived as a subterranean art gallery to display the works of painter M.F. Husain, the Gufa breaks from the rectilinear rigidity of conventional galleries. Doshi envisioned it as a "living organism beneath the earth's skin," designed to protect the artworks from Ahmedabad's harsh sun while providing a contemplative, intimate space.

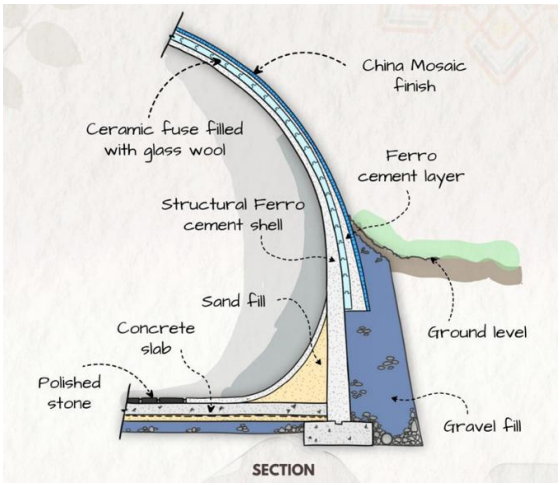


Figure 1 Section from wall showcasing construction details

The structure is embedded about 4 meters below the surface, covered by a mound finished in ceramic mosaic tiles that act as solar reflectors and waterproofing membranes. Beneath this, thin ferrocement shells (25–30 mm thick) form organically curved domes supported by tree-like columns. These domes are punctured by small circular oculi glazed with colored glass fragments that filter daylight into the subterranean chambers, creating a soft, ever-changing play of light reminiscent of sunlight filtering through a forest canopy.

Ventilation operates on the principle of stack effect—cool air enters through shaded openings at the periphery and warm air exits through the higher oculi. The underground temperature remains between 26–30°C, even during peak summers of 45°C. No mechanical cooling system is used, proving that climate-sensitive design can achieve comfort passively.

Structurally, the Gufa's ferrocement technology allowed a free-form roof only 25 mm thick, made by applying cement mortar over steel mesh supported by a temporary framework. The construction method was experimental yet cost-efficient, emphasizing form-making as a tactile process rather than one dictated by rigid geometry.

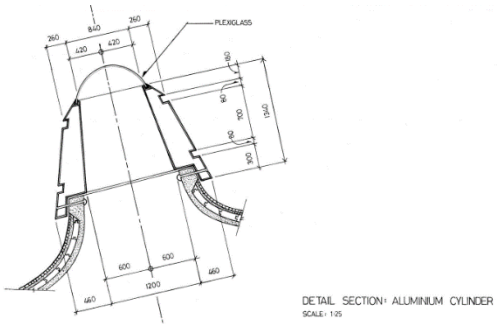


Figure 2 Detail Section: aluminum Cylinder

Figure 3 Oculi for diffusion of natural light inside the museum

The interior experience is *cave-like but spiritual*, invoking an ancestral memory of shelter while maintaining modern sensibilities. The walls—painted with Husain's mythological motifs—merge seamlessly into the curvilinear geometry, blurring boundaries between architecture and art.

The Gufa exemplifies how light, structure, and material can jointly produce both thermal stability and emotional resonance in subterranean environments.

4.2 Louvre Pyramid and Underground Concourse, Paris, France

I. M. Pei's Louvre Pyramid was as controversial as it was visionary when inaugurated in 1989. Beneath the glass pyramid lies a vast subterranean concourse serving as the main entrance to the Louvre Museum, reconfiguring the visitor's spatial journey from the external grandeur of the palace to the hidden world below.

Figure 1 Glass pyramid Lightwell

The pyramid acts as a daylighting instrument rather than merely an architectural icon. Its glass surface—made from low-iron, laminated panes with a total transmittance of 91%—funnels daylight into the underground lobby

20 meters below. Reflective aluminum surfaces and white limestone flooring enhance light diffusion, achieving a maintained illuminance level of 250–300 lux, appropriate for circulation zones and exhibition pre-areas per CIBSE LG08.

The concourse beneath measures approximately 35×35 meters, with a clear ceiling height of 10 meters. Structurally, it relies on Mero-type space frame trusses, transferring the load to reinforced concrete cores on each corner. The roof slab is waterproofed using triple-layer PVC geomembranes with capillary drains, necessary given the high groundwater level of the Seine.

The ventilation system employs displacement air distribution, delivering cool air from floor diffusers while exhausts near the pyramid apex extract warm air. This creates a natural convection loop, improving air quality without drafts. The system maintains indoor CO_2 levels below 900 ppm, complying with ASHRAE 62.1 standards.

Psychologically, Pei transformed the descent underground into a ritual of light. The transparency of the pyramid allows constant visual contact with the sky, mitigating the claustrophobia typically associated with below-grade spaces. Visitors experience a paradox: descending yet uplifted—a spatial inversion that symbolizes enlightenment through descent.

4.3 Tirpitz Museum, Blåvand, Denmark

The Tirpitz Museum, designed by Bjarke Ingels Group (BIG), is a radical reinterpretation of the "invisible museum." Concealed beneath the dunes of Denmark's west coast, it juxtaposes World War II bunkers with contemporary architecture that prioritizes landscape continuity.

BIG's design carves four linear cuts into the dunes, forming a cross-shaped subterranean plan. Each arm of the cross admits daylight through glazed curtain walls, their orientation calibrated to capture soft northern light while avoiding glare. The dunes act as natural shading devices, tempering both light and temperature.

Figure 5 Tirpitz Museum

The building's roof—essentially the dune surface itself—comprises post-tensioned concrete slabs of 300 mm thickness, engineered to resist both soil pressure and freeze-thaw cycles. The walls are cast in high-strength concrete with integrated waterproof admixtures and a dual-layer drainage system to handle groundwater infiltration.

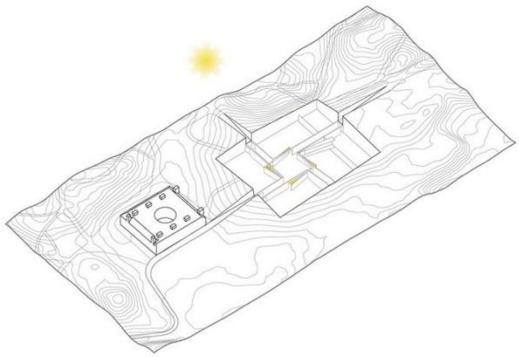


Figure 6 Daylighting in Museum

The internal microclimate maintains a temperature of 20–23°C and relative humidity of 50–55% without continuous mechanical conditioning. Passive ventilation shafts located at each courtyard induce air movement through the stack effect, while mechanical systems activate only during high occupancy.

Spatially, the descent is subtle: visitors approach through dune grass, unaware of the structure until the landscape opens into a glass-edged void. Inside, the play of daylight and shadow reinforces the site's history—darkness recalling wartime bunkers, light symbolizing reconciliation. Acoustic absorption panels within the concrete shells ensure silence and serenity, complementing the museum's themes of memory and time.

The Tirpitz Museum stands as a masterclass in environmental integration—using landform as both thermal mass and aesthetic envelope.

4.4 Amos Rex Museum, Helsinki, Finland

The Amos Rex Museum embodies a civic reinterpretation of the underground typology. Situated beneath a public square, its gallery spaces remain entirely invisible from the street, yet their presence animates the plaza through a sequence of undulating concrete domes—each with a central glass oculus.

These domes, 5 to 9 meters high, are cast from reinforced concrete with integral waterproof admixtures. Each oculus is a triple-glazed, low-E lens designed to transmit 30–40% daylight, balancing visibility and exhibition safety. Light is filtered through fritted glass to achieve an average illuminance of 150–300 lux, suitable for galleries per IESNA RP-30 guidelines.

Figure 7 View of site alongwith the skylights using for capturing natural light

The museum employs a demand-controlled ventilation system that adjusts air exchange rates based on CO_2 sensors. Average fresh air supply is 100 m^3/h per person, with constant humidity control at 50%. Air diffusers are embedded in the floor plinth, ensuring silent air movement and minimal visual intrusion.

The concrete domes double as both structural roof and public landscape, blurring the line between museum and city plaza.

4.5 Lowline Park, New York, USA

The Lowline project reimagines an abandoned trolley terminal as an underground public park. Using heliostats and fiber-optic collectors, sunlight is concentrated and directed through reflective tubes to grow vegetation underground.

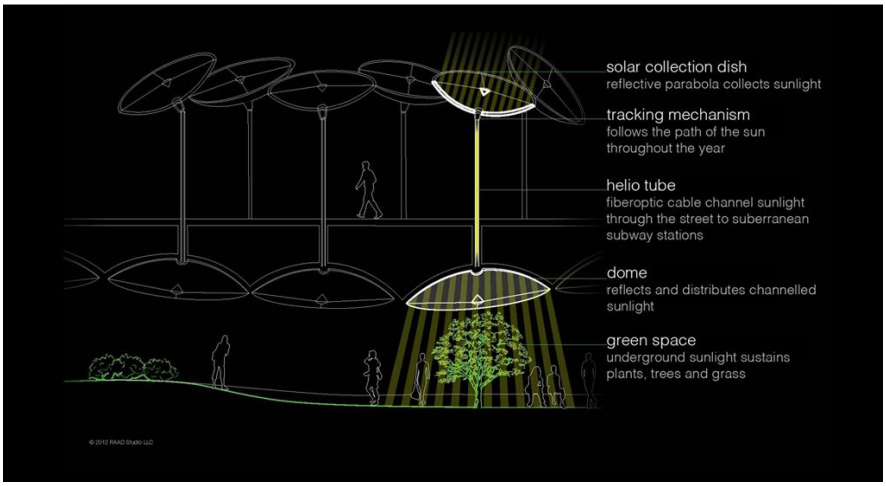


Figure 8 Specifications of Heliostats installed inside the park

The system transmits daylight without heat gain, maintaining ambient temperatures while achieving full-spectrum illumination suitable for plant photosynthesis and human comfort.

5. Comparative Analysis and Discussion

Comparative analysis indicates that all successful underground museums adopt hybrid environmental systems—balancing natural and artificial light sources, passive and mechanical ventilation, and perceptual openness within enclosure. Illuminance levels range from 150–300 lux, humidity is maintained at 45–55%, and CO_2 concentration below 1000 ppm ensures comfort per ASHRAE 62.1. Structural systems evolve from ferrocement shells to post-tensioned slabs and diaphragm walls, demonstrating how material innovation allows greater spatial freedom without compromising waterproofing.

Parameter	Husain–Doshi Gufa	Louvre Pyramid	Tirpitz Museum	Amos Rex	Lowline Park
Lighting Strategy	Oculi & diffused skylights	Glass pyramid & reflectors	Cross skylights under dunes	Glass domes with frit pattern	Fiber-optic daylight collectors
Ventilation	Natural stack effect	Hybrid mechanical	Passive + CO_2 sensors	Demand-controlled HVAC	Natural + mechanical fans
Structure	Ferrocement shells	Diaphragm walls, space frame	Post-tensioned slab	Reinforced concrete domes	Steel and glass system
Temperature Range (°C)	26–30	22–25	20–23	20–24	22–26
Illuminance (lux)	100–200	250–300	150–200	150–300	Variable (100–500)
User Experience	Organic, intimate	Monumental descent	Serene, contemplative	Playful, civic	Interactive, technological

User experience emerges as the ultimate metric of success. Light gradients, acoustics, and circulation hierarchies guide emotional transitions—from anticipation to revelation, intimacy to grandeur. Psychological comfort is achieved through orientation cues (visual contact with sky, gradient lighting, tactile surfaces) and consistent thermal balance. The subterranean museum thus becomes a multi-sensory narrative—an architectural choreography of descent and discovery.

Across all five cases, **light** and **air** emerge as the dual protagonists of underground design. Architects manipulate these intangibles as materials in themselves, crafting atmospheric depth rather than visual spectacle.

- **Lighting as Narrative:** Daylight enters through controlled apertures—small in Doshi's Gufa, grand in Pei's Louvre, fragmented in BIG's Tirpitz, and diffused in Amos Rex. Artificial light is always supplemental, not dominant, preserving circadian balance and visual hierarchy.
- **Ventilation as Invisible Comfort:** Passive systems maintain thermal equilibrium while reducing carbon footprints. Earth-to-air heat exchangers and solar chimneys could further enhance energy independence in future museums.
- **Material and Structural Innovation:** The transition from heavy masonry to lightweight shells reflects a move from defensive to expressive underground design.
- **Psychological Experience:** Visitors' emotional trajectory mirrors spatial progression—from compression to release, darkness to illumination, silence to resonance. Underground museums thus function as metaphors for cultural introspection.

6. Conclusion and Design Recommendations

The evolution of underground museums demonstrates how architecture can transform necessity into narrative. Subsurface design is no longer about concealment—it is about **continuity**: between land and structure, environment and emotion.

The design recommendations emphasize an integrated, performance-driven approach to underground architecture. Hybrid daylighting strategies should be incorporated by combining skylights, light tubes, and reflective optical systems to replicate natural diurnal variations and enhance visual comfort. Ventilation design should prioritize passive–active systems, utilizing earth-tube cooling and solar chimneys as primary mechanisms before relying on mechanical HVAC, thereby improving energy efficiency and indoor air quality. Long-term resilience can be ensured through smart waterproofing solutions, employing layered geomembranes in conjunction with drainage mats to protect against moisture ingress. User psychology must remain central to the design process by maintaining spatial legibility through clear orientation cues, framed views of the sky, and the use of warm, tactile materials that counteract subterranean enclosure. Finally, embedded environmental monitoring systems—including sensors for light levels, carbon dioxide concentration, and humidity—should be integrated to enable dynamic control of comfort conditions and ensure consistent operational performance over time.

Future research should examine how AI-driven environmental systems could adapt lighting and airflow based on real-time user behavior—pushing underground architecture from reactive to responsive design.

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