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Mini Review

Urban biomechanics and seismic resilience: a historical and geotechnical analysis of San Francisco

Abstract

San Francisco serves as a paramount case study in the intersection of urban morphology, structural engineering, and seismic risk. This paper analyzes the "bio-mechanical" evolution of the city's infrastructure: from the contiguous "shoulder-to-shoulder" masonry of its residential districts to the aerodynamic elasticity of its suspension bridges. We review the historical devastation of the 1906 earthquake and fire, contrasting it with modern engineering resilience. Furthermore, responding to the seismic swarms of late 2025 in the Tri-Valley area, we identify soil liquefaction as the critical remaining vulnerability. Consequently, we propose a novel, patent-pending geotechnical intervention: the widespread application of ureolytic bacteria (e.g., *Sporosarcina pasteurii*) to induce rapid calcification of sandy substrates, effectively transitioning the city's foundation from granular soil to a rock-like matrix.

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Introduction

The city that returns

The settlement originally known as *Yerba Buena* was established by Spanish colonists in 1776, anchored by the Mission San Francisco de Asís (Mission Dolores) established by Franciscan Fathers. Following the discovery of gold in the Sierra Nevada (1849–1851) and the subsequent Comstock Lode silver discovery in Nevada, the city, renamed San Francisco, exploded into a bustling metropolis, earning the moniker "Queen of the West".[1]

However, the city's geologic volatility was laid bare on April 18, 1906, when a magnitude 7.9 seismic event and subsequent conflagrations leveled the urban landscape.

By Chadwick, H. D, 1906, U.S. National Archives.

Yet, the reconstruction was swift and spirited. Within three years, the city was rebuilt, financed largely by Amado Peter Giannini's Bank of Italy (later Bank of America), who provided critical loans to the immigrant middle class when other institutions faltered.

As Rudyard Kipling famously observed of the city's unique allure:

"San Francisco has only one drawback: 'tis hard to leave."[2]

Today, the city stands as a cosmopolitan hub, yet it remains defined by the geomechanical forces that birthed it.

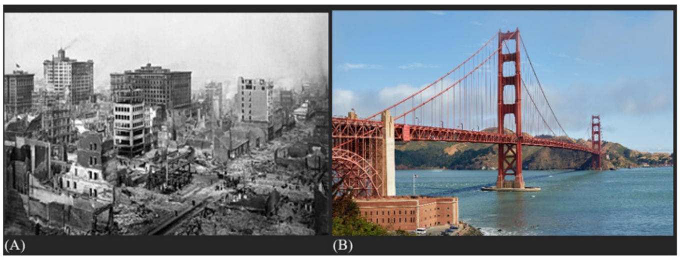

Figure 1 A) Ruin of earthquake; B) Golden gate bridge as seen from battery east.

Urban bio-mechanics: the "shoulder-to-shoulder" morphology

We introduce the term "Urban Bio-Mechanics" to describe how the city's physical structures have evolved, much like biological organisms, to survive their environment.

Structural contiguity and damping

The iconic San Franciscan residential architecture, characterized by "shoulder-to-shoulder" row housing, serves distinct bio-mechanical and economic functions:

a) **Structural coupling:** The high-density, contiguous construction creates a collective structural shield. Much like cellular tissues, the shared walls provide lateral support. This continuity potentially quenches low-frequency vibrations during seismic events, as the friction and mass of the collective block dissipate energy more effectively than isolated structures.

b) **Fire and thermal shielding:** The cement and masonry barriers between units act as firebreaks (or "cement shields"), a direct evolutionary adaptation to the 1906 firestorms intended to mine (stop) the propagation of flames.

c) **Economic efficiency:** This density maximizes real estate utility, accommodating the distinctive even/odd numbering system that facilitates navigation.

Navigational logic

The city's "nervous system" (its street grid) utilizes an alphabetic ordering (A, B, C...) in districts like the Sunset and Richmond. This predictable logic aids the elderly and school-age children in navigating the public transit network (Muni buses and light rail), ensuring social mobility across the challenging topography.

Engineering marvels: the skeleton of the bay

San Francisco's isolation at the tip of a peninsula necessitated the construction of world-class spans, which serve as the city's "skeletal system," designed for flexibility under load.

The golden gate bridge (GGB)

Completed in 1937 by chief engineer Joseph B. Strauss, the GGB spans the confluence of the Pacific Ocean and the SF Bay.[1]

a) **Dimensions:** The single span measures 4,200 feet, suspended by cables 36-3/8 inches in diameter.

b) **Tensile strength:** Each main cable is a bundle of 27,572 individual galvanized wires.[2] The total length of wire used (80,000 miles) is enough to encircle the Earth three times.[3]

c) **Dynamics:** The bridge is designed to act as a harmonic oscillator, capable of swaying up to 27 feet laterally to absorb wind and seismic energy without structural failure. Its "International Orange" hue ensures visibility in heavy marine fog.

The San Francisco–Oakland Bay bridge

Originally completed during the Great Depression (1933–1936), this structure required 200,000 tons of steel. The eastern span, recently replaced with a self-anchored suspension (SAS) design, is an engineering marvel designed to withstand a "maximum credible earthquake" from the nearby Hayward Fault.[3]

Seismology and soil mechanics

The region's tectonic reality is governed by the San Andreas Fault (SAF), a transform boundary where the Pacific Plate slides northwest relative to the North American Plate.

Recent seismic activity (2025-2026)

As noted by *San Francisco Chronicle* reporting (Jack Lee et al.), the region has experienced an unsettling precursor phase. In late 2025, the Tri-Valley area (San Ramon) was subjected to a swarm of over 87 micro-quakes (magnitude > 2.0).[4] While these events release some tectonic stress, they also highlight the vulnerability of the region's soil composition.

The problem: liquefaction

Much of San Francisco's waterfront and financial district is built on reclaimed land, which is essentially sand and fill. During high-magnitude earthquakes, water-saturated sand loses its shear strength and behaves like a liquid (liquefaction).[5] This phenomenon poses the single greatest threat to the city's "shoulder-to-shoulder" housing and infrastructure.

Proposed innovation: microbial-induced calcite precipitation (MICP)

Method for in-situ soil induration via swarm robotic bacterial application

To address the threat of liquefaction, we propose a novel geotechnical intervention inspired by biological processes (biomineralization). We propose the swarm-robotic injection of non-pathogenic, ureolytic bacteria (e.g., *Sporosarcina pasteur*) into the sandy subterranean strata of San Francisco.

The seismic threat on reclaimed land

Liquefaction represents one of the most destructive geological phenomena associated with earthquakes in the San Francisco Bay Area. During the 1989 Loma Prieta earthquake, the Marina District suffered disproportionate damage not due to proximity to the epicenter, but because of its soil composition.[1,2] Large swathes of the Marina, Foster City, and Alameda are constructed on hydraulic fill: loose, saturated, sandy soils dredged from the bay floor. Under seismic loading, the pore water pressure in these soils increases until it equals the overburden pressure, causing the soil to lose shear strength and behave like a liquid.[2,3]

The retrofitting paradox

Current mitigation strategies rely on densification or solidification.[4] Techniques such as vibro-compaction, stone columns, and deep soil mixing are effective but highly invasive. They typically require heavy machinery, significant vertical clearance, and often the partial or total demolition of existing structures to access the foundation soil.[3] For densely populated urban environments, these methods are economically and logistically prohibitive, leaving thousands of residents in high-risk zones.

The novel concept: bio-robotic intervention

This paper proposes a convergence of two emerging technologies to solve this paradox:

a) **Biogeotechnics:** Specifically, Microbially Induced Calcite Precipitation (MICP), a process where bacteria precipitate calcium carbonate to cement soil grains.[5]

b) **Soft robotics:** Specifically, tip-eversion "vine" robots that can burrow through granular media without the high friction or heavy axial force of traditional drilling.

Methodology

The chemistry: hybrid MICP and EICP

The primary stabilization mechanism selected is MICP, utilizing the ureolytic bacterium *Sporosarcina pasteurii*.[6] The bacteria hydrolyze urea to produce ammonium and carbonate ions. In the presence of calcium ions, calcium carbonate ($8CaCO_3$) precipitates at particle contact points, increasing shear strength and stiffness.[4]

$CO(NH_2)_2 + 2H_2O \text{ -> } 2NH_4^+ + CO_3^{2}-$

$Ca^{2+} + CO_3^{2-} \text{ -> } CaCO_3$ (solid)

Addressing soil heterogeneity: Hydraulic fills in the Bay Area often contain lenses of fine-grained silt where bacteria may face pore-size exclusion. To address this, we propose a hybrid protocol that utilizes **Enzyme-Induced Calcite Precipitation (EICP)** using free urease enzymes sized approx 12nm for layers with lower hydraulic conductivity, ensuring continuous stabilization across heterogeneous stratigraphy.[5]

The delivery system: soft robotic burrowers

Traditional injection requires rigid steel pipes and high pressure.

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We propose the use of Tip-Everting Soft Burrowing Robots (TESBRs).

a) **Locomotion:** The robot consists of a flexible, polyethylene membrane that everts (turns inside out) under pneumatic pressure. This mechanism eliminates skin friction against the soil, allowing the robot to grow like a plant root.[6]

b) **Dual-lumen design:** To prevent premature cementation inside the robot, a dual-channel design keeps the biological agent (bacteria/enzyme) separate from the cementation fluid (urea/calcium) until they mix at the injection tip.

c) **Granular fluidization:** The robot tip emits a low-pressure air/fluid jet to locally fluidize the granular medium, reducing penetration resistance and allowing navigation through denser sand lenses.[7]

Theoretical feasibility case study

Site parameters

We model a typical residential lot in the Marina District based on USGS soil profiles:

1) **Lot dimensions:** 9.1m * 30.5m

2) **Target liquefiable layer:** Depth of 4m to 10m (6m thickness)

3) **Soil properties:** Loose silty sand, porosity approx 0.40

4) **Total soil volume:** approx 1,665 m^3

Treatment strategy: columnar reinforcement

Rather than solidifying the entire soil mass, which would be prohibitively expensive and time-consuming, we target a replacement ratio of 20% to create a lattice of stable, cemented "bio-columns." This is analogous to stone column installation, providing sufficient shear resistance to prevent bulk liquefaction.

1) **Target treatment volume:** 333m^3

2) **Pore volume to treat:** approx 133 m^3

Fluid requirements & timeline

Effective MICP typically requires multiple treatment cycles. Assuming 5 cycles with a total fluid injection of 2.0 pore volumes per cycle:

1) **Total fluid required:** 1.33 million liters.

Robotic fleet efficiency

Using a conservative injection/permeation rate of 100 L/hour per robot to prevent hydraulic fracturing (heave):

a) **Swarm size:** 20 autonomous units deployed from small (<1m^2) access pits.

b) **System flow rate:** 2,000L/hr = 2m^3/hr

c) **Execution time:** 1,330 m^3 / 2 m^3/hr ~ 665 hours

Result

The treatment can be completed in approximately 28 days of continuous operation. This timeframe is comparable to standard construction projects but requires zero demolition of the residence.

Discussion

Advantages

a) **Non-destructive:** Access is achieved through small boreholes in sidewalks, backyards, or basements. The residence remains habitable throughout the process.

b) **Environmental sustainability:** The process operates at ambient temperatures and has a significantly lower carbon footprint than Portland cement injection.

c) **Permeability:** Unlike jet grouting, MICP maintains partial soil permeability, preventing the buildup of hydrostatic pressure against basement walls.

Challenges

a) **Ammonium byproducts:** The hydrolysis of urea produces ammonium NH4, which is toxic to aquatic life. A closed-loop extraction system, where robots reverse flow to extract pore fluid after the reaction period, must be implemented to prevent groundwater contamination.

b) **Robot recovery:** While vine robots are retractable, the friction of the cemented soil may trap them. Designing the robots from biodegradable polymers would mitigate the risk of leaving "techno-trash" underground.

Conclusion

San Francisco is a city defined by resilience: rebuilt from the ashes of 1906 and fortified by the engineering of the 1930s. As we face the inevitable recurrence of tectonic activity, we must look beyond steel and concrete to the microscopic world. By harnessing the "bio-mechanical" power of bacteria to calcify our soil, we can effectively retrofit the ground itself, ensuring the "Queen of the West" remains standing for centuries to come.

Acknowledgments

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Conflicts of interest

The author declares that there is no conflict of interest.

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