Subterrane

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The Gravitational Causality Framework for Planetary-Scale Infrastructure Integrity and Force-Indexed Capital

Abstract

This white paper formalizes the Subterrane Causality Framework: a first-principles physical architecture that establishes the **continuous gravitational flow structure as the sole causal field** governing mantle dynamics to infrastructure deformation. This framework **replaces probabilistic hazard with deterministic force-state**, enabling capital instruments indexed to pre-failure physics. The framework establishes a non-probabilistic pathway from planetary physics to sovereign-grade financial instruments via the Causal Integrity Metric (CIM). Gravity and seismic methods are treated as complementary observational projections of the same underlying causal field. CIM is introduced as a force-indexed, pre-failure scalar suitable for direct capitalization.

1. Introduction

Modern infrastructure finance and hazard mitigation rely almost exclusively on probabilistic forecasts derived from historical event catalogs. These approaches price *outcomes* rather than *causes*. Subterrane introduces a causal alternative: capital indexed directly to the evolving physical force state of the Earth through a unified gravitational framework.

This document establishes the physical, epistemic, and financial chain from gravitational first principles to CIM as a contract-grade variable.

2. First-Principles Causal Object: Gravitational Flow Structure

2.1 Definition

The gravitational flow structure is defined as a single, continuous four-dimensional field describing how mass, stress, and potential are distributed and evolve throughout the Earth system—from core to mantle to crust to surface.

2.2 Physical Scope

This field governs: - Mantle convection and buoyancy - Slab pull and lithospheric coupling - Isostatic adjustment - Basin loading - Crustal stress accumulation - Fault locking and release - Infrastructure loading and deformation

There are not separate mantle-scale and crustal-scale causal systems. All expressions derive from the *same continuous gravitational field* at different wavelengths and time constants.

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3. Fundamental Force Closure

All known fundamental interactions were evaluated for relevance at planetary scale:

- **Strong nuclear force:** confined to nuclear binding; no macroscopic stress transport.
- **Weak nuclear force:** contributes only via long-term radiogenic heat production.
- **Electromagnetic force:** governs material response (elasticity, conductivity), not global stress transport.
- **Gravitation:** the only force with infinite range, direct coupling to mass-energy, and the capacity to organize planetary-scale stress and deformation.

Conclusion: Gravity as the Sole First-Order Planetary Driver (CIM Validity Statement)

Only one fundamental interaction remains causally operative across mantle, crust, and infrastructure scales:

Gravitation is the sole first-order driver of planetary mechanics relevant to the Causal Integrity Metric (CIM).

- Strong force: confined to nuclei
- Weak force: contributes only to heat generation
- Electromagnetic force: defines material response, not mass transport
- Thermodynamics: generates density contrasts but **requires gravity to convert them into motion and stress**

Gravity alone transports stress, accumulates strain, organizes seismic locking, and loads engineered structures.

Therefore:

CIM is fundamentally a gravitational metric.
All other interactions collapse into parameters within the gravitational flow structure.

Implication for Finance: All existing risk models (seismic, flood, slope stability) are effectively **higher-order electromagnetic descriptions**; they model material *response* to the primary gravitational driver. By indexing directly to the gravitational field, CIM bypasses these complex, localized response models and captures the **primary causal driver** itself. This is why CIM can be contract-grade where probabilistic models cannot: it is built on a **conserved, fundamental force**, not on statistical approximations of material failure.

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4. Observation as Projection, Not Causation

The gravitational flow structure exists independently of measurement. Observational systems act as *operators* that project this same field into different data spaces:

- **Gravity observations (satellite + marine + terrestrial):** direct measurement of mass redistribution and force gradients.
- **Seismic observations:** indirect sampling via wave propagation through elastic media.
- **Geodetic and structural sensors:** surface deformation and structural response.

These are **measurement-specific views of a single causal object**. Mistaking a gravity anomaly for a separate phenomenon from a seismic velocity anomaly is a **category error**; like confusing a shadow's length for the object casting it. Subterrane's resolution program **inverts the shadows to reconstruct the object**.

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5. Resolution Program: Contract-Grade Reconstruction

To make the gravitational flow structure suitable as a financial reference, Subterrane implements a dedicated resolution program:

5.1 New Seismic Acquisition

Purpose-built station networks along priority structural corridors to increase spatial completeness and signal-to-noise.

5.2 High-Fidelity 1D Vertical Profiles

True Vp and Vs depth profiles at each station to establish physically correct column physics from surface to deep mantle.

5.3 Improved 3D Tomography

Tomographic inversion anchored to the improved 1D columns and jointly constrained with gravity data to produce a sharpened volumetric reconstruction of the same gravitational flow field.

This program does not create causality. It increases the *resolution of the pre-existing causal field* until it becomes contract-grade.

6. Crustal Causal Envelopes and Locked Zones

From the resolved gravitational flow field, Subterrane derives crustal causal envelopes:

- Admissible domains of stress accumulation
- Physical boundaries of seismic locking
- Time-dependent strain migration corridors

Mapped faults serve as surface calibrations only. Locked zones are interpreted as *expressions of deep gravitational control*, not as independent probabilistic hazards.

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7. The Causality Lens

The Causality Lens is the formal operator mapping:

> Gravitational flow field → Local force and stress state

For any location and time, it yields: - Stress tensor - Temporal evolution of stress - Irreversibility thresholds

7.1 Causal Nodes

A causal node is defined as a location where engineered infrastructure directly interfaces with the gravitational flow field (e.g., quay walls, dam foundations, tunnels, pipelines). At each node, the Causality Lens provides: - Baseline force state - Live force state - Distance to irreversible topology

This is the exact boundary where planetary physics becomes capital exposure.

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8. Causal Integrity Score (CIM)

For a defined system with N causal nodes, CIM is defined as:

$CIM = 100 - \Sigma(\Delta S_i \cdot R_i \cdot w_i)$

Where:

> ΔS_i = causal departure from baseline at node i
>
> R_i = irreversibility coefficient
>
> w_i = systemic and economic criticality weight

8.1 Interpretation

CIM is:

- Not a probability of failure
- Not an actuarial risk rating
- Not an event-triggered index

It is a *force-indexed scalar* expressing how far a system has moved toward irreversible geometry under the same gravitational flow structure.

8.2 Control Hierarchy

- First-order control: gravitational flow field
- Second-order expression: seismic strain release
- Third-order observation: structural sensor response

8.3 The Causal Integrity Metric (CIM): Dual-Layer Derivation

(Executive Summary + Technical Appendix)

The Causal Integrity Metric is the scalar compression of how the gravitational flow structure is deforming a system's engineered interfaces.
To make CIM contract-grade, this section presents a **two-layer derivation**:

1. **Executive Summary** - for sovereigns, investors, and decision-makers
2. **Technical Appendix** - for engineers, geophysicists, and auditors

This dual structure ensures CIM is both **understandable** and **scientifically defensible**.

8.3A - Executive Summary (Non-Technical Derivation)

CIM quantifies how far a system has moved toward irreversible deformation under the gravitational field. Each causal node contributes a penalty based on three components:

1. Causal Departure (ΔS_i)

How far the node has drifted from its certified baseline force-state toward a calibrated pre-failure threshold.

- $\Delta S_i = 0 \rightarrow$ baseline
- $\Delta S_i = 1 \rightarrow$ pre-failure geometry
- Computed from live force-state compared with baseline irreversibility boundaries

2. Irreversibility (R_i)
How much of the deformation would **remain** if loads were relaxed.

- 0 → reversible (elastic)
- 1 → irreversible (plastic/damaged)
- Derived from displacement cycles, pore-pressure behaviour, and structural diagnostics

3. Criticality (w_i)
The importance of the node to systemic function.

- Economic importance
- Safety exposure
- Network redundancy / centrality
- Typically scaled from 1 to 5 for sovereign systems

System-Level CIM
CIM = 100 – $\Sigma(\Delta S_i \times R_i \times w_i)$

A system with minimal causal drift (low ΔS), high reversibility (low R), and redundancy (low w) retains a high CIM.
A system under deep stress with irreversible deformation at a critical node shows a reduced CIM.

Interpretation:
CIM expresses *how close the system is to irreversible topology*, using force-state rather than probability.

8.3B- Technical Appendix (Formal Derivation)

(For engineers, geophysicists, quants, and audit authorities.)
This section provides the rigorous physical and mathematical basis for ΔS_i, R_i, and w_i.

8.3B.1a Stress Monitoring Coupling at Causal Nodes

At each causal node, the Causality Lens yields a local Cauchy stress tensor $\sigma_{ij}(x_i, t)$ consistent with the gravitational flow field, seismic history, and structural topology at that location. To make this field contract-grade and auditable, Subterrane couples σ_{ij} to a dedicated stress-monitoring suite installed at the infrastructure interface.
Each node is equipped with standard structural and geotechnical instrumentation – including, as appropriate, embedded strain gauges and fibre-optic sensors in steel and concrete, inclinometers and earth-pressure cells in the ground, GNSS monuments on critical superstructure, InSAR deformation coverage, piezometers, and strong-motion sensors in seismic regions. These instruments produce an observation vector

$\mathbf{m}_i(t)$ comprising strains, displacements, rotations, pore pressures and dynamic response histories associated with node i.
A forward structural operator H maps the local stress tensor into predicted observables,

$$\mathbf{m}_i^{\text{pred}}(t) = H[\sigma_{ij}(x_i, t)],$$

from which a residual

$$\mathbf{r}_i(t) = \mathbf{m}_i^{\text{obs}}(t) - \mathbf{m}_i^{\text{pred}}(t)$$

is computed and minimized subject to the gravitational and seismic constraints on σ_{ij}. This procedure yields a sensor-calibrated stress tensor $\hat{\sigma}_{ij}(x_i, t)$ at each node, which is then used to compute the stress invariant $J_{2i}(t)$, the normalized causal departure $\Delta S_i(t)$, and the irreversibility factor $R_i(t)$.

In this way, $\Delta S_i(t)$ at each node is not an abstract construct but a direct, physically measured reflection of how the infrastructure and foundation are actually loading and evolving under gravity over time. The CIM score reported to capital and governance is therefore anchored simultaneously in the global causal field and the instrumented reality of the asset itself.

8.3B.1 Derivation of ΔS_i- Causal Departure from Baseline

1. Stress Tensor from the Causality Lens
The gravitational flow field G(x, t) is mapped through the Causality Lens L to yield the local Cauchy stress tensor at node i:
$\sigma_{ij}(x_i, t) = L[G](x_i, t)$

2. Deviatoric Stress
$s_{ij} = \sigma_{ij} - (1/3)\ \sigma_{kk}\ \delta_{ij}$

3. Second Stress Invariant (J_2)
$J_{2i}(t) = 0.5 \times s_{ij}(t) \times s_{ij}(t)$

4. Calibration Thresholds
Each node has three material-mechanical thresholds:

- J_{2i}^{0} - baseline (certified inception)
- J_{2i}^{EL} - elastic upper bound
- J_{2i}^{PF} - pre-failure onset

5. Raw Causal Departure
$\Delta\tilde{S}_i(t) = (J_{2i}(t) - J_{2i}^{0}) / (J_{2i}^{PF} - J_{2i}^{0})$

6. Clamping to Physical Bounds

$\Delta S_i(t) = \min(\max(\Delta\tilde{S}_i(t), 0), 1)$

Meaning

- $\Delta S_i = 0 \rightarrow$ identical to baseline
- $\Delta S_i = 1 \rightarrow$ at pre-failure threshold
- Intermediate values quantify causal drift under the gravitational field

Additional observables (horizontal displacement, rotation, settlement, pore-pressure) may be incorporated via a weighted expansion, but J_2 remains the invariant anchor.

8.3B.2 Derivation of R_i — Irreversibility Coefficient

R_i measures the proportion of deformation at node i that is **non-recoverable** if external loads were reduced.

Energy-Based Definition

$E_i^{TOT}(t)$ = total strain energy density
$E_i^{IRR}(t)$ = irreversible strain energy density
Then:
$R_i(t) = E_i^{IRR}(t) / E_i^{TOT}(t)$

Calibration Methods

- Residual vs peak displacement following load cycles
- Hysteresis in displacement or pore-pressure response
- Development of shear bands
- Crack propagation
- Constitutive models (e.g., Mohr-Coulomb, Cam-Clay, damage mechanics)

Bounds

$0 \leq R_i \leq 1$

Interpretation

- $R_i \approx 0 \rightarrow$ elastic response (no damage)
- $R_i \approx 1 \rightarrow$ irreversible damage accumulation

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8.3B.3 Derivation of w_i - Systemic and Economic Criticality Weight

w_i encodes the systemic value of the node:

1. Economic Criticality (E_i)
Throughput, revenue, supply-chain dependence.

2. Safety Criticality (S_i)
Population exposure, environmental hazard, industrial risk.

3. Topological Centrality (C_i)
Redundancy, re-routing options, graph-theoretic importance.
Combined via:
$w_i = \alpha E_i + \beta S_i + \gamma C_i$
Weighting coefficients (α, β, γ) are set through governance between:

- Asset owner
- Regulator
- Capital provider

Typical sovereign-grade scale: **1–5**.

8.3B.4 CIM as a System-Level Mapping

For system m:
$CIM_m(t) = 100 - \Sigma_i [\Delta S_i(t) \times R_i(t) \times w_i]$

Physical Chain
$G(x, t) \rightarrow \sigma_{ij} \rightarrow J_{2i} \rightarrow \Delta S_i \rightarrow R_i \rightarrow$ Node penalty $\rightarrow \Sigma \rightarrow CIM_m$

Financial Chain
CIM_m → Coupon behaviour → Threshold triggers → Intervention capital → Sovereign guarantees

Interpretation
CIM_m is a lossless compression of how the unified gravitational field is deforming engineered systems.

8.3B.5 Auditability

Each term is independently verifiable:

- **ΔS_i** - from structural sensors, gravity-seismic inversions, FE models
- **R_i** - from displacement hysteresis, pore-pressure cycles, damage mechanics
- **w_i** - from regulated governance and system valuation

This ensures CIM is **contract-grade, audit-grade, and sovereign-grade**.

8.4 CIM as a Financial Compression Function

The CIM equation is a **lossless compression algorithm** for planetary force-state at the infrastructure interface. **ΔS** is the gravitational field's local expression. **R** is the material's thermodynamic answer to that field. **w** is civilization's value function. CIM **does not model risk**; it **reports the primary physical independent variable** to which all material risk is ultimately coupled.

8.5 Temporal Calibration and Gravitational Memory

The gravitational flow structure is inherently time-dependent. Mass redistribution, stress migration, and strain accumulation evolve continuously in time. Capital, however, operates on discrete intervals. To make the Causal Integrity Metric (CIM) contract-grade, Subterrane explicitly governs the time axis in two layers:

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1. Continuous Physical Time

The gravitational flow field $G(x,t)$ is a continuous four-dimensional function describing how stress, potential, and deformation evolve throughout the Earth system.

The Causality Lens transforms this into a local stress state at each node:

$$\sigma_{ij}(x_i,t) = L[G](x_i,t)$$

This continuous evolution includes mantle forcing, crustal stress migration, pore-pressure response, and structural loading cycles.

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2. Discrete Contract Time

Financial instruments, reporting cycles, and sovereign governance require **discrete, timestamped evaluations**. Subterrane defines:

$$t_0, t_1, t_2, \dots, t_k$$

as formally governed evaluation epochs (e.g., daily, weekly, monthly, quarterly), each tied to the Gregorian calendar.

CIM is evaluated only at these epochs, even though the underlying physics is continuous.

Gravitational Memory (The Critical Bridge)

Although the observational record is not continuous at every point, the Earth system possesses **gravitational memory**:

The present stress and strain state already encodes the integrated effect of all past loading.

Thus:

- $\Delta S_i(t_k)$ reflects cumulative drift from baseline up to epoch t_k
- $R_i(t_k)$ reflects cumulative irreversible deformation
- w_i remains fixed between governance intervals

No reconstruction of the full historical forcing function is required. The **current force-state is the history**.

This is the key reason CIM can be evaluated at discrete times without losing physical integrity.

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3. Time-Stamped System Integrity

CIM becomes a temporal scalar:

$$\mathrm{CIM}_m(t_k) = 100 - \sum_i [\Delta S_i(t_k)\, R_i(t_k)\, w_i]$$

Each value is:

- **anchored to a specific calendar date and time**
- derived from the best-available reconstruction of the gravitational field and structural response up to that epoch
- **auditable** via sensor data, gravity–seismic inversions, and engineering diagnostics

This allows:

Discretised time

Clear observation windows for couponing, threshold detection, and governance checkpoints.

Absolute time

Alignment with regulatory cycles, sovereign reporting, and contractual obligations.

Continuous physics

No distortion of the underlying causal field.

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4. Implication for Capital

CIM becomes:

a time-stamped compression of gravitational memory at the infrastructure interface.

The past is embedded in the current state.
The future is expressed as the trajectory of **ΔS and R** toward or away from irreversible topology.

This temporal formalisation turns CIM from a static scalar into a **governed temporal primitive** suitable for sovereign-grade instruments.

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9. Financial Implications

Because CIM is indexed to force rather than to loss events:

- Capital can be written on pre-failure deformation
- Triggers activate at irreversibility thresholds
- Intervention capital is deployed before catastrophe

This enables a new class of *causal capital instruments* distinct from insurance, catastrophe bonds, and resilience finance.

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10. Unified Bottom-Up Causal Chain

1. Continuous gravitational flow structure
2. Observational projections (gravity, seismic, geodetic)
3. Resolution program (acquisition → 1D → 3D)
4. Crustal causal envelopes and locked-zone control
5. Causality Lens at node scale
6. CIM as system-level financial scalar

All sovereign-grade instruments are capital layers built on top of this chain.

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11. Doctrinal Statement

Subterrane operates on a single continuous gravitational flow structure that governs mantle, crust, faults, and infrastructure alike. Gravity and seismic methods are observational projections of the same causal field. The Causal Integrity Metric (CIM) is the financial compression of how that field is currently deforming critical engineered systems.

THE SUBTERRANE DOCTRINAL AXIOM

1. **One Causal Field:** A single, continuous gravitational flow structure governs stress and deformation from the mantle to the foundation pile.
2. **One Measurement Truth:** Gravity and seismic data are complementary projections of this field, not separate realities.
3. **One Financial Primitive:** The Causal Integrity Metric (CIM) is the direct scalar readout of this field's interaction with critical infrastructure.
4. **One Capital Alignment:** Finance must be indexed to CIM to escape the probabilistic destruction cycle.

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12. Applications and Strategic Outlook

The framework directly supports: - Sovereign infrastructure integrity programs - Port, dam, and corridor protection - Pre-failure intervention finance - Long-duration resilience capital.

By aligning capital with the underlying physics of force and deformation, Subterrane establishes a new financial layer indexed to the causal structure of the Earth itself.

End of White Paper