Strengthening Subsea Cable Resilience Through Protection and Restoration

From reactive repair to proactive resilience

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Abstract

Subsea power and telecommunication cables underpin global digital connectivity and the emerging cross-border energy transition. While installation and protection have historically dominated engineering focus, recent incidents and geopolitical developments have highlighted that system resilience is ultimately defined by the speed, certainty, and effectiveness of restoration and repair.

This paper examines how subsea cable repair has evolved from reactive, vessel-centric operations to an increasingly intelligence-led and design-integrated discipline, and how future repair strategies must adapt to growing operational, environmental, and security constraints. Drawing on practical experience from shallow waters, congested ports, reservoirs, and constrained coastal environments, it reviews common fault mechanisms and their implications for repair planning, mobilisation, and execution.

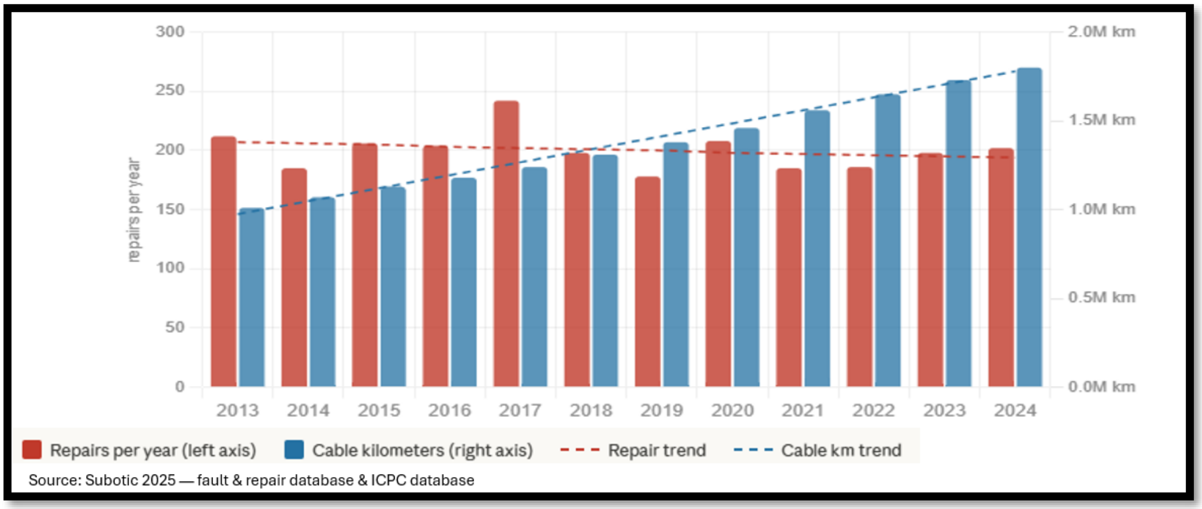
The paper argues that rather than viewing repair as a downstream contingency, future resilience depends on embedding restoration readiness into early-stage design, routing, and stakeholder planning — proposing a practical framework for transitioning from reactive repair to proactive restoration across six simultaneous frontiers: technology leverage, shared stewardship, effective marine spatial planning, appropriate O&M modelling, intergovernment collaboration, and policy and governance reform.

1. Global scale and repair statistics

Subsea cables carry 99% of all intercontinental data traffic. With over 600 systems spanning more than 1.8 million kilometres of seabed, they constitute the most critical and least visible infrastructure on Earth. The scale of this network — and the fragility of the ecosystem designed to repair it — is widely underappreciated by governments, industry and the public alike.

199	**1.8M+**	**+77%**	**<70**
Average repairs/year	**Cable km in service**	**Cable growth**	**Repair ships**
2013–2024 (ICPC)	as of 2024	2013–2024	globally (2025)

The most important headline statistic is the relationship between growth and fault rate. Despite cable network length growing by 77% since 2013 — from approximately 1.0 million km to 1.8 million km — the number of repairs per year has remained essentially flat at around 199. This is a remarkable achievement, reflecting improvements in cable burial standards, route engineering, and installation quality control. The fault rate per kilometre has fallen by over 40% since 2010.



Source: Subotic 2025 — fault & repair database & ICPC database

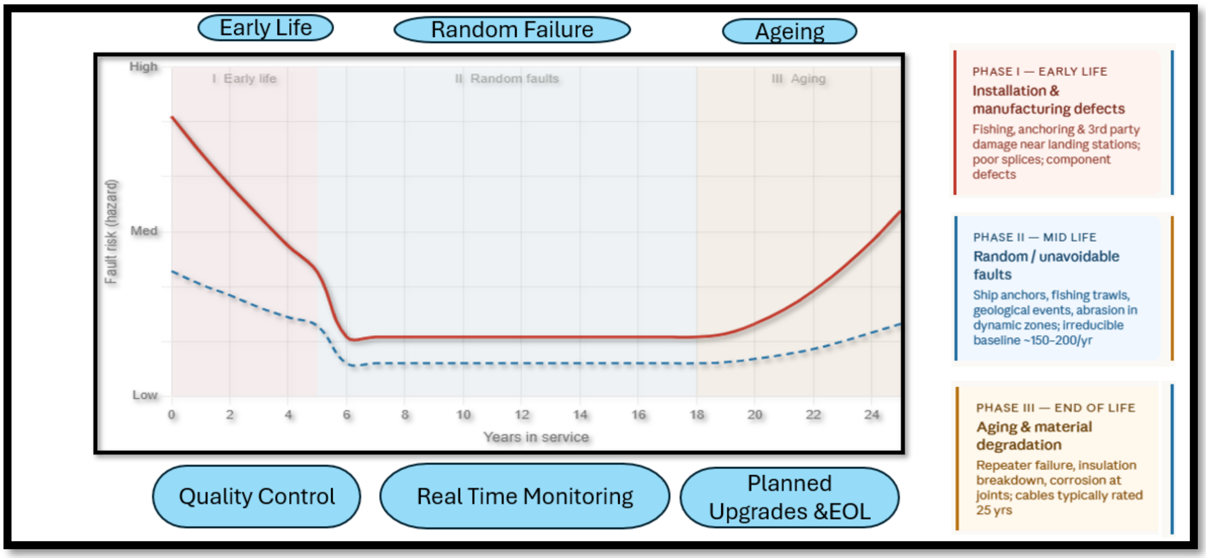
However, this positive trend masks a structural crisis in the repair ecosystem. The TeleGeography/Infra-Analytics 2025 report — commissioned by the SubOptic Association — projects a 48% net increase in cable kilometres by 2040, while simultaneously finding that approximately two-thirds of cable maintenance vessels will have reached end-of-life by then. The report calls for 15 replacement vessels plus 5 additional vessels, primarily for Asia — a total investment of approximately $3 billion to sustain current service levels. This figure covers maintenance of current capability only; it does not include the investment needed to improve repair times or extend coverage to underserved regions.

Key insight

The world's cable network is growing faster than the infrastructure needed to repair it. Average repair time in the North Atlantic is 15 days; in the Asia-Pacific it averages 30 days or more. The worst recorded case — entirely due to regulatory delay, not technical difficulty — took 947 days (ICPC 2023). The $3 billion fleet investment gap is the most immediately quantifiable constraint, but permitting reform would deliver faster results for lower cost.

2. Fault risk across a cable's service life — the bathtub curve

Classical reliability engineering describes a 'bathtub curve' of failure probability over a system's lifetime: elevated in the early phase due to manufacturing and installation defects, low and stable in the middle due to random external events, and rising again at end of life as materials degrade and components age. This model — derived from the Weibull distribution and widely used in aerospace and power generation — applies directly to subsea cable infrastructure.



PHASE I — EARLY LIFE
Installation & manufacturing defects
Fishing, anchoring & 3rd party damage near landing stations; poor splices; component defects

PHASE II — MID LIFE
Random / unavoidable faults
Ship anchors, fishing trawls, geological events, abrasion in dynamic zones; irreducible baseline ~150–200/yr

PHASE III — END OF LIFE
Aging & material degradation
Repeater failure, insulation breakdown, corrosion at joints; cables typically rated 25 yrs

Adapted from classical reliability engineering (Weibull bathtub curve) — applied to subsea cable infrastructure lifecycle

Phase I — Early life (years 0–6): Installation and manufacturing defects

The first phase is characterised by elevated fault risk driven by installation quality and early design decisions. Fishing and anchoring near landing stations, poor splices, and component defects are the primary causes. This is where quality control investment delivers its highest return — pre-installation surveys, CBRA burial depth analysis, and factory acceptance testing all compress the early-life risk period.

- Fishing, anchoring and third-party damage near landing stations account for the majority of Phase I faults
- Poor splices — including those caused by inadequate training, unsuitable working conditions at sea, or incorrect materials — contribute a significant share
- Component defects from manufacturing, particularly in repeater electronics and cable armour, account for the remainder
- Effective interventions: thorough geophysical and geotechnical surveys; CBRA burial depth analysis; zone-matched armour (DA/SA/LW); rigorous factory acceptance testing (FAT) and system acceptance test (SAT)

Phase II — Mid-life (years 6–18): Random unavoidable faults

The middle period establishes an irreducible fault baseline of approximately 150–200 repairs per year globally. These faults are caused by ship anchors, fishing trawls, geological events and abrasion in dynamic seabed zones. They cannot be eliminated, but they can be reduced through monitoring and deterrence, and their impact can be minimised through faster detection and response.

- Ship anchors and fishing trawls account for approximately 86% of all mid-life faults — the single most important target for prevention
- Geological events including turbidity currents, slope failures and seismic activity cause occasional large-scale incidents with multiple simultaneous break points
- Effective interventions: DAS/DFOS distributed acoustic sensing; AI+AIS vessel behaviour analytics; cable protection zone enforcement; guard vessel patrols; community fishing liaison

Phase III — End of life (years 18–25+): Ageing and material degradation

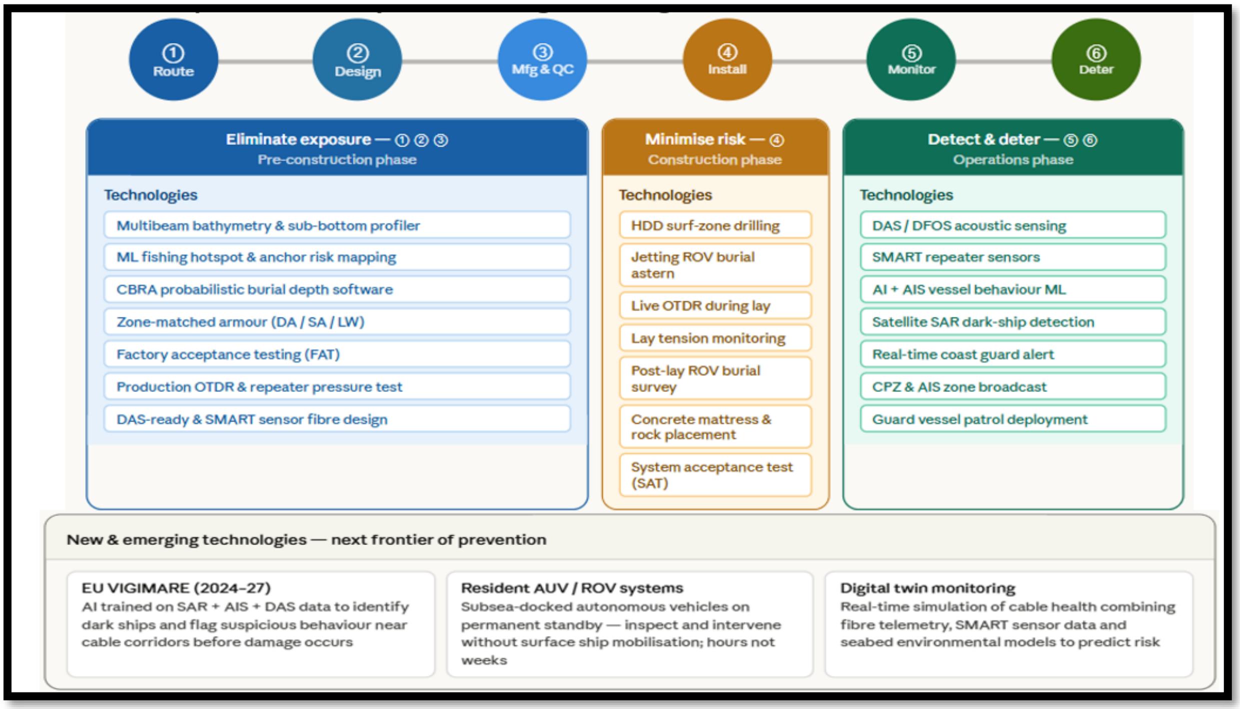
As cables approach and exceed their 25-year design life, fault frequency rises due to repeater failure, insulation breakdown and corrosion at joints. This phase requires planned maintenance — systematic health monitoring, repeater replacement programmes and decommissioning planning.

- Repeater failure is the primary end-of-life failure mode; replacement units require 12–18 months to manufacture at significant cost, making stockpiling impractical
- Insulation breakdown and conductor corrosion at joints become increasingly common beyond 20 years
- Effective interventions: digital twin health monitoring; planned repeater replacement; end-of-life planning integrated with capacity expansion decisions

> **The intervention message**
>
> A cable managed with quality control in Phase I, real-time monitoring in Phase II, and planned upgrades in Phase III follows the lower curve — with substantially reduced fault frequency throughout its service life. The difference between the curves represents billions of dollars in avoided repair costs and days of avoided outage over a 25-year system life. (Adapted from Weibull bathtub curve — classical reliability engineering)

3. Prevention is better than cure — the lifecycle approach

The most cost-effective repair is the one that never happens. A structured prevention lifecycle approach organises all interventions across six stages from initial route engineering through in-service deterrence. Each stage has a distinct set of enabling technologies; together they address the three strategic objectives of eliminating exposure, minimising risk, and detecting and deterring threats. The fault rate per cable-kilometre has fallen over 40% since 2010 — demonstrating that prevention works when systematically applied.



Eliminate exposure — ① ② ③
Pre-construction phase

Technologies
- Multibeam bathymetry & sub-bottom profiler
- ML fishing hotspot & anchor risk mapping
- CBRA probabilistic burial depth software
- Zone-matched armour (DA / SA / LW)
- Factory acceptance testing (FAT)
- Production OTDR & repeater pressure test
- DAS-ready & SMART sensor fibre design

Minimise risk — ④
Construction phase

Technologies
- HDD surf-zone drilling
- Jetting ROV burial astern
- Live OTDR during lay
- Lay tension monitoring
- Post-lay ROV burial survey
- Concrete mattress & rock placement
- System acceptance test (SAT)

Detect & deter — ⑤ ⑥
Operations phase

Technologies
- DAS / DFOS acoustic sensing
- SMART repeater sensors
- AI + AIS vessel behaviour ML
- Satellite SAR dark-ship detection
- Real-time coast guard alert
- CPZ & AIS zone broadcast
- Guard vessel patrol deployment

New & emerging technologies — next frontier of prevention

EU VIGIMARE (2024–27)
AI trained on SAR + AIS + DAS data to identify dark ships and flag suspicious behaviour near cable corridors before damage occurs

Resident AUV / ROV systems
Subsea-docked autonomous vehicles on permanent standby — inspect and intervene without surface ship mobilisation; hours not weeks

Digital twin monitoring
Real-time simulation of cable health combining fibre telemetry, SMART sensor data and seabed environmental models to predict risk

Stage 1-3 Eliminate exposure – pre construction

Survey data streams — the ten inputs AI now fuses simultaneously

Modern route design ingests data from multiple survey types simultaneously. Where this process once took months of sequential manual analysis, AI-assisted route optimisation can process all streams in parallel and score candidate corridors within hours. The ten data streams fall into two categories:

Field surveys ① to ⑥	Data layer overlays ⑦ to ⑩
① Geophysical — multibeam bathymetry, side-scan sonar, sub-bottom profiler, water column imaging	⑦ Historical AIS density — fishing track heat-maps, anchor pattern density by vessel class and season
② Geotechnical — sediment coring, cone penetration testing (CPT), burial feasibility classification	⑧ Fault history database — past cable failure locations, causes, depth correlations (ICPC database)
③ UXO survey — magnetometer & gradiometer; historical ordnance clearance in conflict zone areas	⑨ Satellite SAR imagery — seabed change detection, sand wave migration over time
④ Oceanographic — current velocity, turbidity corridors, storm sediment flow patterns	⑩ CPZ mapping — existing infrastructure, crossing agreements, spatial conflict data
⑤ Environmental & biological — marine protected areas, coral mapping, seabed ecology assessments ⑥ Geohazard — seismic fault mapping, slope stability, landslide risk, gas hydrate zones	

AI-powered route optimisation and CBRA automation

- Multi-variable route scoring — AI simultaneously weighs all ten survey layers across every candidate corridor, scoring hazard, burial feasibility, fishing density, anchor risk, seismic exposure and sediment mobility
- Probabilistic CBRA automation — ML models replace months of manual probabilistic analysis; compute optimal burial depth per segment calibrated against vessel traffic distributions and anchor penetration databases
- Climate change extrapolation — AI projects sediment mobility, turbidity corridor shift and wave seabed impact 25 years forward to ensure routes remain safe at end-of-life
- Live ROV video QA (Video analytics) — AI analyses installation footage in real time, flagging burial non-conformances and armour damage as the cable is laid

Stage 4 Minimise risk - construction phase

During installation, the primary objective is to achieve the burial depth specified by the CBRA without creating damage. Key technologies include: HDD surf-zone drilling (eliminates the most vulnerable shoreline section); jetting ROV burial astern; live OTDR during lay; lay tension monitoring; post-lay ROV burial survey; and concrete mattress protection at crossing points.

Stage 5-6 Detect and deter – operation Phase

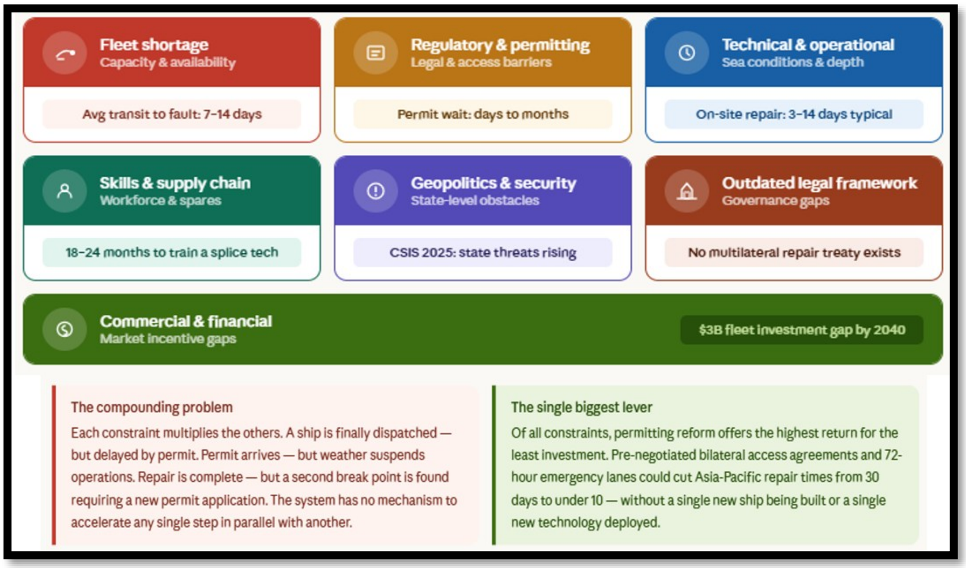
Once in service, DAS/DFOS distributed acoustic sensing turns the cable fibre itself into a continuous sensor. SMART repeater sensors provide discrete point measurements at each amplifier location. AI + AIS vessel behaviour analytics, satellite SAR dark-ship detection, EU VIGIMARE (Horizon 2024–27), CPZ & AIS zone broadcast, and guard vessel patrols complete the deterrence layer.

The result

The fault rate per cable-km has fallen over 40% since 2010 through better surveys, deeper burial, improved armour and AI monitoring. Prevention is demonstrably working — the challenge is to accelerate and broaden its application globally. (Source: SubOptic 2025 / ICPC)

4. Constraints and challenges — why repair still takes weeks

Despite prevention gains, when a fault occurs, restoration timelines remain unacceptably long. Seven distinct constraint categories compound each other in ways the industry has not yet systematically addressed.



Fleet shortage
Capacity & availability
Avg transit to fault: 7–14 days

Regulatory & permitting
Legal & access barriers
Permit wait: days to months

Technical & operational
Sea conditions & depth
On-site repair: 3–14 days typical

Skills & supply chain
Workforce & spares
18–24 months to train a splice tech

Geopolitics & security
State-level obstacles
CSIS 2025: state threats rising

Outdated legal framework
Governance gaps
No multilateral repair treaty exists

Commercial & financial
Market incentive gaps
$3B fleet investment gap by 2040

The compounding problem
Each constraint multiplies the others. A ship is finally dispatched — but delayed by permit. Permit arrives — but weather suspends operations. Repair is complete — but a second break point is found requiring a new permit application. The system has no mechanism to accelerate any single step in parallel with another.

The single biggest lever
Of all constraints, permitting reform offers the highest return for the least investment. Pre-negotiated bilateral access agreements and 72-hour emergency lanes could cut Asia-Pacific repair times from 30 days to under 10 — without a single new ship being built or a single new technology deployed.

4.1 Fleet shortage — capacity and availability

Fewer than 70 repair ships exist globally for 600+ cable systems. The TeleGeography/Infra-Analytics (2025) report — the most comprehensive analysis to date — finds that roughly 65% of cable maintenance vessels will reach end-of-life within 15 years. The report calls for 15 replacement vessels plus 5 additional vessels primarily for Asia: a $3 billion investment gap. Most current vessels are converted secondhand ships from other industries, raising concerns about efficiency and reliability.

- Geographic distribution is severely skewed — the Indian Ocean, West Africa and Pacific Islands have minimal coverage; transit time alone can consume 7–14 days
- Simultaneous faults overwhelm available capacity — the 2025 Red Sea incident severed multiple cables with only one available vessel nearby
- 70% of cable maintenance firms and 61% of subsea cable owners question the ability of the current system to service the sector for the next 15 years (TeleGeography/Infra-Analytics survey, 2025)
- New vessel construction requires 3+ years and a financing model — current 1–3 year maintenance contracts are too short to underwrite the 20-year payback on a new ship

4.2 Regulatory and permitting — legal and access barriers

98% of cable faults occur in territorial waters (TW) or exclusive economic zones (EEZ), each requiring national permits before a repair vessel can begin work. 136 jurisdictions were involved in 2023 repairs alone.

- Longest recorded repair: 947 days — entirely due to regulatory delay, not technical difficulty (ICPC 2023)
- No international emergency override mechanism exists; each state has full discretion on permit timing and conditions

- Conflict zone denial — Red Sea, South China Sea; no access even with valid permits during active hostilities
- The single biggest lever: pre-negotiated bilateral access agreements and 72-hour emergency lanes could cut Asia-Pacific repair times from 30 days to under 10 without a single new ship being built

The $3B figure — source

TeleGeography & Infra-Analytics (2025). The Future of Submarine Cable Maintenance: Trends, Challenges, and Strategies. Commissioned by the SubOptic Association. Available: blog.telegeography.com/submarine-cable-maintenance-data — 'An investment of $3 billion is necessary just to maintain current service levels, not improve them.'

4.3 Technical and operational — sea conditions and depth

- Deep-water grappling at 6,000 m uses essentially the same method as 1866 — locating and hauling cable takes days
- Weather windows — monsoon season, typhoons and Atlantic storms regularly suspend operations for days at a time
- Fault location — OTDR gives ~1 km accuracy; grapnel search in deep water covers a large seabed area
- Multiple break points — a single turbidity current event can sever cable in 5–8 places, each requiring a separate permit and repair operation

4.4 Skills and supply chain — workforce and spares

The industry explicitly identifies the shortage of specialised workers as a key bottleneck. The subsea cable workforce faces structural pressures that cannot be resolved quickly regardless of investment.

- Subsea cable splice technicians require extended multi-year training encompassing theoretical foundations, supervised workshop practice, and sea time — the National Cable Splicing Certification Board requires a minimum of two years of related experience before certification examination even for terrestrial power cable splicing (NCSCB)
- Aging workforce — median age is rising and few new entrants are joining a career that involves significant periods at sea on unpredictable schedules
- Spare parts mismatch — correct armour section and repeater units for each proprietary cable system must be pre-positioned on the right ship in the right zone
- Repeater lead time — custom units take 12–18 months to manufacture; stockpiling is impractical due to cost and design specificity
- Market economics — thin repair margins mean operators extend ship life to 40 years rather than invest in new-builds or training programmes

4.5 Geopolitics and security — state-level obstacles

The Center for Strategic and International Studies (CSIS 2025) documents a clear trend: the threat to subsea cables has shifted from being primarily accidental to increasingly involving deliberate or state-adjacent interference.

- Baltic Sea 2024–25 — multiple cables severed in quick succession; damage patterns consistent with anchor dragging by shadow fleet vessels linked to Russian state interest. (suspected and subject to trial result)
- Red Sea 2024–25 — Houthi attacks backed by Iran created repair scenarios where vessels could not safely operate; four cables severed simultaneously
- Taiwan Strait — Chinese fishing and military vessels regularly operate near cable landing points; Taiwan documents repeated cuts near outlying islands attributed to Chinese-flagged vessels
- Trusted vendor shortage — HMN Technologies (formerly Huawei Marine) and SBSS hold a significant share of Asia-Pacific repair capacity; European allied nations are reluctant to use Chinese state-linked operators on sensitive routes

4.6 Outdated legal framework — governance gaps

- The 1884 Convention — primary international cable law, 140 years old — predates fibre optics, AI and grey-zone hybrid warfare; penalties are trivially low relative to repair costs of $500,000–$100 million per incident
- No international emergency override — no mechanism to compel permit issuance; each state has full discretion
- No multilateral repair treaty — despite cables being classified as critical infrastructure by the UN, G7, EU and NATO, no treaty specifically governs the right to repair them
- Plausible deniability — anchor-drag damage treated as accidental even when evidence of intent exists; attribution is legally contested under the 1884 Convention and UNCLOS

4.7 Commercial and financial — market incentive gaps

- Thin repair margins — operators cannot justify new-ship capex; economics favour extending ships to 40 years
- Short maintenance contracts (1–3 years) are too short to underwrite the 20-year payback on a new vessel build
- Insurance gaps in conflict zones — private insurers exclude Red Sea, South China Sea; owners bear full unhedged repair risk

The compounding problem

Each constraint multiplies the others. A ship is finally dispatched — but delayed by permit. Permit arrives — but weather suspends operations. Repair is complete — but a second break point requires a new permit application. The system has no mechanism to accelerate any single step in parallel with another. The 947-day case was not an outlier of bad luck — it was a predictable outcome of a system with no emergency override.

5. O&M delivery models — selecting the right approach

Subsea cable operation and maintenance (O&M) is not a single industry — it is a spectrum of commercial arrangements ranging from full asset ownership by the cable owner to complete delegation to sovereign state entities. The appropriate model for any given cable system depends on five interacting variables: the scale of the cable portfolio, the geopolitical and security context of the route, the operator's appetite for capital expenditure versus operating expenditure, the required speed of response to a fault, and the geographic coverage and regulatory complexity of the corridors served.

No single model is optimal across all contexts. The industry norm is a layered hybrid — a primary O&M arrangement supplemented by an OEM backstop for specialist work and increasingly by a government security overlay for strategically sensitive routes. Understanding the characteristics, strengths and constraints of each model is essential for operators making long-term O&M investment decisions.

Model	1 — Asset ownership	2 — OEM / EPC + LTSA	3 — Consortium	4 — Managed services	5 — Govt / sovereign
Capex	Very high ($100M+/ship)	Low	Medium (shared)	Low (zero ships)	Very high (public)
Control	Highest	Medium (SLA)	Medium (zone)	Lower	High (own waters)
Response	Fastest	Fast (SLA)	Fast (pre-pos.)	Medium	Medium
Best for	Hyperscalers	Single-cable owners	Regional telcos	Mid-size operators	Govts / island nations
Examples	Google, Meta, NTT	SubCom, ASN, NEC	Yokohama Zone	Global Marine, Orange Marine	Japan ($300M NEC), US Fleet

5.1 Model selection — the five key considerations

Selecting the right O&M model — or right combination of models — requires structured analysis across five dimensions. Each dimension constrains the viable model range; the intersection of all five determines the optimal approach.

Consideration 1 -Scale of cable portfolio

Scale is the primary economic filter. The relationship between portfolio size and O&M model viability is direct — as cable kilometres increase, the utilisation rate of a dedicated vessel rises and the economics of asset ownership improve.

Portfolio scale	Viable models	Rationale
Large — >30,000 km	Model 1 (preferred); Model 3 as supplement	Own vessel utilisation rate justifies capex; Google/Meta threshold
Medium — 5,000–30,000 km	Model 3 (consortium zone); Model 4 (managed services)	Portfolio too small for own vessel; consortium pre-positioning delivers speed
Small — <5,000 km	Model 2 (OEM LTSA); Model 3 (zone membership)	No viable own-vessel economics; OEM expertise critical for repeater work

Consideration 2- Gopolitical and security

Security context has become the most rapidly changing selection variable since 2022. The concentration of repair capacity in Chinese state-linked entities — primarily HMN Technologies (formerly Huawei Marine) and SBSS — has prompted allied-nation governments and security-conscious cable owners to impose restrictions on contractor selection for sensitive routes.

- High sensitivity route (near Taiwan, South China Sea, Baltic, North Atlantic military corridors) — Models 1 or 5 required; Chinese state-linked OEM contractors excluded under most allied-nation government guidance
- National security mandate (government-owned or dual-use cables) — Model 5 mandatory; Japan and US government programmes provide the template
- Low sensitivity commercial route — full market available; cost and response time dominate contractor selection

CSIS 2025 finding
Chinese state firms HMN Technologies and SBSS dominate the repair market in Asia-Pacific. Allied nations are increasingly reluctant to use them on security-sensitive routes. Japan's $300M NEC Marine commitment and the US Cable Security Fleet Act are direct responses — ensuring trusted-nation capacity exists as an alternative regardless of commercial economics. (CSIS 2025: state threats rising)

Consideration 3 – Capex appetite and opex

The capex/opex choice reflects the cable owner's balance sheet strategy and risk tolerance. Three positions exist in practice:

- Capex-heavy / opex-light — own the vessel, control the costs, absorb utilisation risk. Rational for operators with long time horizons and large portfolios. Model 1.
- Opex-only / zero capex — pay for maintenance through service contracts or consortium fees, with no vessel investment. Accepts higher per-event cost in exchange for balance sheet simplicity. Models 2, 3 and 4.
- Shared capex model — consortium members share vessel acquisition costs, reducing individual exposure while retaining some asset ownership economics. Model 3 variant where members co-own the vessel.

The financing problem
Current maintenance contracts run 1–3 years — far too short to underwrite a 20-year new vessel payback. Closing the $3B fleet investment gap requires a structural shift to long-term contracts (10–20 years), government co-investment under Model 5 frameworks, or multilateral development bank financing. Without this shift, market economics will continue to favour vessel life extension over new builds. (TeleGeography/Infra-Analytics 2025)

Consideration 4 – Speed of response

Response speed is the most direct determinant of outage duration and its economic and social consequences. Three speed tiers map to different model characteristics:

Speed tier	Target mobilisation	Model implication
Fastest — immediate dispatch	<24 hours from fault detection	Model 1 (own vessel) or Model 3 with pre-positioned consortium ship in zone
SLA-contractual windows	24–72 hours (typical SLA minimum)	Model 2 or 4 with tight SLA; Model 3 without pre-positioning

Best-effort acceptable	Days to weeks	Model 2 standard LTSA; Model 4 managed services without standby premium

Consideration 4 – Geographic coverage & jurisdiction complexity

Geographic scope and regulatory complexity interact directly with model choice. A cable that crosses a single national EEZ has a fundamentally different O&M challenge from one that traverses 10 jurisdictions. Jurisdiction complexity is also the variable where political action — pre-negotiated bilateral access agreements and 72-hour emergency permit lanes — can substitute for additional vessels.

- Single nation / own waters — Model 1 or 5 sufficient; permit environment is entirely within the owner's or home government's control
- Regional multi-nation (2–6 EEZs) — Model 3 consortium zone governance handles permit coordination efficiently across the defined region; bilateral access agreements manageable
- Global transoceanic (10+ EEZs) — Models 1 or 4 with embedded regulatory liaison capability; critical dependency on pre-negotiated access agreements for each jurisdiction; ICPC model bilateral agreement templates are the practical starting point

5.2 Industry norm — the hybrid approach

The theoretical model categories above are analytical tools rather than mutually exclusive choices. In practice, the global industry has converged on a hybrid structure that layers models to cover each other's weaknesses:

Layer	Model	Function
Primary	Models 1 or 3	Handles the bulk of routine maintenance and emergency response. Choice between asset ownership and consortium zone depends on portfolio scale. Google and NTT use Model 1; most regional telcos use Model 3.
OEM backstop	Model 2	Retained in parallel for work that requires the manufacturer's proprietary tooling and expertise — primarily repeater replacement and complex joint repairs. Even hyperscalers with own ships maintain OEM LTSAs for this purpose.
Security overlay	Model 5	Increasingly common since 2022. Government subsidy or ownership ensures trusted-nation repair capacity exists for sensitive routes regardless of commercial economics. Japan $300M NEC Marine and US Cable Security Fleet Act are the benchmark programmes.

The hybrid principle

No single model handles all the realities of operating a transoceanic cable system. Geography, security, economics and technical specialisation pull in different directions simultaneously. The hybrid structure uses each model where its specific advantage is greatest, and lets the layers cover each other's weaknesses. A cable operator who tries to solve all problems through a single model will either overpay (if they own a vessel they underutilise) or underperform (if they rely on a managed services contract that cannot deliver the response times their business requires).

6. A four-pillar framework for faster repair and lasting resilience

Faster repair is not achievable through any single intervention. The constraints are systemic — technical, logistical, regulatory and geopolitical — and progress on any one front is limited by the others. A four-pillar framework organises the required actions into coherent simultaneous workstreams.

Technology & innovation
Pillar 1

DETECT FASTER · LOCATE PRECISELY
- DAS / DFOS distributed acoustic sensing
- SMART repeater sensors
- Resident AUV / ROV systems
- AI vessel behaviour analytics
- Next-gen cable materials & armour

Target: detect in hours · repair in days

Shared stewardship
Pillar 2

ENVIRONMENT · COMMUNITIES · STAKEHOLDERS
- Environmental route responsibility
- Community fishing liaison
- Spatial planning & CPZ zones
- Marine stakeholder cooperation
- Pre-negotiated govt repair access

Reduce fault probability at source

Ship & spares strategy
Pillar 3

RIGHT ASSET · RIGHT PLACE · BEFORE FAULT
- 20 new vessels needed by 2040
- Pre-positioned standby ships
- Distributed cable depots
- Trusted operator diversity
- Long-term maintenance contracts

$3B investment gap — critical to close

Policy & governance
Pillar 4

CLEAR LAW · FAST PERMITS · GLOBAL NORMS
- Classify cables as critical infrastructure
- 72-hr emergency permit lanes
- Jurisdiction harmonisation
- Update 1884 Convention / UNCLOS
- Public-private partnerships

Permits alone could cut 30-day repairs to <10

Pillar 1 — Technology and innovation

Technology interventions address the detection, localisation and repair phases of the fault response cycle. The goal is to compress the time from damage to confirmed fault location from days to hours, and from fault confirmation to vessel mobilisation from weeks to days.

- DAS / DFOS (Distributed Acoustic Sensing / Distributed Fibre Optic Sensing) — the cable fibre detects damage events in near-real time; the cable becomes its own sensor across its full length
- SMART repeater sensors — pressure, temperature and acoustic sensors at each repeater provide continuous health data and early fault prediction
- Resident AUV/ROV systems — subsea-docked autonomous vehicles on permanent standby; inspect and intervene without surface ship mobilisation, reducing response from weeks to hours
- AI vessel behaviour analytics — ML models trained on AIS data identify anchor-drag signatures and loitering with minutes of notice, before contact
- Next-generation cable materials — improved armour configurations and polymer insulation extend service life and reduce Phase I vulnerability

Pillar 2 — Shared stewardship

Most cable damage is preventable. The shared stewardship pillar addresses the human dimension — the 86% of faults caused by fishing and anchoring that are fundamentally about people who either do not know where cables are or do not have economic alternatives to operating near them.

- Environmental route responsibility — routing decisions that respect marine protected areas and reduce ecological impact, building community goodwill and reducing legal conflict
- Community fishing liaison — structured engagement with coastal fishing communities; local knowledge as an early-warning asset

- Spatial planning and CPZ zones — formal cable protection zones filed with maritime authorities, shown on ECDIS navigation charts, broadcast via AIS
- Marine stakeholder cooperation — structured dialogue with offshore wind operators, port authorities, dredging companies and the fishing industry to de-conflict seabed use
- Pre-negotiated government repair access — bilateral agreements that pre-clear repair vessel access to EEZs before faults occur

Pillar 3 — Ship and spare parts strategy

The logistics pillar is the most immediately actionable — it requires capital and coordination rather than new science or treaty reform. The TeleGeography/Infra-Analytics (2025) report provides the clearest quantification: 20 new vessels (15 replacements + 5 net-new for Asia) at a total investment of approximately $3 billion.

- Pre-positioned standby ships — the consortium zone model (Yokohama Zone) reduces average dispatch time from 14 days to under 24 hours for faults within the zone
- Distributed cable depots — regional spares inventories matched to local cable specifications, eliminating international freight delays for armour sections and proprietary repeater units
- Trusted operator diversity — ensure sufficient repair capacity with allied-nation operators; the CSIS recommendation to reduce reliance on Chinese state-linked firms (HMN Tech, SBSS) in sensitive corridors
- Long-term maintenance contracts (10–20 years) — provide the revenue certainty needed to finance new vessel construction, replacing the current norm of 1–3 year contracts

Pillar 4 — Policy and governance

The governance pillar has the highest potential return per unit of investment. Permitting reform alone — without new ships, new technology or new law — could cut Asia-Pacific repair times from 30 days to under 10.

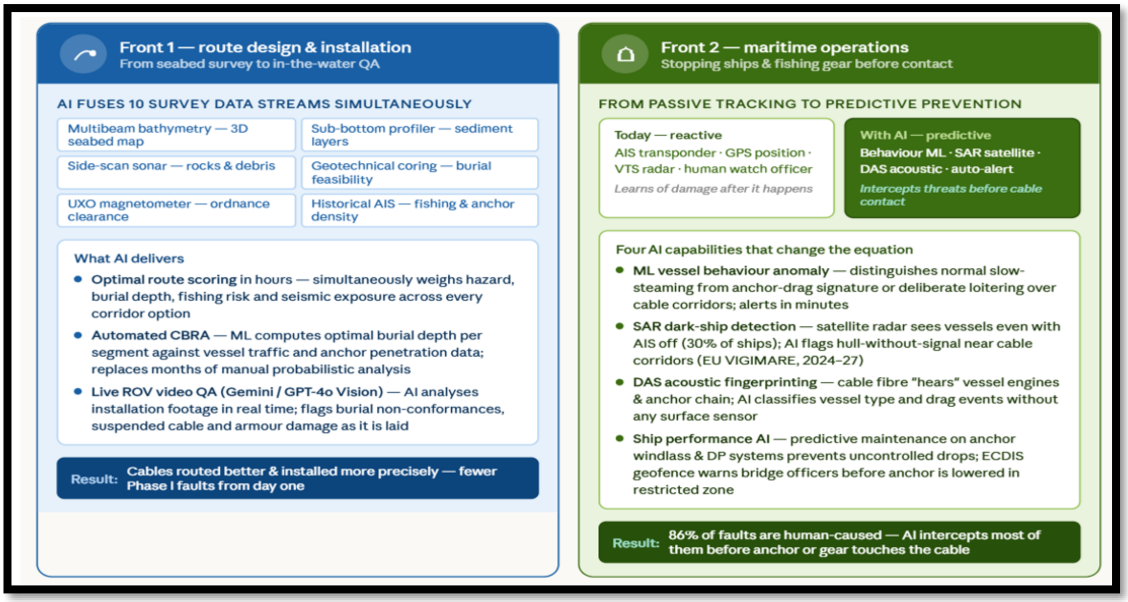
- Classify cables as critical national infrastructure — triggers emergency access provisions, security funding streams and legal protection frameworks
- 72-hour emergency permit lanes — pre-negotiated bilateral and multilateral agreements for repair vessel access; the ICPC has model templates but implementation requires diplomatic engagement
- Update the 1884 Convention and UNCLOS provisions — modernise attribution, penalties and access rights; the 140-year-old framework predates the entire concept of the internet
- No multilateral repair treaty exists — a specific gap; the Chicago Convention (ICAO) provides the model for what cable infrastructure needs but does not yet have
- Public-private partnerships — government co-investment in trusted-vendor capacity (Japan's $300M NEC Marine model); government information sharing on vessel behaviour near cable corridors; joint emergency response protocols

15–30+ days	**7–10 days**	**2–4 days**
Today — unoptimised	Near-term — pillars 3 & 4	Future — all four pillars

The stated dates are indicative and based on current global average timelines, adjusted to support improved service delivery.

7. AI as a force multiplier for cable protection

AI does not replace the engineer, the captain or the repair crew — it gives them intelligence they could never process manually. Two distinct application fronts are transforming the industry simultaneously.



Front 1 — route design & installation
From seabed survey to in-the-water QA

AI FUSES 10 SURVEY DATA STREAMS SIMULTANEOUSLY

Multibeam bathymetry — 3D seabed map	Sub-bottom profiler — sediment layers
Side-scan sonar — rocks & debris	Geotechnical coring — burial feasibility
UXO magnetometer — ordnance clearance	Historical AIS — fishing & anchor density

What AI delivers

- **Optimal route scoring in hours** — simultaneously weighs hazard, burial depth, fishing risk and seismic exposure across every corridor option
- **Automated CBRA** — ML computes optimal burial depth per segment against vessel traffic and anchor penetration data; replaces months of manual probabilistic analysis
- **Live ROV video QA (Gemini / GPT-4o Vision)** — AI analyses installation footage in real time; flags burial non-conformances, suspended cable and armour damage as it is laid

Result: Cables routed better & installed more precisely — fewer Phase I faults from day one

Front 2 — maritime operations
Stopping ships & fishing gear before contact

FROM PASSIVE TRACKING TO PREDICTIVE PREVENTION

Today — reactive	With AI — predictive
AIS transponder · GPS position · VTS radar · human watch officer	Behaviour ML · SAR satellite · DAS acoustic · auto-alert
Learns of damage after it happens	*Intercepts threats before cable contact*

Four AI capabilities that change the equation

- **ML vessel behaviour anomaly** — distinguishes normal slow-steaming from anchor-drag signature or deliberate loitering over cable corridors; alerts in minutes
- **SAR dark-ship detection** — satellite radar sees vessels even with AIS off (30% of ships); AI flags hull-without-signal near cable corridors (EU VIGIMARE, 2024–27)
- **DAS acoustic fingerprinting** — cable fibre "hears" vessel engines & anchor chain; AI classifies vessel type and drag events without any surface sensor
- **Ship performance AI** — predictive maintenance on anchor windlass & DP systems prevents uncontrolled drops; ECDIS geofence warns bridge officers before anchor is lowered in restricted zone

Result: 86% of faults are human-caused — AI intercepts most of them before anchor or gear touches the cable

Front 1 — Route design and installation

- Route scoring in hours (previously months) — all ten survey streams processed in parallel; AI scores every candidate corridor against all risk factors simultaneously
- Automated CBRA — ML computes optimal burial depth per segment against vessel traffic distributions and anchor penetration databases, replacing months of manual probabilistic analysis
- Live ROV video QA (Vision class models) — AI analyses installation footage in real time, flagging burial non-conformances and armour damage as the cable is laid rather than in a post-survey report months later

Front 2 — Maritime operations: from reactive to predictive

Today's baseline of AIS transponder data, GPS/GNSS positioning and VTS radar tells operators where vessels are. AI adds the ability to predict what they are about to do — and to intervene before damage occurs.

- ML vessel behaviour anomaly detection — distinguishes normal slow-steaming from anchor-drag signature or deliberate loitering over cable corridors; alerts in minutes rather than days after the fact
- Satellite SAR dark-ship detection — synthetic aperture radar satellites detect vessel hulls regardless of AIS transponder status; approximately 30% of vessels operating near sensitive routes go AIS-dark (CSIS 2025)
- DAS acoustic vessel fingerprinting — the cable fibre 'hears' vessel engines and anchor chain; AI classifies vessel type and drag events without any surface sensor
- EU VIGIMARE (Horizon Europe 2024–27) — purpose-built AI platform fusing SAR, AIS, coastal radar and DAS data; trained on the Baltic Sea incident corpus; designed to trigger alert before anchor reaches seabed

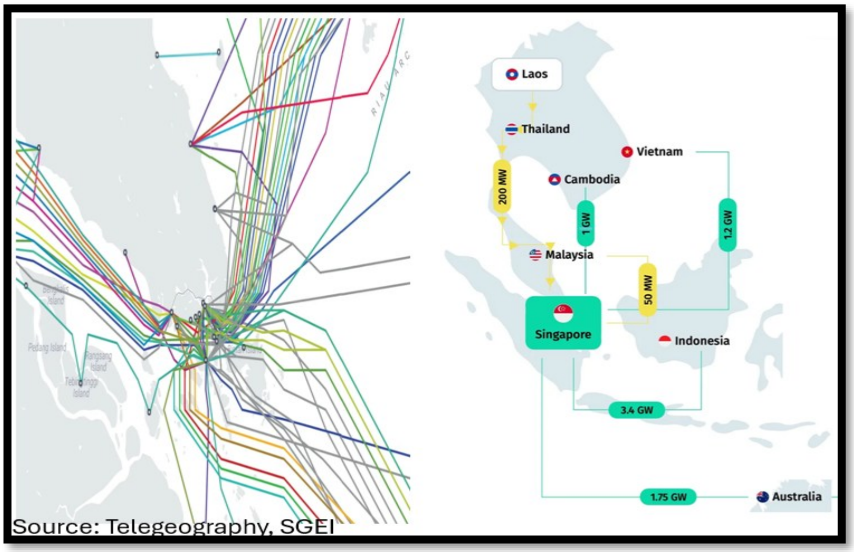
- Ship performance AI — predictive maintenance on anchor windlass and DP systems prevents uncontrolled drops; ECDIS geofencing warns bridge officers before anchor is lowered in restricted zones; port congestion AI routing reduces 'convenience anchoring' over cable corridors near busy ports

The AI advantage — cited figure

86% of cable faults are human-caused (ICPC). Most are detectable in advance. AI does not eliminate the need for repair ships, but it substantially reduces how often they are needed. The EU VIGIMARE programme (Horizon Europe 2024–27) represents the most ambitious current investment in AI-enabled cable protection, explicitly targeting the dark-ship problem and the gap between AIS coverage and real vessel behaviour.

8. Singapore — convergence of digital and energy infrastructure

Singapore is simultaneously the world's densest telecom cable hub — with 25+ cable systems converging on landing stations — and the anchor point for the region's most ambitious power import programme. Both sets of cables share the same seabed, face identical threats, and confront identical regulatory barriers.



Source: Telegeography, SGEI

The power import context

Singapore's Energy Market Authority (EMA) is developing the ASEAN Power Grid interconnection, with planned imports from five countries across subsea HVDC cable links:

- Australia — 1.75 GW via the Sun Cable AAPowerLink project (world's longest proposed subsea HVDC cable at approximately 4,200 km)
- Indonesia — 3.4 GW from Riau archipelago and Sumatra solar/wind projects
- Vietnam — 1.2 GW from offshore wind development in southern Vietnam
- Malaysia — 200 MW existing interconnection with expansion under discussion
- Lao PDR — 200 MW pilot under the LTMS-P multilateral trading framework (pilot commenced 2022)

The shared challenge and O&M synergy opportunity

- Same seabed corridor — telecom and power cables share the Strait of Malacca and Singapore Strait approaches; one anchor drag event can damage both simultaneously
- Same threat agents — fishing trawls, ship anchors and vessel traffic are the primary risk to both cable types; identical 86% human-activity cause profile
- One shared repair ship — capable of working on both HV power cables and fibre-optic telecom cables; reduces per-sector cost by up to 50%
- Joint monitoring centre — single NOC combining DAS fibre sensing, SMART power cable sensors and AIS vessel analytics; one AI system watching data and energy cables together
- One CPZ framework — a single spatial planning regime covering both infrastructure types for all participating nations reduces regulatory complexity from ten separate national processes to one
- Pre-negotiated repair access — bilateral agreements covering both cable types simultaneously across all participating nations' EEZs; one diplomatic negotiation rather than many.

The intergovernmental imperative

ASEAN is entering a critical phase of subsea infrastructure expansion, driven by the ASEAN Power Grid—which aims to interconnect regional electricity systems for energy security and renewable integration—and the rapid growth of submarine fibre networks supporting digital connectivity . Given the region's archipelagic geography, submarine cables are essential for both power transmission and communications, but their deployment remains fragmented across technical, regulatory, and operational domains . To address this, ASEAN requires a coordinated framework that aligns power and telecom corridor planning, introduces compatibility-based vessel allocation (fibre, power, and hybrid), and establishes shared mechanisms for installation, maintenance, and emergency response. Such an approach will be critical to optimise scarce marine resources, reduce delays, and ensure resilient, efficient delivery of cross-border energy and digital infrastructure across the region.

9. Conclusion — a multi-frontier challenge

Faster repair and lasting resilience require simultaneous progress across six distinct but interconnected frontiers. No single lever is sufficient. A cable operator who invests in the best technology but ignores permitting will still wait weeks for access. A government that reforms permits but allows the repair fleet to age will still lack ships. The six frontiers must advance together:

🟦	**Technology leverage**	DAS sensing, SMART repeaters, AI analytics, resident AUV/ROV, live ROV video QA — making faults detectable in hours and repairable in days rather than weeks
🟩	**Shared stewardship**	Community engagement, CPZ planning, environmental responsibility — reducing the 86% of faults that are human-caused before they happen
🟧	**Effective marine spatial planning**	Unified CPZ frameworks covering telecom and power cables, seabed use de-confliction across offshore energy sectors — the Singapore convergence model as regional template

🟪	**Appropriate O&M modelling**	Right model for the right context — asset ownership, consortium zone, managed services or sovereign overlay, in hybrid combinations driven by portfolio scale, security posture and geography
🟥	**Intergovernment collaboration**	Pre-negotiated bilateral repair access, 72-hour emergency permit lanes, regional alignment across ASEAN and Indo-Pacific — the highest-return, lowest-cost intervention available today
🟩	**Policy and governance**	Update the 1884 Convention, classify cables as critical infrastructure, modernise attribution and penalties, develop a multilateral repair access treaty, establish PPP frameworks for fleet investment

The core message

A well-installed cable, continuously monitored by intelligent systems, backed by pre-positioned trusted-operator ships with pre-cleared permits, operating within a protected corridor known to every mariner and fisher in the region — will fail far less often, and when it does fail, will be restored in days not months. **Prevention and preparation are not costs. They are the investment that keeps the world connected.**

About the author

Mohanan Panayamadam is a Singapore-based engineer working on subsea cable systems and marine renewable energy projects. He is currently a Principal Project Manager at Surbana Jurong Group, where he supports the planning and delivery of subsea telecom, power cable and floating solar PV (FPV) developments across Southeast Asia. His work includes cable route studies, marine surveys, permitting coordination, and owner's engineer support from early-stage assessments through to construction planning. He has been involved in projects related to cross-border power interconnections, with a focus on cable routing, protection approaches, and integration of survey data into engineering decisions. His current interests include improving practical approaches to subsea cable protection, restoration, and resilience, particularly by considering repair needs during early-stage design and planning.

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