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Original Research

Innovative engineering solutions for the crossing strait tunnel

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Abstract: This perspective article examines the crossing strait tunnel (CST) as a sophisticated and integrated system, in which safety, construction efficiency, and energy sustainability represent interconnected priorities for next-generation projects. In response, this paper identifies and proposes key technologies necessary to advance long CST development. Analysis of global cases reveals a predominant trend towards significantly larger cross-sections in this century compared to the mid-1900s. Accordingly, the paper proposes integrated evacuation frameworks for both cross-sectional and longitudinal layouts, incorporating energy balance considerations to enhance overall operational safety and efficiency. To achieve rapid tunneling in challenging marine environments, the concept of an offshore floating platform (OFP) is introduced as a foundation for deepwater construction. The OFP is designed to serve as a hub for the concurrent launch and operation of multiple tunnel boring machines (TBMs), integrating robotic systems, autonomous controls, and advanced information technology (e.g., real-time monitoring) to enable efficient tunneling advancement. Furthermore, the OFP's role in achieving energy and ecological balance is conceptualized. Collectively, these proposed solutions aim to address the unique challenges of long CSTs and stimulate discussion on sustainable and efficient tunnel development.

Keywords: Crossing strait tunnel, Disaster prevention, Energy, Ecology, Offshore floating platform

1. Introduction

The Crossing Strait Tunnel (CST) represents a critical category of fixed links designed to overcome the most formidable maritime barriers, specifically the deep and wide straits that separate major landmasses. While significant fixed links, such as the Fehmarnbelt Tunnel [1], Rogfast [2], Geojedo Tunnel [3], Hong Kong-Zhuhai-Macao Bridge [4], and Shenzhen-Zhongshan Link [5] are constitute significant engineering achievements, they primarily cross bays or narrower sea channels. In contrast, true CSTs, exemplified by the landmark Seikan Tunnel [6, 7] and the Channel Tunnel [8], confront uniquely challenging environments characterized by considerable lengths and depths. These pioneering projects have demonstrated the profound potential of CSTs to deliver substantial regional economic and sustainable transport benefits. Historically, the developmenet of fixed linkages began with large-span bridges, progressed to bridge-island-tunnel (BIT) combinations, and culminated in long railway tunnels. BIT schemes originated in the USA in the early 1930s, with later implementations in Scandinavia during the late

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1990s and in Eastern Asia [9]. For the most demanding strait crossings, a through-tunnel solution is often not only optimal but also the sole technically viable option.

When envisioning the next generation of CSTs, however, a critical limitation arises: the applicability of existing engineering paradigms. Developed primarily from experience with shorter or less complex crossings, these paradigms are inadequate for addressing the deeply intertwined systemic challenges of future large-span CSTs. These challenges encompass (1) ensuring robust safety and evacuation for large-cross-section tunnels under extreme emergencies, (2) managing immense energy consumption throughout the entire project lifecycle, and (3) achieving feasible construction timelines in demanding open-sea environments.

This perspective contends that a fundamental shift towards an integrated co-design framework is therefore necessary. The proposed framework consists of a coherent system of three interrelated elements: an integrated safety and evacuation system that rethinks tunnel layouts, a sustainable energy ecosystem centered on a multi-functional Offshore Floating Platform (OFP) serving as an "energy island," and an innovative OFP-centric construction methodology for parallelized tunneling operations.

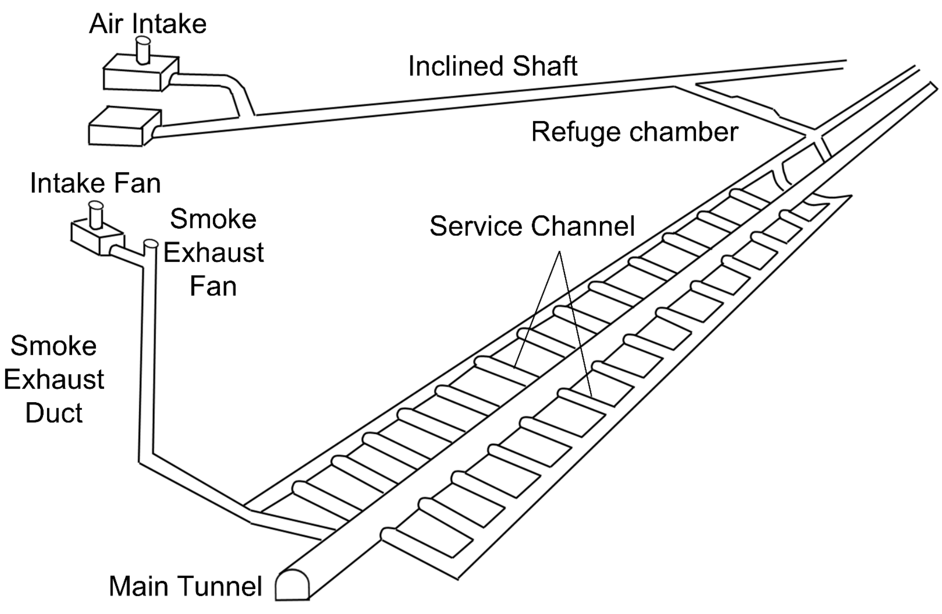
The paper is structured as follows. First, it provides a retrospective analysis of major tunnel cases, focusing on disaster prevention performance during fire emergencies and operational energy consumption. Building on this foundation, the study reviews current standards and layout strategies for large-section tunnels, leading to a proposal for an optimized emergency layout for future CSTs. Finally, the paper outlines a suite of construction innovations centered on the OFP as a multi-functional hub. These innovations include launching multiple TBMs from multiple, strategically placed OFPs, submerged tunneling, and seabed docking stations. These elements are functionally integrated with the OFP serving as an "energy island," leveraging renewable sources (e.g., wind, solar PV, wave power, water electrolysis) and advanced storage systems (e.g., batteries, capacitors, compressed air energy storage) to achieve on-site power balance, reduce construction timelines, and enhance ecological sustainability.

2. Retrospect of the cross-strait tunnel

2.1 Disaster prevention

Disaster prevention, whether addressing natural hazards or human-induced accidents during construction or operation, is a paramount concern in cross-strait tunnel planning, alongside technical feasibility and economic viability. The most critical construction-phase risk is water inrush at the excavation face, while fire emergencies represent the primary operational threat.

Figure 1 illustrates the emergency response systems of theSeikan Tunnel and Channel Tunnel. Both employ sophisticated infrastructure integrating ventilation, evacuation, and rescue functions within multi-tunnel layouts. In the Seikan Tunnel (Figure 1a), two parallel service tunnels connect to the main tunnel via cross-passages and interface with vertical escape shafts. The Channel Tunnel (Figure 1b) features a central service tunnel linked to twin main tunnels by cross-passages and equipped with dedicated ventilation shafts for routine and emergency operations. These systems, however, necessitate extensive underground construction, resulting in significant project delays and high lifecycle costs [7, 10].



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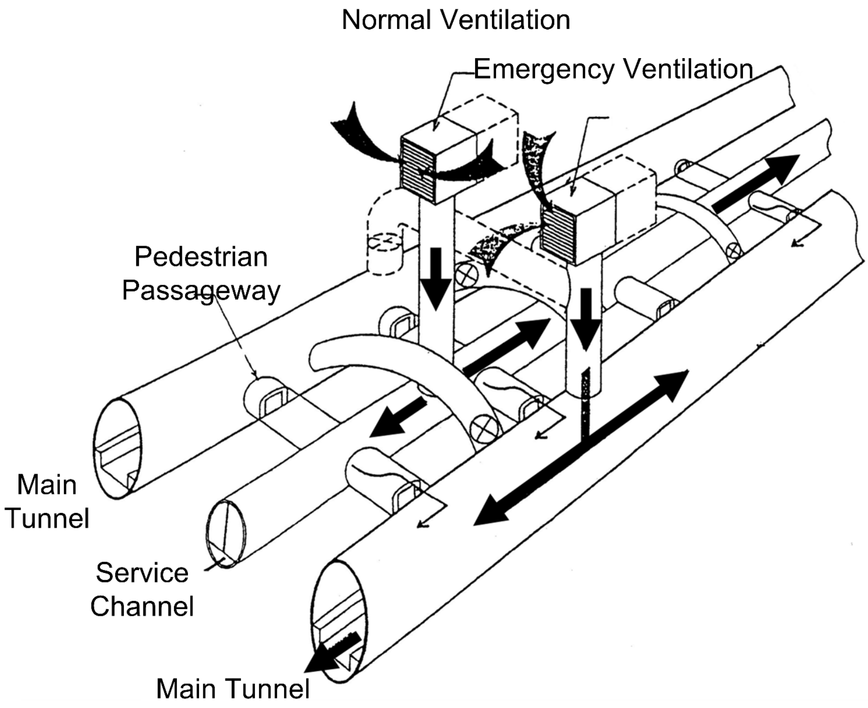


(b)

(a) Seikan Tunnel (modified from [7]); (b) Channel Tunnel (modified from [10])

Figure 1. Layout of tunnel evacuation routes

Historical evidence substantiates these challenges. During the construction of the Seikan Tunnel, which used the drill-and-blast methodology, pre-excavated pilot tunnels were later repurposed as service conduits, enabling preliminary geological prospecting. Despite these provisions, recurrent inrush incidents within fractured geological formations precipitated multi-year schedule disruptions [11]. This demonstrates the inherent vulnerability of complex subsea infrastructure to geotechnical uncertainties.

A fire was reported in 1996, following the opening of the Channel Tunnel [12]. No significant hazard to people, facilities, or tunnel linings occurred due to the success of the emergency system. Conversely, the Seikan Tunnel evacuation event [13] starkly highlights systemic inadequacies in passenger egress protocols. Passengers had to walk 2.5 km before reaching the designated refuge area, as shown in Figure 2, where they waited for a cable car to transport them to ground level. It took more than 6 hours to evacuate 125 people. Even though the rescue was successful, the evacuation was physically demanding for passengers and comparatively length. These interconnected operational failures, specifically manifested in inadequate refuge density, dependency on mechanized rescue systems, and unsustainable evacuation timelines, collectively demonstrate how conventional safety architectures fragment emergency protocols. Such configurations prove fundamentally inadequate for next-generation mega-tunnels, wherein exponential length scaling disproportionately escalates evacuation risks.

2.2 Energy-consuming

Energy provision and dynamic load management represent critical engineering challenges throughout the lifecycle of tunnel construction. As quantified in Table 1, a 15-meter-diameter TBM requires instantaneous power inputs of up to 20 MW during active boring operations. Contextualized through municipal electricity infrastructure benchmarks, this instantaneous load is equivalent to the peak power demand of a medium-sized county in China, with approximately 220,000 residents. This operational intensity necessitates robust grid infrastructure integrated with adaptive real-time load balancing systems.

Operational energy intensity presents a primary sustainability challenge in subsea tunnel engineering. The Channel Tunnel has exceptionally high electricity consumption, with annual demand equivalent to powering over 110,000 European households [14]. Ventilation systems account for a significant portion of non-traction energy requirements, mainly due to the need to maintain service tunnel pressure differentials that prevent smoke migration during emergencies. This critical safety function limits energy efficiency, as conventional longitudinal ventilation system incur substantial aerodynamic losses that significantly affect overall consumption profiles. Simultaneously, the Seikan Tunnel faces ongoing seawater intrusion through segment joints at a rate of 57,600 m^3/day [15], resulting in annual drainage costs and accelerating chloride-induced corrosion in critical infrastructure components [16].

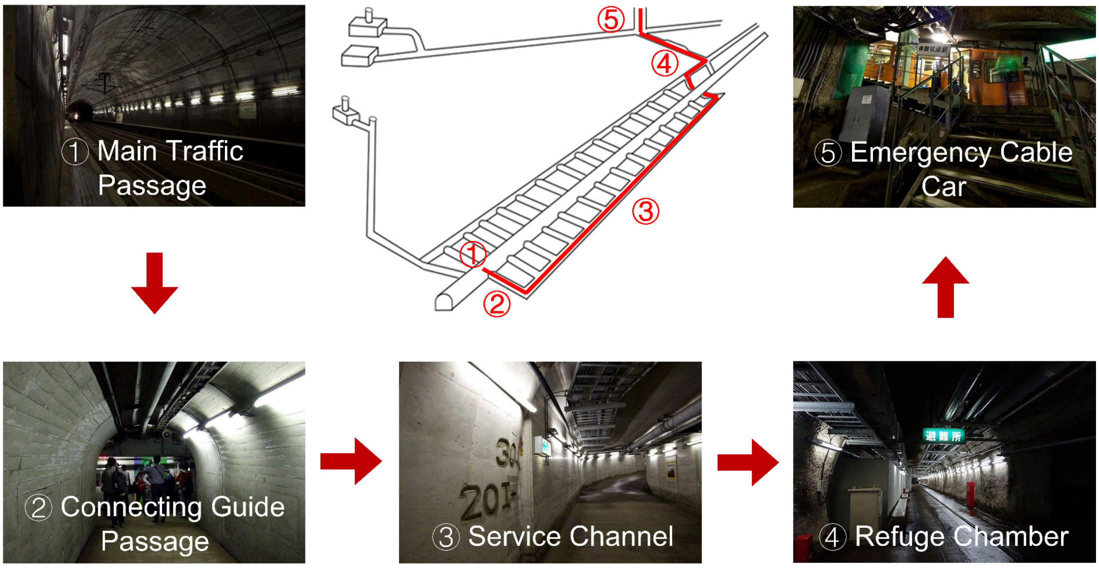


Figure 2. Evacuation of passengers during a fire alarm

Table 1. Power required of the TBM tunneling system

System	Nominal power (MW)	Remarks
TBM (ϕ15.56)	8.8	
Slurry cycle system	6	Two pumps for adding bentonite, four pumps for dredging sludge.
Sludge desiccation system	3.5	Including swirler, draining, roller screen, and pumps.
Pressure filtration system	1.8	Motors for mixing, pressing, and transporting waste sludge.
Ventilation system	0.2	Workers in the TBM operation.
Total	20.3	

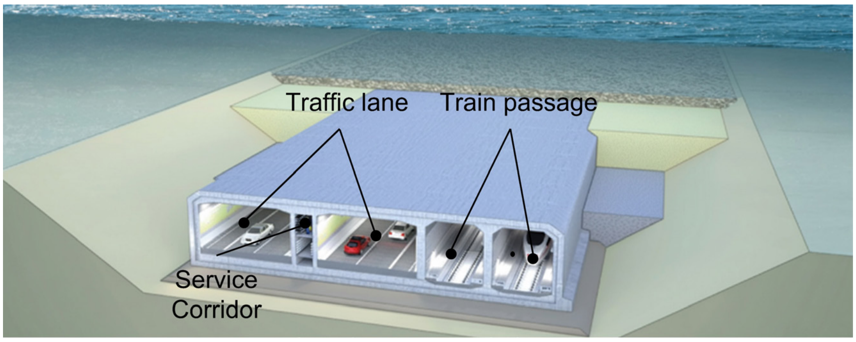
3. Perspective technologies in preventing disasters of long CST

3.1 Current standards

The risks associated with CST construction include hydrological hazards (such as water or mud inrush), ground subsidence, dust, and high temperatures. During operation, incidents such as fire, impact, explosion, or inundation are the primary concerns. Disaster prevention is the most important task during CST planning. In standards such as the Code for Design of Railway Tunnel (TB 10003-2016) [17], tasks are classified as evacuation and rescue design, both during construction and operation.

Disaster prevention systems for immersed tunnels generally have straightforward configurations, as shown in comparative case studies in Figure 3. The Fehmarnbelt fixed link, currently under construction, highlights typical features of modern immersed tunnels. In contrast, the operational Oresund tunnel serves as a well-established example. Both designs feature a single evacuation corridor serving both vehicle lanes and rail tracks, balancing operational efficiency and emergency response capabilities. However, these tunnels are relatively short. Their simple linear evacuation model may face severe challenges in future tens-of-kilometers-long, deep-sea CSTs regarding escape distance, ventilation efficiency, and system reliability.

Recently, large-diameter road tunnels have become increasingly common in long tunnel projects. Their emergency plans use lateral passages between two tunnels, taking advantage of the ample cross-sectional space for emergency exits and rescue corridors, as shown in Figure 4. This design significantly improves evacuation efficiency and enables more effective deployment of specialized rescue vehicles. The growing preference for large-diameter road tunnels indicates a shift in the industry towards optimized emergency solutions. However, as tunnel length and depth reach extremes, this design poses unprecedented engineering challenges for the construction safety and long-term watertight integrity of cross-passages, as well as for ventilation and smoke extraction over ultra-long distances. Furthermore, it must address emerging risks such as electric vehicle battery fires, necessitating fundamental enhancements to the entire safety system.



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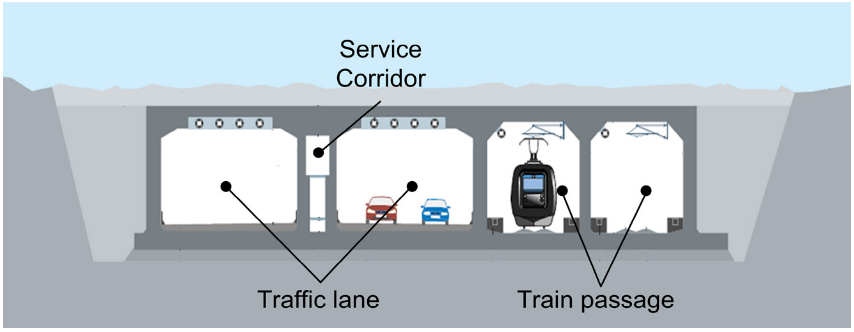
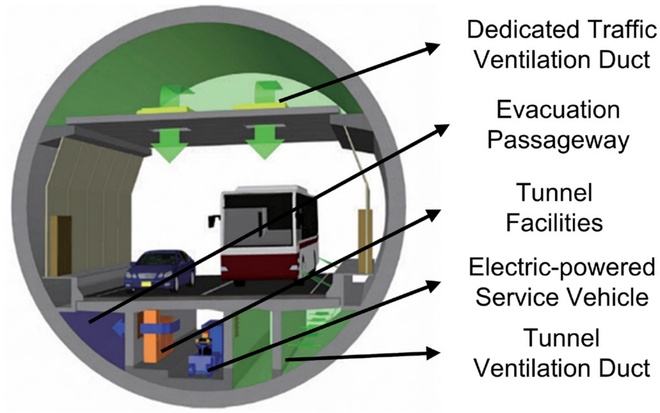


(b)

(a) Fehmarnbelt fixed linkage [18]; (b) Øresund tunnel [19]
Figure 3. Evacuation scheme of immersed tunnels



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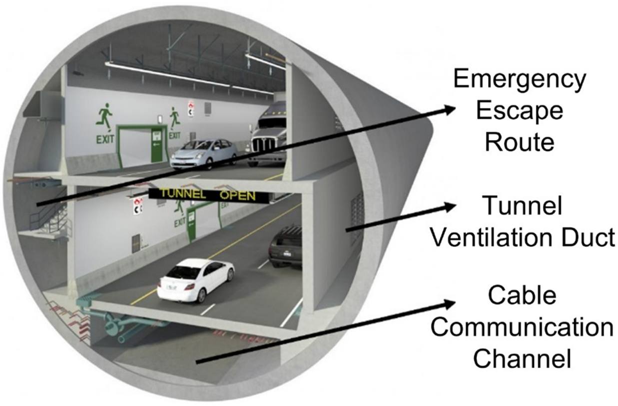


(b)

(a) Tuen Mun–Chek Lap Kok link [20]; (b) SR 99 Bored Tunnel [21]
Figure 4. Layout of large-diameter TBM tunnels

3.1.1 Evacuation and rescue

The Code for Design on Rescue Engineering for Disaster Prevention and Evacuation of Railway Tunnel (TB 10020 -2017) [22] specifies the requirements for rescue stations, refuge shelters, emergency exits, and evacuation passages, including supporting systems for ventilation, lighting, power supply, communication, monitoring, and firefighting. Although such regulatory frameworks are fundamental for disaster mitigation, their prescriptive mandates have limited applicability to mega-projects. For instance, rigid specifications governing the geometric configuration of evacuation passages may be operationally impractical in complex subsea environments due to geotechnical constraints. For future CSTs, standardized evacuation layouts based on fixed intervals may be neither economically nor physically feasible, highlighting the urgent need for a new resilience-based concept featuring performance-based design and dynamic risk assessment.

3.1.2 Ventilation

Fresh air should be provided in accordance with the Code for Design on Operation Ventilation of Railway Tunnel (TB 10068-2010) [23], whether during construction, operation, or emergency. The provisions specify that the quantity of clean air must be no less than 3 m3/(min·person). An additional requirement is that air velocity during the construction phase should be between 0.15-1.0 m/s. Preventing the spread of smoke is helpful during evacuation. However, this ventilation design based on fixed per-capita indices may lead to prohibitive energy consumption and engineering difficulties when confronting fire emergencies in future CSTs with ultra-large cross-sections and extreme lengths. The case of the Channel Tunnel demonstrates that the energy required to maintain pressure differentials for smoke control constitutes a major operational cost. Therefore, next-generation CSTs require innovative, intelligent ventilation strategies capable of dynamic adjustment based on real-time disaster scenarios, achieving a fundamental optimization between safety and sustainability.

3.1.3 Drainage

According to current codes, including the Technical Code for Waterproofing and Drainage of Railway Tunnels (TB 10119-2000) [24], the waterproofing and drainage system for railway tunnels must follow the principle of a "combined waterproofing-drainage-interception strategy, tailored to local conditions." This requires establishing reliable waterproofing and drainage structural layers during construction, and installing longitudinal and transverse blind drains and central gutters during operation, supported by redundant drainage pump stations for emergencies. While effective for conventional tunnels, this system faces adaptation challenges for future long, deep-sea CSTs. The persistent, large-scale seawater seepage (57,600 m^3/day) in the Seikan Tunnel, along with its associated long-term drainage energy costs and structural corrosion issues [15, 16], highlights the potential lifecycle cost and sustainability deficits of the current "drainage-prioritized" strategy. For future CSTs in more severe geological conditions, a paradigm shift towards an "active, total-closure" waterproofing system or new drainage concepts integrated with overall energy recovery may be necessary to address the limitations of the current paradigm.

3.2 Possible layout of CST

3.2.1 Cross-section

Ensuring safe operation under all circumstances is the fundamental design criterion for a CST. This requires an integrated emergency system designed for: (1) rapid egress from disabled vehicles, (2) ergonomic temporary refuge shelters with life-support, and (3) high-capacity transport for mass evacuation. The proposed large-diameter TBM railway tunnel cross-section is systematically organized into five functionally interdependent zones (Figure 5):

- Operational zone (I): Supports unidirectional high-speed rail operations while incorporating emergency evacuation pathways directly linked to refuge areas, ensuring passenger safety without disrupting regular rail services;
- Response corridor (II): Provides dedicated access for emergency responders and maintenance operations, designed for rapid movement and equipment deployment during both routine and crisis scenarios;
- Refuge system (III&III'): Zone III offers protected shelters with essential life-support supplies, complemented by Zone III's autonomous evacuation vehicles for efficient passenger transfer to safety;
- Integrated safety systems (IV): Combines fire detection, ventilation control, and robotic monitoring into a unified emergency response network, enabling real-time hazard management;
- Infrastructure core (V): Consolidates critical infrastructure, including power, communications, and water systems, with provisions for future expansion, such as on-site wastewater treatment.

3.2.2 Longitudinal layout

Given the infeasibility of direct vertical egress in deep subsea tunnels, the proposed longitudinal strategy adopts a modular design. This framework is based on a recurring unit spacing, illustrated here with by a 200-meter interval for reference, although the optimal dimension will be determined through further detailed analysis. As shown in the longitudinal profile (Figure. 6a), each module incorporates a protected shelter (with an interior layout exemplified in Figure. 6b), compliant with TB 10020-2017 [25]) , and an Automated Evacuation Vehicle (AEV) boarding point, together forming a "Dual-Refuge System."

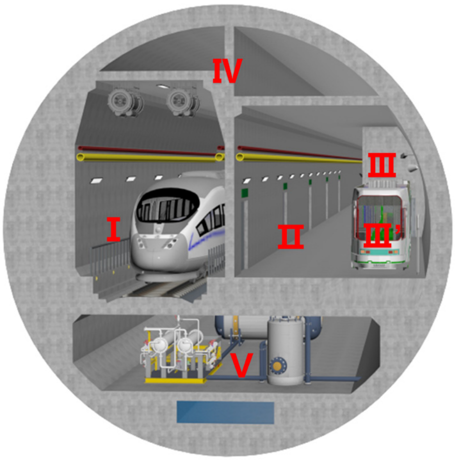
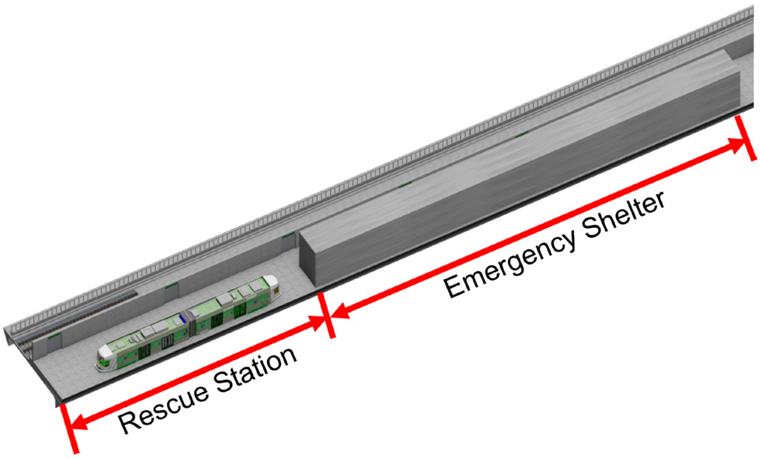


Figure 5. Cross-sectional layout of large-diameter CST



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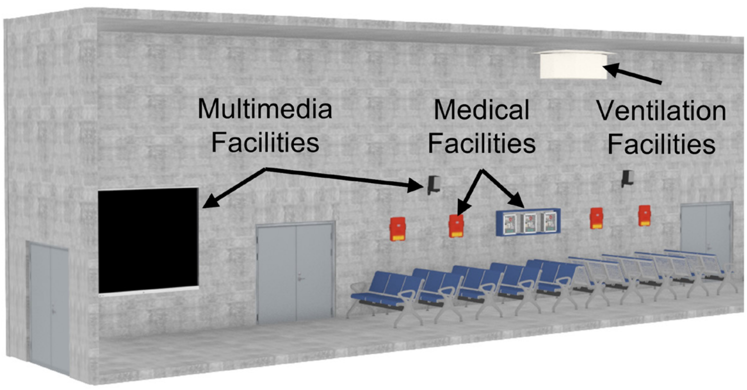


(b)

(a) Longitudinal profile design of emergency shelter and rescue station; (b) Interior layout of emergency shelter
Figure 6. Longitudinal layout of emergency shelter and rescue station

The system operates on a phased logic. Occupants first evacuate to a nearby shelter (Figure 6b) for immediate protection. Concurrently, Automated Evacuation Vehicles (AEVs) are dispatched via the dedicated Response Corridor (II) to the assigned boarding point within the modular layout, transporting evacuees in an orderly manner to the tunnel portal and ultimate safety. This "Phased Refuge and Circulatory Transport" approach establishes a distributed, self-reliant evacuation network, eliminating dependence on vertical shafts. Clear zoning and pre-positioned resources within each module ensure efficient and systematic emergency response.

Crucially, the cross-sectional functional zones and longitudinal modular units are designed as an integrated whole. The Infrastructure Core (V) in each module houses the power distribution and control systems for life-support, ventilation, and drainage. The Integrated Safety Hub (IV) provides the monitoring and control network that connects all longitudinal modules, enabling coordinated system-wide response during an incident.

3.2.3 Ventilation

Human respiratory demands require 300 mL/min of oxygen (approximately 21.6 L/h) and produce 22.6 L/h of CO_2, with normal ventilation requiring 0.5 m³/h per person. Given the substantial evacuation loads in long subsea tunnels described in Section 3.2.2, traditional mountain tunnel ventilation systems may be unsuitable for CST applications. Instead, hybrid systems combining aircraft cabin air recirculation (e.g., 50% fresh air mixing) and submarine CO_2 scrubbing technologies could optimize energy use while effectively controlling particulate matter.

3.2.4 Drainage system

The drainage system in subsea tunnels must address significant challenges related to seawater intrusion. Historical data from the Seikan Tunnel project indicate that water inflow rates in similar geological conditions can reach 5,7600 m³/day in critical sections. This level of leakage necessitates robust drainage solutions with substantial energy requirements for pumping operations. The proposed electrolytic bath system offers a dual-function alternative, simultaneously processing intruding seawater and generating valuable byproducts. Through electrolytic desalination, the system can reduce the energy consumption associated with drainage. Furthermore, the oxygen byproduct (yielding approximately 0.8 m³ per m³ of processed seawater at STP) can supplement ventilation systems, while the hydrogen output (1.6 m³ per m³ of seawater) provides potential backup power generation capacity (Figure 7).

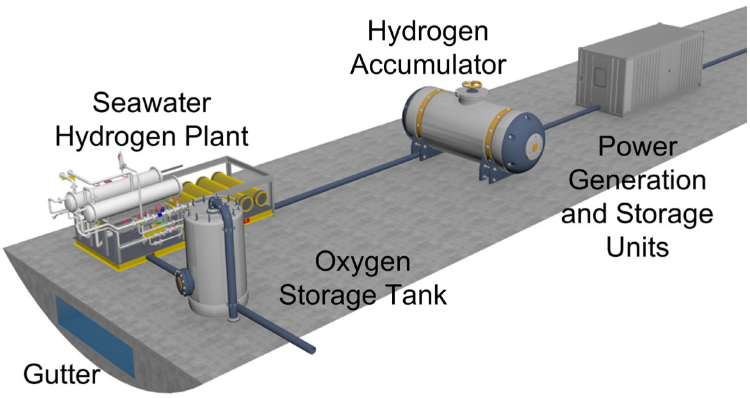


Figure 7. Layout of electrolytic system

4. Speed up CST construction

4.1 Current technologies

4.1.1 Multiple launching from lands

Shortening the construction period of a long tunnel reduces investment costs would save investment. In mountain tunneling, multiple headings can be achieved by using additional vertical or slope shafts, which can also serve for ventilation or rescue access during operation. For the Tokyo Bay fixed linkage artificial island, located in a shallow sea area, a vertical shaft was constructed to launch shield driving machines (TBM) into soft soil sites [26, 27], as shown in Figure 8. This vertical shaft was then used as a ventilation shaft during operation. The nearly 9.5 km long tunnel was excavated as two 4.7 km portions. 8 TBMs were launched from the Kawasaki city bank at Ukishima access, Kawasaki artificial island (100 m in diameter, containing a ventilation tower in operation), and Kisarazu artificial island (transition to the bridge), meeting each other in the middle of their routines. Once again, a 4.7 km tunneling length was divided into two 2.85 km short portions. Efficient construction rewards were obviously associated with the advanced technologies.

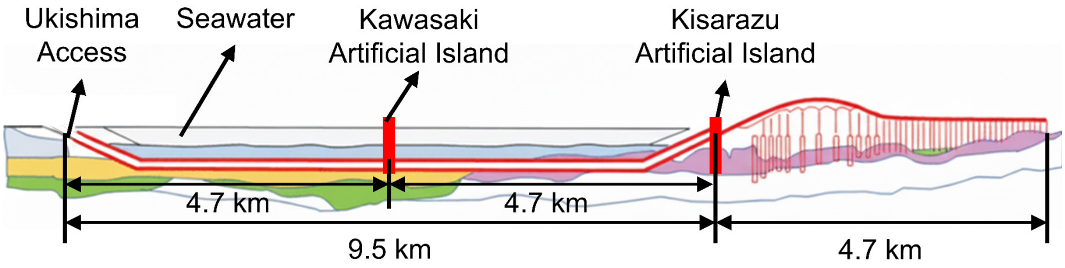


Figure 8. Longitudinal profile of TTBH and geology at Tokyo Bay [26, 28]

Constructing artificial islands for crossing strait tunnels (CST) in deep and wide seas is impractical. To ensure the stability of an island embankment, a gentle slope is needed, which results in a larger sea area being occupied, as shown in Figure 9. For instance, a slope ratio of 1:2 significantly increases the land area required for the island, as depicted in Figure 10, negatively affecting marine ecology. The material needed for even a single reclamation is substantial. Table 2 presents the material consumption for constructing an artificial island with a 100-meter diameter using a 1:2 slope (calculated with Eq. (1)). As sea depth increases, the slope may need to be adjusted to 1:5 for stability, further increasing costs both economically and ecologically. Additionally, for CSTs exceeding 100 km in length, several artificial islands would still be insufficient.

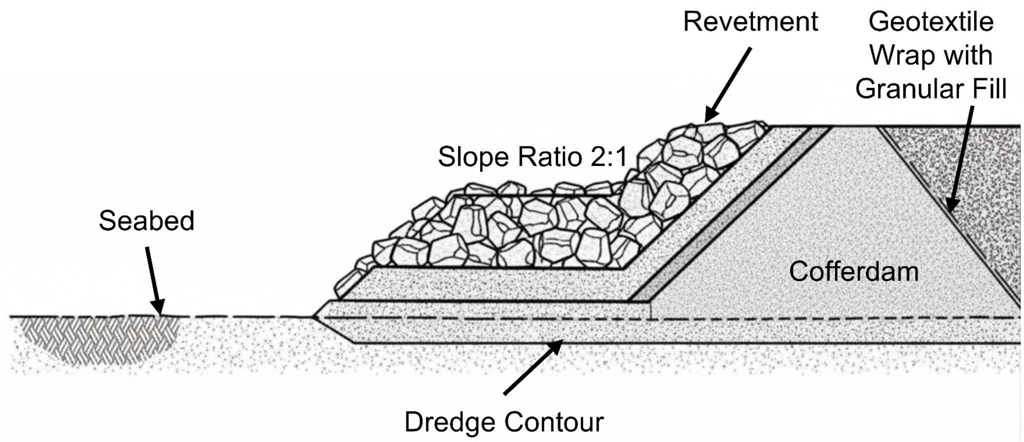


Figure 9. Revetment of artificial island in the tunnel project (modified from [29])

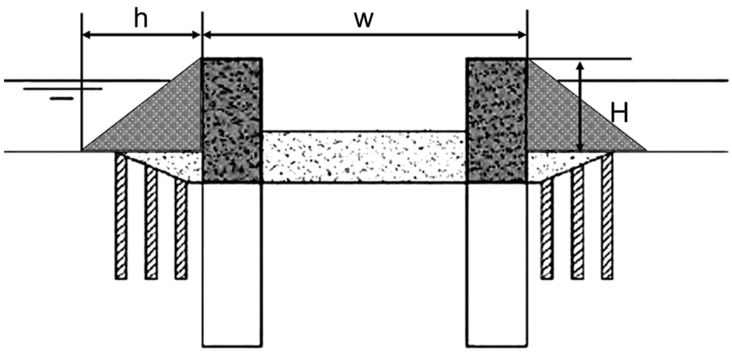


Figure 10. Quantity concept of an artificial island

$$V=\pi H3\times W22+W2\times W+w2+W+w22$$

Equation (1)

Table 2. The reclaim works required with depth (H/w = 1/2)

H/m	w/m	W/m	W/w	V/m³
10	20	100	5/1	132,927
20	40	100	2.5/1	330,747
100	200	100	1/2	5,756,666

4.1.2 Ground penetrating shield tunnel (GPST)

Another advancement in TBM for land is the Ground Penetrating Shield Tunnel [30], as shown in Figure 11. It not only saves cost and time in constructing a vertical shaft, but also represents a significant innovation in smart tunneling, inspired by the concept of an animating earthworm.
Traditional shield tunneling requires the installation of launching and receiving shafts before excavation can begin. For ultra-long subsea tunnel projects spanning tens of kilometers, constructing these vertical access points often necessitates the use of large caissons or artificial islands in deep waters. Such operations can disrupt marine ecosystems and pose technical challenges, including the treatment of deepwater foundations and the sealing of high-pressure areas. The pre-construction phase of these subsea shafts can alter the stress field of the seabed, potentially leading to unpredictable interactions between marine sedimentary layers and tunneling activities, especially in geologically complex submarine environments.

GPST technology revolutionizes subsea tunnel construction by eliminating the need for vertical shafts, offering significant benefits for transoceanic tunnels, where traditional shaft construction would require extensive marine operations with considerable environmental impact. The continuous propulsion mechanism enables navigation through diverse seabed strata, from soft alluvial deposits to complex rock formations, while maintaining the pressure equilibrium necessary for ultra-long underwater tunneling. These features make GPST particularly suitable for next-generation megaprojects, such as transoceanic transport corridors and submerged energy pipelines.

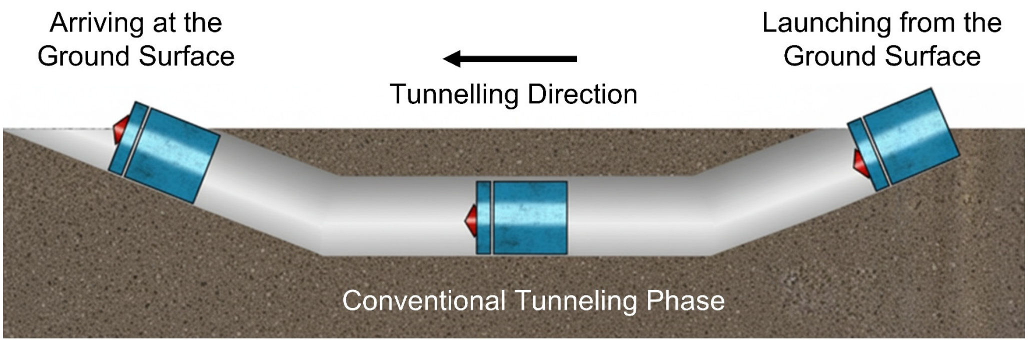


Figure 11. Sketch of the GPST method [30]

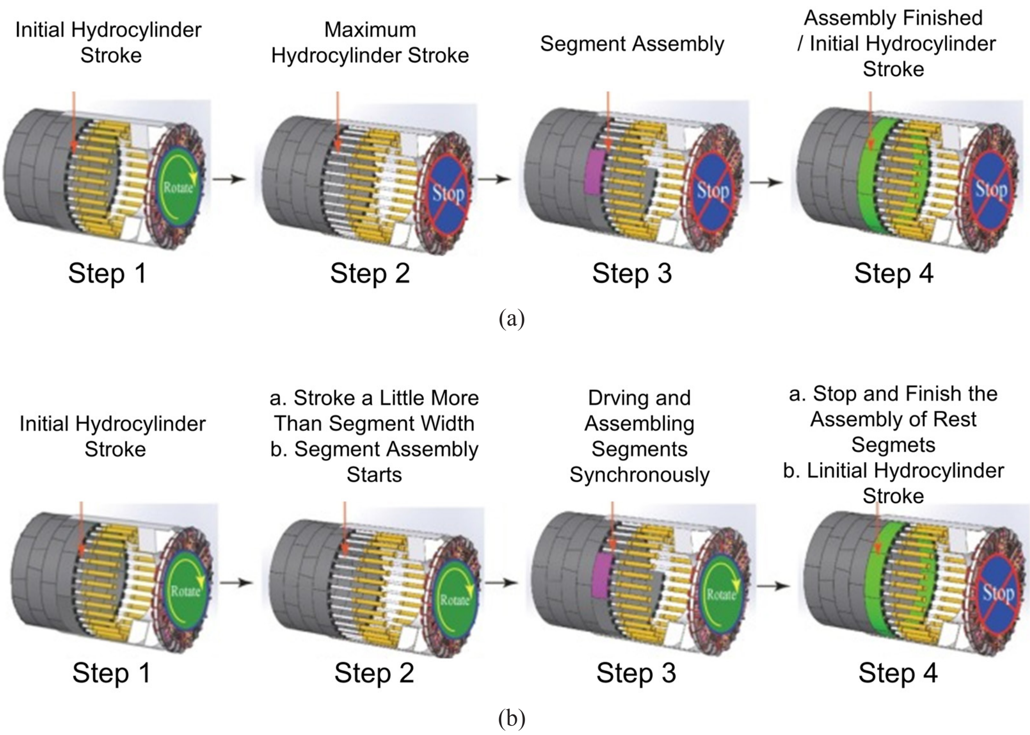
4.1.3 Intelligent driving of TBM in soft ground

In recent years, there have been notable advancements in TBM technology, particularly in synchronized propulsion and segment assembly, supported by the broader trend of AI-driven automation and intelligent system integration [31, 32]. One notable innovation is synchronous shield tunnelling technology (STSS), achieved through active control of the shield thrust system oil pressures [33]. The key to this method is the full utilisation of the additional stroke of the hydraulic jacks, generated by the axial insertion of a key block during segment assembly. This approach enables dynamic coordination of the TBM's advance rate with the segment installation process, thereby addressing the inefficiencies and delays typical of conventional methods. The fundamental differences between this synchronous method and the conventional shield tunnelling approach are illustrated in Figure 12, which compares conventional shield tunneling with the newer synchronous shield tunneling method.

Moreover, the implementation of digital twin frameworks has enabled real-time, multi-objective optimization of complex TBM functions, resulting in greater precision in tunneling operations [34, 35]. Another key innovation is the synchronized segment assembly system, which utilizes the extended stroke of hydraulic jacks activated by the axial engagement of a key block to dynamically align the TBM's advance rate with segment installation dynamically. This method effectively reduces the inefficiencies and support delays commonly associated with conventional assembly techniques [36].

Additionally, projects such as the Luotian Reservoir-

Tiegang Reservoir Water Conveyance Tunnel have adopted synchronous in-situ concrete lining techniques [37]. By integrating continuous belt muck removal and invert trestle bridge technology, these projects have enabled the parallel execution of tunneling, muck disposal, and lining processes. This approach shortens project timelines and reduces environmental impacts. Collectively, these technological advances represent a significant step towards highly efficient and intelligent TBM construction practices.



(a) Conventional shield method; (b) STSS shield tunnelling method

Figure 12. Processes of conventional shield method and STSS shield tunnelling method [33]

4.2 Dragon Palace: an integrated offshore floating platform (OFP)

The Offshore Floating Platform (OFP), conceptualized as the "Dragon Palace," represents the cornerstone of the proposed framework for long CSTs. It is envisioned not merely as a construction base, but as a multi-functional hub that integrates tunneling launch operations, energy generation, and ecological management into a single, sustainable system. This section details its core functions and the synergistic technologies that enable them.

4.2.1 Multiple launching at sea level

An innovative idea is to launch TBM from an OFP [38]. Figure 13a illustrates the concept of launching TBM diving from OFP, which is analogous to diving tunneling (DT), as depicted in Chinese mythological stories, such as the Sea Dragon. DT from OFPs would be positioned at any selected location along the CST.

Shortening the construction period would yield a return on investment. OFP can be self-sustaining during tunneling and after a CST project, as it can serve as a base to produce clean energy or marine products. As shown in Figure 13b, fabricating more OFP as the Dragon bases to launch TBM from sea level would accelerate the construction of long CST.

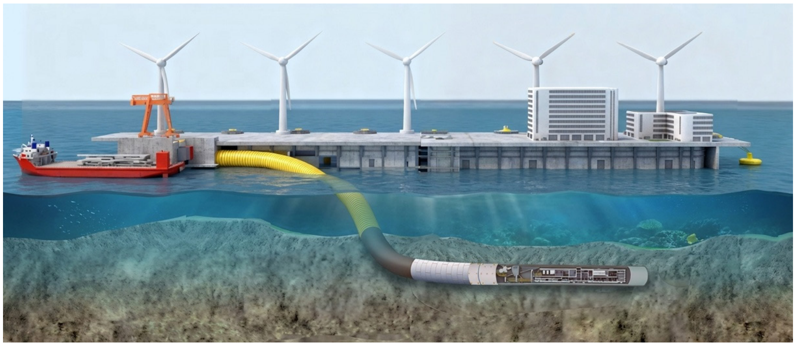
4.2.2 Self-Sustaining energy island

A large-diameter TBM requires a substantial amount of electrical power. Table 1 shows the power requirement of a TBM 15.56 system used in soft ground in Shanghai. Sufficient electrical power must be generated for both tunneling activities and living in an OFP. Transmitting electricity over long distances from land is expensive, incurs losses during transmission, and is time-consuming during to construct.

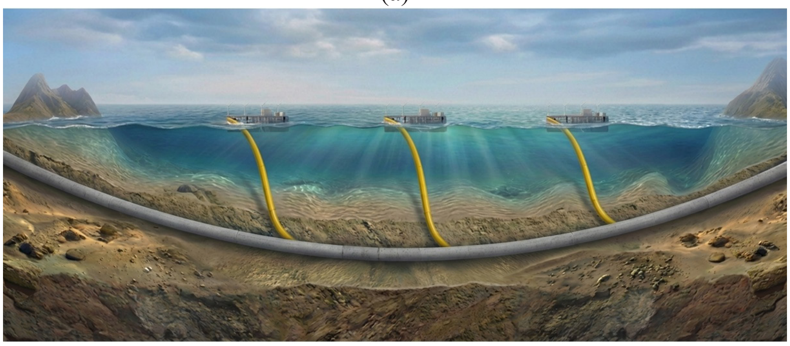
Recently, OFPs have been developed for wind turbines (WTs) and photovoltaic (PV) systems to generate electric power, as well as for deep-sea aquaculture and other offshore applications, such as oil platforms. Therefore, OFP could be built as an energy island, as shown in Figure 14, equipped with WT, PV, wave power generators, electrolysis of seawater, and other capacitors or CAES to store electrical power. For instance, five 5-MW wind turbines could supply the power required for a single TBM operation [39].

The electricity generated can be stored for immediate use through various feasible and emerging technologies. Battery energy storage systems are becoming increasingly mature. It was recently reported that the Nanhai battery station in Foshan, with a capacity of approximately 300 MW/600 MWh, occupies about 4 hectares of land [40]. Installing a battery station on an OFP to meet a 30 MW power requirement would occupy roughly 3,000 m² of the platform. Supercapacitors are another type of high-capacity storage device with a smaller footprint [41].

Compressed air energy storage (CAES) is attracting attention due to its significant capacity potential, although it is currently limited to applications in rock caverns with deep cover layers. CAES could be integrated into the OFP using flexible storage solutions or by employing supercritical state compressed air [42]. Additionally, electrolysis units could be installed to convert clean energy into hydrogen for storage on the OFP, offering an alternative pathway for energy management [43].



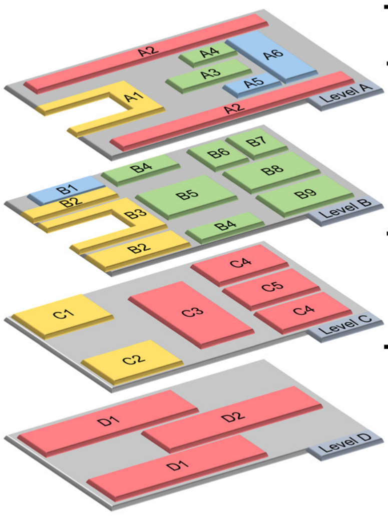
(a)



(b)

(a) Launching; (b) Multiple OFPs for DT

Figure 13. Launching TBM (Sea Dragon) at sea level from OFP (Dragon Palace) [38]



Level A (h = 5 m)	A2	Generation facilities
Level C (h = -5 m)	C3	Hydrogen production
	C4	Battery station
	C5	Hydrogen storage
Level D (h = -10m)	D1	Watertight compartment
	D2	Compressed-air energy storage

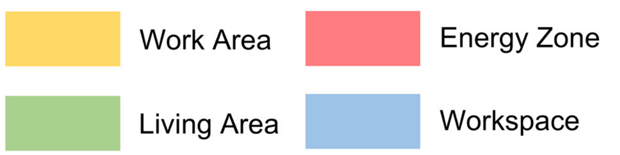


Figure 14. OFP as energy island

4.2.3 Autonomous diving tunneling-Dragon-1

The feasibility of managing parallel tunneling operations from multiple OFPs depends on a high degree of automation and intelligence. This perspective introduces the "Dragon-1" system, an Autonomous Diving Tunneling (ADT) framework designed as the operational core of the OFP hubs. The success of autonomous systems in other domains, such as drones and autonomous trains [44, 45], highlights the potential for a paradigm shift in tunneling, supported by advancements in modular and standardized offshore platforms [46, 47].

The Dragon-1 system requires developments in several key areas to manage the complex processes of TBM propulsion, steering, segment assembly, and real-time decision-making in challenging subsea conditions. One critical aspect is the autonomous construction process for driving and lining the tunnel, which involves the seamless integration of excavation and structural support placement, as illustrated in Figure 15.

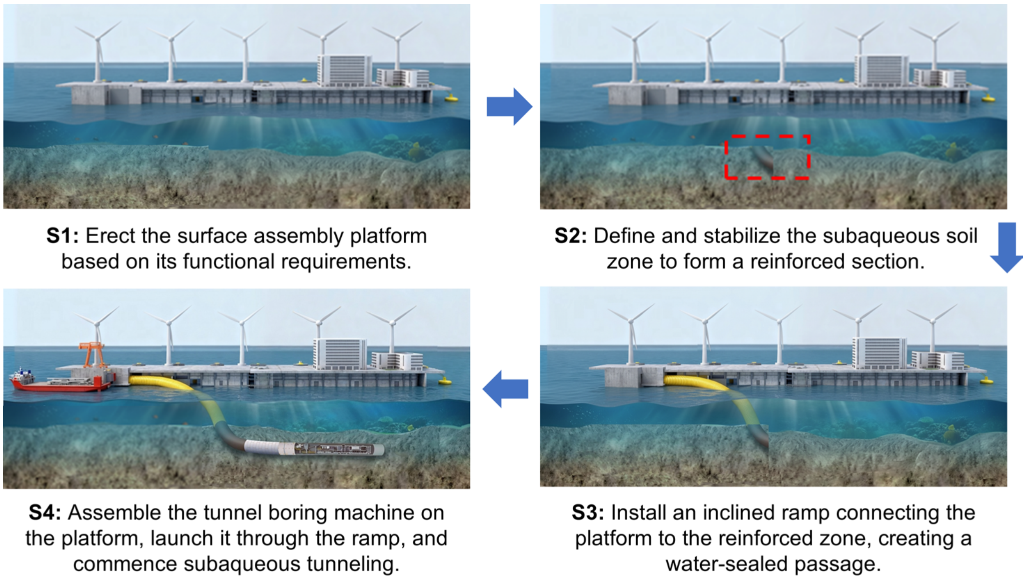


Figure 15. Craft process on driving and lining of CST [48]

Integrating robotic systems and advanced information technology (e.g., real-time monitoring, data-driven control) is essential for enabling precise, efficient, and safe tunneling advancement. Such integration is increasingly supported by machine learning models for condition monitoring and predictive maintenance of offshore equipment [49]. The OFP serves as the ideal control and support base for deploying these autonomous technologies, creating a tightly integrated construction ecosystem based on modularization and standardization principles [50].

4.2.4 Ecological island

OFP could serve as an ecological island, as shown in Figure. 16, to treat waste solids and water from DT and OFP. Dregs from DT are typically discharged into the ocean, which can have catastrophic effects on marine life. However, if disposed of properly they could be used as a mineral resource for construction materials. Sand from dregs is the main component of concrete, whereas clay can be used as an ingredient in producing cementitious materials. OFP could also be used to improve the living conditions of sea fish and other marine plants.

5. An integrated co-design framework for next-generation CSTs

This section advances the discourse from retrospective analysis to prospective synthesis. It systematically elaborates on the internal logic, scientific challenges, and implementation trajectory of the proposed integrated co-design framework. Developed in direct response to the fundamental constraints of depth, distance, and the open-sea environment inherent to Crossing Strait Tunnels (CSTs), the framework represents a paradigm reconstitution across safety, energy, and construction systems. The discussion proceeds in three parts: first, it deconstructs the critical interdependencies within the framework and outlines a corresponding research agenda; second, it elucidates how the framework collectively redefines the feasibility envelope for CSTs; and finally, it proposes a staged research and development pathway to translate this conceptual vision into practical reality.

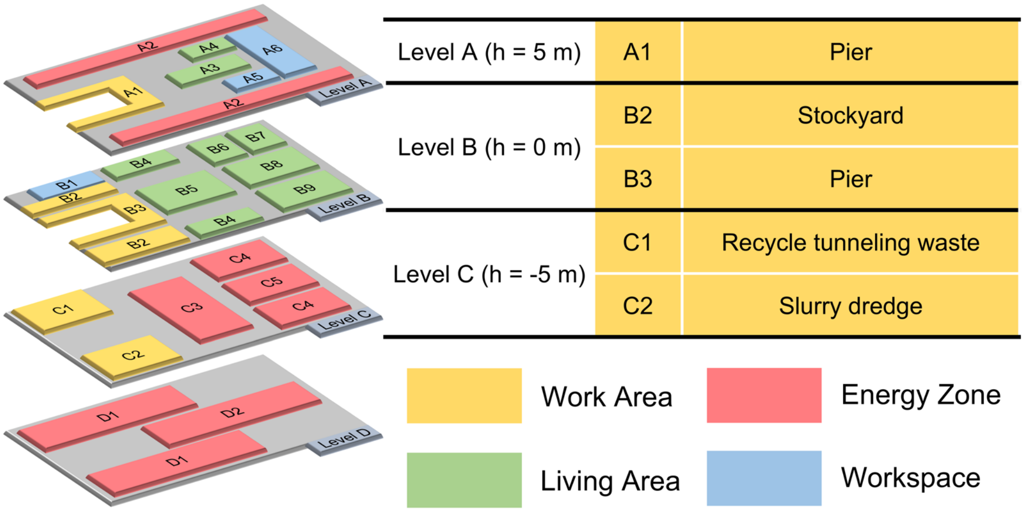


Figure 16. Ecological solutions

5.1 Critical interdependencies and a forward-looking research agenda

The proposed integration of safety, energy, and construction systems creates a tightly coupled network in which the performance of each subsystem depends on the state of the others. This interdependence underpins the framework's potential robustness but also presents its main scientific challenge: How can the complex, non-linear interactions within this socio-technical network be rigorously modeled, optimized, and validated? Future research must prioritize the following critical interfaces:

(1) The dynamic interface between safety and construction logistics: The conceptual integration of evacuation infrastructure within the primary tunnel bore introduces a dynamic spatial allocation problem. Key research frontiers include developing high-fidelity agent-based models to simulate crowd dynamics during emergencies within these integrated layouts, together with real-time, adaptive logistics algorithms. These tools must optimize the trade-off between reserved safety space and construction material flow, responding dynamically to project phases such as TBM advancement or lining installation.

(2) The real-time nexus of energy supply and operational demand: The hypothesis that an Offshore Floating Platform (OFP)-based "energy island" can achieve power self-sufficiency during both construction and operation must address highly stochastic supply and demand. Essential research includes creating multi-physics simulation platforms that model the coupled behavior of intermittent renewable sources (wind, solar, wave), large-scale storage systems (batteries, CAES), and highly variable loads from multiple TBMs, ventilation, and safety systems. The results from such platforms will inform the design of resilient microgrid control architectures capable of managing MW-level power fluctuations while guaranteeing priority power for critical safety functions.

Addressing these questions through integrated modeling and simulation is the essential first step in transitioning the framework from a compelling concept to a quantifiable engineering proposition.

5.2 Redefining the feasibility envelope for large-scale subsea tunnels

The rationale for this framework arises from the recognition that conventional project delivery models, which have been successful for shorter subsea links, reach fundamental scalability limits at the scale of next-generation CSTs. The framework not only improves upon these models but also aims to systematically dismantle the key barriers that define the current feasibility frontier.

(1) Safety: From Fixed Infrastructure to Managed Resilience. Traditional prescriptive safety codes, based on fixed-distance refuge stations and ventilation shafts, result in exponentially increasing cost and complexity as tunnel length increases. The proposed integrated safety system shifts the paradigm towards managed resilience, utilizing real-time monitoring, dynamic resource allocation, and potentially mobile safety stations. This approach aims to make safety performance a function of systemic responsiveness rather than linear infrastructure density, thereby mitigating the direct cost-time impact of sheer tunnel length.

(2) Energy: From grid dependency to embedded autonomy.Gigawatt-scale power transmission over tens of kilometers from shore-based grids introduces prohibitive efficiency losses, costs, and vulnerabilities. The framework proposes embedded energy autonomy through the OFP hub. By collocating generation from offshore renewables with the primary point of consumption, it aims to eliminate long-distance transmission losses and establish a robust, operationally essential microgrid. This paradigm of

embedded energy autonomy is therefore a core feasibility requirement, not merely an additional sustainability feature, for open-sea megaprojects.

(3) Construction: From linear sequencing to parallelized manufacturing.The critical path duration of a project launched from one or two coastal sites scales linearly with tunnel length, leading to decades-long timelines that escalate financial risk. The framework introduces a parallelized manufacturing paradigm, where multiple TBMs operate concurrently from distributed OFP hubs. This strategy fundamentally alters project scheduling, compressing the critical path and transforming the project's financial profile and risk landscape.

In essence, the framework is architected to operate beyond the scalability thresholds of current best practices, proposing a new system where the integrated whole enables what is currently infeasible for the isolated parts.

5.3 A staged pathway from concept to implementation

Translating this integrated framework into practice requires a coordinated, multi-stage research and development program.

5.3.1 Foundational research and enabling technologies (near-term)

(1) Development of integrated multi-scale simulation tools: Create a cross-domain computational platform capable of co-simulating evacuation dynamics, energy system flows, and discrete-event construction logistics to explore emergent behaviors and identify critical coupling points.

(2) Interface and protocol definition:Conduct focused studies on key technical interfaces, such as power management protocols between the OFP microgrid and high-power TBM drives, human-factors engineering for multi-functional tunnel spaces, and communication standards for autonomous construction robotics.

(3) Formulation of system-level performance metrics: Establish a new set of Key Performance Indicators (KPIs) designed to evaluate the integrated system's overall efficacy, economic viability, and resilience, moving beyond siloed metrics for safety, cost, or schedule alone.

5.3.2 Technology prototyping and validation (medium-term)

(1) OFP multi-functional hub prototyping testing: Design, build, and operate a scaled prototype of the OFP in a relevant marine environment to validate the concurrent operation of renewable energy systems, energy storage, and simulated TBM support logistics.

(2) Advanced digital twin development:Construct a comprehensive, physics-based digital twin of the entire CST project lifecycle. This twin would serve as a virtual testbed for system integration, control strategy optimization, and risk assessment under a wide range of scenarios.

(3) Human-in-the-loop safety and operational validation: Execute large-scale virtual and mixed-reality simulations to test evacuation procedures, maintenance operations, and crew responses within the proposed integrated layouts, refining designs based on human performance data.

5.3.3 Pilot-scale integration and demonstration (long-term)

(1) Targeted pilot project implementation: Apply the core principles and technologies of the framework to a strategically selected, real-world project of significant but sub-CST scale (e.g., a long undersea link between islands) to provide invaluable data on integrated construction sequencing, operational workflows, and real-world economics.

(2) Collaborative development of new standards: Actively engage with international standards organizations, regulatory bodies, and industry partners to develop new codes, standards, and contractual models that are conducive to and supportive of co-designed, multi-functional infrastructure systems.

6. Closing remarks

The development of next-generation CSTs represents a major challenge in civil engineering, requiring a fundamental reconceptualization rather than incremental improvements. This perspective contends that overcoming the interconnected constraints of safety, energy, and construction in such megaprojects necessitates a systemic shift to an integrated co-design framework.

At the core of this framework is the transformation of the OFP into a multi-functional, sustainable hub, referred to as the "Dragon Palace." It centralizes energy generation, tunneling operations, and ecological management, enabling the parallel launch of autonomous TBMs and establishing on-site energy autonomy. This decouples project feasibility from distant logistics and grid dependency. Simultaneously, the proposed integrated safety system, featuring a "Dual-Refuge" layout, redefines resilience by shifting from static, infrastructure-dependent protection to dynamic, intelligently managed evacuation processes.

Collectively, these innovations are intended to redefine the feasibility envelope for CSTs. They transform safety from a linear cost driver into a function of system intelligence, convert energy from a distant liability into an embedded asset, and compress schedules by shifting from linear sequencing to parallelized construction. The integrated system aims to achieve what is presently infeasible through isolated solutions.

Realizing this vision requires addressing the complex interdependencies within this socio-technical system. A structured, collaborative approach is essential, requiring a rigorous multi-stage research agenda. This agenda must span integrated simulations, technology prototyping, and pilot demonstrations to develop the framework from a compelling concept into a validated engineering proposition.

In conclusion, the future of the most ambitious subsea fixed links depends not on scaling past solutions, but on co-designing resilient, self-sustaining systems. The proposed framework provides a cohesive roadmap for this effort. While significant challenges remain, the potential to revolutionize long-distance subsea connectivity, with broad implications for infrastructure in other extreme environments, fully justifies the concerted pursuit of this new paradigm.

Authors' contributions

The study was conducted by Yuan Yong, responsible for conceptualization, methodology, and original draft writing; Yao Xupeng, who contributed to conceptualization and investigation; Xiong Xinhang, in charge of visualization, reviewing, and editing; Chai Rui, providing supervision; and Zhang Jiaolong, who also participated in reviewing and editing.

Conflicts of interest

All authors (Yuan Yong, Yao Xupeng, Xiong Xinhang, Chai Rui, Zhang Jiao-Long) declare that they have no conflict of interest or financial conflicts to disclose.

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