

RESEARCH TITLE

Strategic Civil Engineering Management of Marine Port Infrastructure: Asset Lifecycle, Structural Capacity, and Resilience Planning in the Red Sea Corridor – A Case Study of the Sudanese Sea Ports Corporation (2018–2022)

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Abstract

The civil engineering infrastructure of marine ports represents the critical physical interface between global maritime logistics and terrestrial supply chains. Effective civil engineering management of these assets—encompassing quay walls, breakwaters, dredged channels, heavy-duty pavements, and marine structures—is paramount for ensuring operational safety, maximizing asset lifespan, and optimizing lifecycle costs. This paper presents a comprehensive civil engineering management analysis of the Sudanese Sea Ports Corporation (SSPC) infrastructure, utilizing data from the 2022 Annual Statistical Report. By shifting the analytical lens from purely operational logistics to civil infrastructure asset management, this study evaluates the structural capacity, geotechnical demands, and maintenance challenges of the Sudanese port system. Key findings highlight the critical need for structural rehabilitation of aging quay walls, the implementation of risk-based maintenance strategies for heavy-duty port pavements subjected to extreme axle loads (e.g., 2.8 million tons of cement imports), and the strategic management of bathymetric assets through optimized dredging campaigns. Furthermore, the paper addresses the paradox of managing expanding civil infrastructure demands amidst severe macroeconomic constraints and declining real revenues. The study proposes a robust, evidence-based strategic framework integrating Building Information Modeling (BIM), Structural Health Monitoring (SHM), and lifecycle cost analysis (LCCA) to enhance the resilience, sustainability, and civil engineering management maturity of the Sudanese maritime sector.

Key Words: Civil Engineering Management, Port Infrastructure, Asset Lifecycle Management, Marine Concrete Durability, Port Pavement Design, Dredging Management, Structural Health Monitoring, Sudanese Sea Ports Corporation.

الإدارة الاستراتيجية للهندسة المدنية في البنية التحتية للموانئ البحرية: دورة حياة الأصول، والقدرة الإنشائية، وتخطيط المرونة في ممر البحر الأحمر: دراسة حالة مؤسسة الموانئ البحرية السودانية (2018-2022)

المستخلص

تمثل البنية التحتية للهندسة المدنية في الموانئ البحرية الواجهة المادية الحيوية التي تربط بين منظومة اللوجستيات البحرية العالمية وسلاسل الإمداد البرية. وتعد الإدارة الفعالة لهذه الأصول من منظور الهندسة المدنية، بما يشمل جدران الأرصفة البحرية، وكاسرات الأمواج، والقنوات المجروفة، والأرصفة ذات الأحمال الثقيلة، والمنشآت البحرية، أمراً بالغ الأهمية لضمان السلامة التشغيلية، وتعظيم العمر الافتراضي للأصول، وتحسين تكاليف دورة الحياة. تقدم هذه الورقة تحليلاً شاملاً لإدارة الهندسة المدنية للبنية التحتية التابعة لمؤسسة الموانئ البحرية السودانية، اعتماداً على بيانات التقرير الإحصائي السنوي لعام 2022م. ومن خلال تحويل زاوية التحليل من التركيز على اللوجستيات التشغيلية البحتة إلى إدارة أصول البنية التحتية المدنية، تقيم هذه الدراسة القدرة الإنشائية، والمتطلبات الجيوتقنية، وتحديات الصيانة في نظام الموانئ السودانية. وتبرز النتائج الرئيسية الحاجة الملحة إلى إعادة التأهيل الإنشائي لجدران الأرصفة البحرية المتقدمة، وتطبيق استراتيجيات صيانة قائمة على المخاطر للأرصفة المينائية ذات الأحمال الثقيلة المعرضة لأحمال محورية شديدة، مثل واردات الأسمت البالغة 2.8 مليون طن، فضلاً عن الإدارة الاستراتيجية للأصول الباثيمترية من خلال حملات تجريف محسنة. كما تتناول الورقة مفارقة إدارة الطلب المتزايد على البنية التحتية المدنية في ظل قيود اقتصادية كلية حادة وتراجع الإيرادات الحقيقية. وتقتصر الدراسة إطاراً استراتيجياً قوياً قائماً على الأدلة يدمج نمذجة معلومات البناء، ومراقبة السلامة الإنشائية، وتحليل تكلفة دورة الحياة، بما يعزز مرونة قطاع النقل البحري السوداني واستدامته ونضج إدارة الهندسة المدنية فيه.

الكلمات المفتاحية: إدارة الهندسة المدنية، البنية التحتية للموانئ، إدارة دورة حياة الأصول، متانة الخرسانة البحرية، تصميم أرصفة الموانئ، إدارة التجريف، مراقبة السلامة الإنشائية، مؤسسة الموانئ البحرية السودانية.

1. Introduction

1.1 Background and Context

Marine ports are complex civil engineering systems comprising a diverse array of interconnected infrastructure assets. These include quay walls, jetties, breakwaters, navigational channels, heavy-duty aprons and yard pavements, and specialized structures for bulk and liquid cargo handling. The civil engineering management of these assets is a multidisciplinary endeavor that bridges structural engineering, geotechnical engineering, hydraulic engineering, and construction management. In the context of the Red Sea corridor, ports face unique environmental and operational challenges, including high salinity, elevated temperatures, aggressive marine borer activity, and the increasing physical demands of modern, larger-tonnage vessels.

The Sudanese Sea Ports Corporation (SSPC) manages a network of ports along the western coast of the Red Sea, with Port Sudan serving as the primary national gateway. The civil infrastructure of these ports was developed over several decades, with various sections dating back to the mid-20th century. As global shipping evolves toward larger vessels and heavier cargo loads, the physical limits of this aging civil infrastructure are increasingly tested. Consequently, the focus of port administration must shift from reactive maintenance to proactive, strategic civil engineering asset management.

1.2 Problem Statement

While the operational and logistical performance of the SSPC has been documented, there is a distinct lack of literature analyzing the civil engineering management aspects of the Sudanese port infrastructure. The 2022 Annual Statistical Report reveals significant operational data—such as the handling of 11.5 million tons of trade, including massive volumes of heavy bulk cargo like cement (2.8 million tons) and wheat (2.8 million tons)—but it does not explicitly address the structural and geotechnical toll these operations take on the civil assets.

Furthermore, the SSPC is operating within a constrained macroeconomic environment. Nominal port revenues have declined significantly in real terms due to currency devaluation. This financial constraint creates a critical challenge for civil engineering managers: how to maintain, rehabilitate, and upgrade multi-million-dollar marine infrastructure assets with shrinking capital and operational expenditure (CAPEX and OPEX) budgets. The misalignment between the physical degradation of civil assets and the available financial resource for their upkeep poses a severe risk to port safety, operational continuity, and long-term economic viability.

1.3 Research Objectives

This paper aims to achieve the following objectives from a civil engineering management perspective:

1. To evaluate the physical capacity and structural design limits of the SSPC's marine infrastructure (berths, depths, and quay walls) against current and projected operational demands.
2. To analyze the geotechnical and structural engineering implications of the specific cargo profiles handled by the ports, particularly heavy bulk and containerized loads.
3. To assess the challenges of hydrographic and dredging management in maintaining the required navigational drafts (ranging from 8.6m to 14.6m) in the Red Sea environment.
4. To propose an Infrastructure Asset Management (IAM) framework tailored for the SSPC, integrating lifecycle cost analysis, risk-based maintenance, and digital engineering tools (BIM and Digital Twins) to optimize civil infrastructure performance under financial constraints.

1.4 Paper Structure

The remainder of this paper is structured as follows: Section 2 reviews the literature on civil engineering management in marine environments. Section 3 outlines the analytical methodology. Section 4 details the civil infrastructure architecture of the SSPC. Section 5 examines the structural and geotechnical demands imposed by cargo handling. Section 6 discusses dredging and hydrographic management. Section 7 addresses asset management under financial constraints. Section 8 explores digitalization in civil port management. Section 9 provides a strategic framework for infrastructure modernization, and Section 10 concludes the study.

2. Literature Review

2.1 Infrastructure Asset Management (IAM) in Marine Ports

Infrastructure Asset Management (IAM) is a systematic, coordinated process practiced by organizations to optimally manage their physical assets over their lifecycle. In the context of marine ports, IAM encompasses the planning, acquisition, operation, maintenance, rehabilitation, and disposal of civil infrastructure. The International Organization for Standardization (ISO 55000) provides the foundational framework for IAM, emphasizing the alignment of asset management objectives with organizational goals.

For port authorities, the primary challenge in IAM is balancing the deteriorating condition of aging marine structures with the need to maintain high levels of service. Marine environments are highly aggressive; reinforced concrete structures in splash and tidal zones are particularly susceptible to chloride ingress, leading to corrosion of steel reinforcement, concrete spalling, and loss of structural integrity. Effective IAM requires transitioning from time-based or reactive maintenance to condition-based and risk-based maintenance (RBM) strategies. RBM prioritizes maintenance interventions based on the probability of asset failure and the consequence of that failure on port operations and safety.

2.2 Structural and Geotechnical Engineering of Quay Walls

Quay walls are the most critical and capital-intensive civil assets in a port. They must resist a complex combination of lateral earth pressures, hydrostatic pressures, wave loads, and massive concentrated loads from mooring bollards, fenders, cargo handling equipment (e.g., Ship-to-Shore cranes). The design of quay walls, whether gravity-based, sheet pile, or diaphragm wall structures, requires rigorous geotechnical analysis to ensure global and local stability against sliding, overturning, and bearing capacity failure.

In many older ports, the original design loads for quay walls are significantly lower than the demands imposed by modern cargo handling equipment and larger vessels. Upgrading the structural capacity of existing quay walls without disrupting port operations is a major civil engineering management challenge. Techniques such as micropile underpinning, concrete jacketing, and the installation of tie-back anchors are frequently employed, requiring sophisticated construction management and phased execution planning.

2.3 Port Pavement Engineering and Heavy-Duty Surfacing

Port pavements are subjected to extreme loading conditions that far exceed those of standard highway pavements. The loads include high static loads from stacked containers, intense dynamic loads from rubber-tired gantry (RTG) cranes and straddle carriers, and concentrated point loads from heavy cargo such as steel coils and bulk cement bags.

Civil engineering management of port pavements involves the design of rigid (jointed plain concrete) or flexible (asphalt) pavements capable of withstanding these loads without

excessive rutting, cracking, or differential settlement. The subgrade preparation and base course compaction are critical, as differential settlement in port yards can severely impair the operation of automated cargo handling equipment. Maintenance management of port pavements requires regular condition surveys, such as the Pavement Condition Index (PCI), to schedule timely crack sealing, joint resealing, and slab replacement, thereby extending the pavement lifecycle.

2.4 Hydrographic Management and Dredging Engineering

Maintaining the design depth of navigational channels and berthing pockets is a continuous civil and hydraulic engineering challenge. Siltation, driven by tidal currents, wave action, and riverine inputs, gradually reduces the available draft. Dredging is the primary engineering intervention to manage this.

Dredging management involves not only the physical removal of sediments using capital or maintenance dredgers but also the environmental management of the dredged material (spoils). In the Red Sea, the presence of coral reefs and sensitive marine ecosystems necessitates careful planning of dredging campaigns to minimize turbidity and ecological impact. Furthermore, the civil engineering management of dredging requires accurate bathymetric surveys, sediment transport modeling, and the optimization of dredging fleets to minimize OPEX.

2.5 Digitalization and Building Information Modeling (BIM) in Port Civil Works

The integration of digital technologies into civil engineering management is transforming how port infrastructure is designed, constructed, and maintained. Building Information Modeling (BIM) allows for the creation of intelligent 3D models that contain rich data about the physical and functional characteristics of port assets. When extended to the operational phase (often referred to as BIM for Facility Management or BIM-FM), it enables civil engineering managers to visualize underground utilities, track the maintenance history of specific quay wall segments, and simulate structural stresses.

Coupled with the Internet of Things (IoT) and Structural Health Monitoring (SHM) sensors (e.g., strain gauges, tiltmeters, corrosion probes), digital twins of port infrastructure can provide real-time data on asset conditions. This digital transformation is critical for optimizing maintenance budgets and preventing catastrophic structural failures.

3. Methodology

3.1 Data Collection and Sources

This study utilizes quantitative and qualitative data extracted from the *Sudanese Sea Ports Corporation (SSPC) 2022 Annual Statistical Report*. The dataset provides detailed metrics on port infrastructure dimensions (berth lengths, depths, areas), cargo handling volumes (by type and tonnage), fleet movements, and financial revenues. To contextualize the civil engineering implications of this data, secondary data regarding marine concrete degradation rates, port pavement design standards, and dredging OPEX benchmarks were sourced from civil engineering literature and industry guidelines (e.g., PIANC, ASCE).

3.2 Analytical Framework: Capacity-Demand Gap Analysis

The core analytical framework employed in this study is the Civil Infrastructure Capacity-Demand Gap Analysis. This framework evaluates the physical and structural capacity of the port assets against the operational demands imposed by the cargo and vessel profiles.

1. **Capacity Assessment:** Evaluating the design parameters of the civil assets, including quay wall structural limits, fender/bollard energy absorption and safe working loads, pavement bearing capacities, and navigational draft limits.

2. **Demand Assessment:** Quantifying the physical demands of the operations, including vessel deadweight tonnage (DWT), mooring line forces, cargo axle loads, stacking heights, and dredging volumes required to maintain drafts.
3. **Gap Identification:** Identifying areas where operational demands exceed or closely approach the design capacity of the civil infrastructure, indicating a high risk of accelerated degradation or structural failure.

3.3 Asset Condition and Lifecycle Cost Modeling

To address the financial constraints faced by the SSPC, the study applies conceptual models of Risk-Based Maintenance (RBM) and Lifecycle Cost Analysis (LCCA). While specific condition rating data for the Sudanese ports is not publicly available in the statistical report, the framework demonstrates how civil engineering managers should utilize the operational data to prioritize maintenance interventions. The LCCA model evaluates the total cost of ownership for civil assets, including initial construction, routine maintenance, periodic rehabilitation, and eventual replacement, discounted to present value.

4. Civil Infrastructure Architecture and Capacity Analysis

4.1 Spatial Distribution and the Primacy of Port Sudan

The SSPC's civil infrastructure portfolio is heavily centralized around Port Sudan, located at longitude 37°13' E and latitude 19°39' N. The civil layout of Port Sudan is divided into specialized functional zones, a design philosophy that dictates specific structural and geotechnical requirements for each sector.

4.1.1 Northern Berth: General Cargo and RoRo Infrastructure

The Northern Berth is a massive civil engineering complex comprising 12 berths with a total quay length of 1,660 meters and a total area of 716,136 square meters.

- **Structural and Hydraulic Design:** The berths have depths ranging between 8.6 and 10.7 meters. From a civil engineering perspective, this relatively shallow draft indicates that the quay walls were likely designed as gravity structures or shallow sheet piles, optimized for the geological conditions of the immediate foreshore. The structural design must accommodate the impact forces of vessels up to 20,000 DWT. This requires specific fender systems (e.g., cylindrical or cell fenders) capable of absorbing the kinetic energy of these vessels, and bollards with a Safe Working Load (SWL) commensurate with the mooring line tensions of 20,000-ton ships.
- **Pavement and Yard Management:** The 716,136 sqm area is dedicated to general cargo, steel, timber, and vehicles. The civil management of this zone requires heavy-duty pavements capable of withstanding the point loads of steel coils and the high-frequency turning movements of heavy forklifts and RoRo vehicles. Differential settlement in this area would severely disrupt vehicle processing, necessitating rigorous subgrade compaction during construction and continuous pavement monitoring.

4.1.2 Green Berth: Deep-Water Dry Bulk Infrastructure

The Green Berth represents the most robust deep-water civil infrastructure in Port Sudan, featuring 4 berths with a total length of 1,232 meters and depths ranging between 14.2 and 14.6 meters.

- **Geotechnical and Structural Implications:** Achieving a depth of 14.6 meters requires significant capital dredging and the construction of high retaining quay walls,

likely of diaphragm or deep sheet pile construction, to retain the massive lateral earth and hydrostatic pressures associated with such depths. The area spans 976,477 square meters. The structural design must accommodate vessels up to 50,000 DWT. The kinetic energy of a 50,000 DWT bulk carrier berthing at the Green Berth is exponentially higher than at the Northern Berth, requiring high-reaction fender systems (e.g., super cone or arch fenders) and high-capacity quick-release mooring hooks.

- **Bulk Handling Civil Works:** This berth specializes in dry bulk. The civil infrastructure here must support heavy continuous ship unloaders and conveyor galleries. The foundations for these structures require deep piling to transfer the immense dynamic loads and vibrations into the bearing stratum, avoiding resonance with the quay wall structure.

4.1.3 Southern Berth: Grain and Specialized Bulk Infrastructure

Located south of the port entrance, the Southern Berth features a total length of 1,765 meters and an average width of 500 meters, encompassing 542,210 square meters. It contains 6 berths (1,527 meters) capable of receiving vessels up to 70,000 DWT.

- **Foundation Engineering for Silos:** The presence of a specialized grain handling station with a 50,000-ton capacity introduces severe geotechnical challenges. The foundations for grain silos must be designed to prevent differential settlement, which can cause catastrophic structural failure of the silo bins. In marine environments with potentially weak, compressible subsoils, deep foundation systems (such as bored piles or driven precast concrete piles) are mandatory. The civil engineering management of this zone requires continuous settlement monitoring of the silo foundations, especially during the loading and unloading cycles of the 50,000-ton grain capacity.

4.1.4 Khair Berth: Petroleum and Hazardous Cargo Infrastructure

The Khair Berth is a highly specialized civil structure located on a rocky ridge, with a width of 14.2 meters and a length of 310 meters.

- **Structural Design in Aggressive Environments:** Being situated on a rocky ridge presents unique geotechnical advantages (high bearing capacity) but construction challenges (blasting and rock excavation). The narrow width (14.2m) dictates a highly specialized structural cross-section, likely a reinforced concrete trestle or jetty structure. The civil engineering management of Khair Berth is dominated by safety and environmental protection. The concrete mix design must incorporate strict durability parameters to resist not only marine chloride attack but also chemical spills from petroleum products. The deck must be designed with specialized drainage systems and containment bunds to prevent hydrocarbon runoff into the Red Sea.

4.2 Secondary Ports: Decentralized Asset Management

The SSPC also manages a decentralized portfolio of secondary ports, each with distinct civil engineering characteristics:

- **Osaif Port (Livestock):** 10 berths, 400 meters total length. The civil infrastructure here must prioritize animal welfare, requiring specialized non-slip pavement surfaces, extensive drainage systems for washdown water, and shaded structures. Drainage management is critical to prevent the contamination of the marine environment with organic waste.
- **Suakin Port:** 25 berths, 2,145 meters total length. As one of the older ports, Suakin's civil infrastructure likely faces the most severe degradation. Managing the

maintenance of 2.1 km of quay walls and associated pavements with limited budgets requires a rigorous condition assessment program to prioritize interventions.

- **Saloom Port:** 8 berths, 656 meters total length. Located 10 km west of Port Sudan, it includes customs and quarantine facilities. The civil management here involves not only marine structures but also the terrestrial civil works (buildings, roads, utilities) associated with the customs zone.

5. Structural and Geotechnical Demands Imposed by Cargo Handling

The operational data from the SSPC provides profound insights into the physical loads imposed on the port's civil infrastructure. Civil engineering management must translate these cargo volumes into structural stress, pavement wear, and geotechnical settlement risks.

5.1 Heavy Bulk Cargo and Pavement Degradation

In 2022, the ports handled massive volumes of heavy bulk and general cargo, most notably:

- **Cement:** 2,802,805 tons
- **Wheat:** 2,818,719 tons
- **Edible oils:** 1,527,684 tons
- **Sugar:** 1,291,035 tons
- **Fertilizers:** 1,143,410 tons

The importation of 2.8 million tons of cement represents an extreme civil engineering challenge. Cement is typically imported in bulk or in 50kg bags stacked on pallets. When stacked in the port yard, the static loads on the pavement are immense. Furthermore, the handling of cement involves heavy wheel loaders and fork-lifts operating continuously in the same traffic lanes, leading to severe surface abrasion and rutting in flexible pavements, or edge-breaking in rigid concrete pavements.

From a management perspective, the civil engineering team must implement a strict yard zoning policy, designating specific high-capacity pavement zones for cement and heavy bulk storage. The pavement design for these zones must utilize high-strength concrete (e.g., >40 MPa) with steel fiber reinforcement or heavy-duty asphalt with polymer modifiers. Maintenance management must shift to a rapid-repair protocol, utilizing fast-setting concrete or cold-patch asphalt to minimize yard downtime.

5.2 Containerization and Dynamic Loading

The handling of 219,854 TEUs and 4,006,945 tons of containerized cargo introduces dynamic loading conditions. Containers are typically stacked 4 to 5 high in the yard. The civil engineering management of container yards focuses on the bearing capacity of the subgrade and the interlocking concrete block paving (ICBP) or reinforced concrete slabs used for surfacing.

The repeated passage of Rubber-Tired Gantry (RTG) cranes, which can weigh over 100 tons, imposes high wheel loads. The civil management challenge is to prevent the "pumping" effect, where fine subgrade particles are forced up through the pavement joints due to dynamic pressure, leading to voids beneath the pavement and subsequent cracking. Regular joint sealing and subgrade stabilization via polyurethane injection are critical maintenance activities.

5.3 Petroleum Handling and Structural Integrity

The oil and petroleum sector handled 3,759,376 tons in 2022. The Khair Berth, with its 310-meter length, is the focal point for this trade. The civil engineering management of petroleum jetties requires stringent adherence to international safety codes (e.g., OCIMF guidelines).

The structural integrity of the loading arms, piping supports, and the jetty deck itself must be monitored for fatigue cracking caused by the dynamic loads of waves and the vibration of pumping operations. Cathodic protection systems must be regularly tested to ensure the steel piles supporting the jetty are not corroding in the highly conductive saline environment.

6. Dredging, Bathymetry, and Hydrographic Management

Maintaining the design depths of the berths is a continuous and costly civil engineering operation. SSPC's infrastructure features varying in depth requirements:

- Northern Berth: 8.6 - 10.7 meters
- Green Berth: 14.2 - 14.6 meters
- Southern & Khair Berths: Accommodate up to 50,000 and 70,000 DWT vessels, requiring corresponding deep-water pockets.

6.1 Siltation and Sediment Transport Dynamics

The Red Sea, while generally characterized by clear waters, experiences localized siltation in port basins due to tidal currents, wave-induced longshore drift, and the resuspension of sediments by vessel propellers. The civil engineering management challenge is to predict siltation rates and plan maintenance dredging campaigns accordingly.

Over-dredging leads to unnecessary capital expenditure, while under-dredging risks vessel groundings, which can cause catastrophic damage to the quay walls and result in massive operational disruptions. Hydrographic surveys must be conducted quarterly using multi-beam echo sounders to generate accurate bathymetric maps. These maps are fed into sediment transport models to optimize the frequency and volume of dredging.

6.2 Dredging Fleet Management and OPEX Optimization

Dredging is a major component of the port's Operational Expenditure (OPEX). Civil engineering managers must decide whether to utilize in-house dredging equipment (e.g., trailer suction hopper dredgers) or to contract external dredging companies. Given the financial constraints highlighted in the SSPC revenue data, optimizing the dredging OPEX is critical.

Techniques such as "rainbowing" (pumping dredged material directly onto adjacent land for reclamation) can be more cost-effective than loading into hopper barges and transporting to offshore disposal sites, provided environmental regulations permit. Furthermore, the civil management team must ensure that the dredged material is free from hazardous contaminants, particularly near the Khair Berth and Northern Berth, where historical hydrocarbon or chemical spills may have contaminated the seabed.

6.3 Breakwater and Shoreline Protection

Maintaining the navigational channels requires not just dredging the basins but managing the breakwaters and shoreline protection structures that prevent silt from re-entering the channels. The civil engineering management of these structures involves regular inspections of the armor units (e.g., tetrapods, dolos, or rock armor) for displacement or breakage due to wave action. Scour protection at the toe of the breakwaters must be monitored and replenished with rock fill to prevent undermining and structural collapse.

7. Asset Management and Lifecycle Costing under Financial Constraints

A critical finding from the SSPC 2022 data is the steady decline in nominal port revenues, dropping from 451,712 (in millions/billions of SDG) in 2018 to 285,770 in 2022. When adjusted for the severe hyperinflation and currency devaluation experienced by the Sudanese

Pound during this period, the real-term financial resources available for civil infrastructure maintenance have collapsed. This creates a severe crisis in civil engineering asset management.

7.1 The Deferred Maintenance Trap

When capital and operational budgets are slashed, civil engineering managers are often forced to defer non-critical maintenance. This leads to the "deferred maintenance trap." A minor crack in a quay wall that could have been sealed for a few hundred dollars, if left untreated, allows chlorides to reach the steel reinforcement. The resulting corrosion expands, spalling the concrete cover. The eventual repair requires scaffolding, concrete demolition, rebar replacement, and concrete patching, costing tens of thousands of dollars.

For the SSPC, the decline in real revenue means that deferred maintenance is likely accumulating rapidly across the 1,660 meters of Northern Berth, the 1,232 meters of the Green Berth, and the extensive yard pavements. The civil engineering management imperative is to break this cycle by adopting a Risk-Based Maintenance (RBM) approach.

7.2 Implementing Risk-Based Maintenance (RBM)

RBM prioritizes maintenance interventions based on a matrix of *Probability of Failure* and *Consequence of Failure*.

- **High Consequence / High Probability:** Immediate intervention. (e.g., severe corrosion at the mooring bollard foundations of the Green Berth, where failure would prevent 50,000 DWT vessels from berthing, halting the bulk import of essential grains).
- **High Consequence / Low Probability:** Preventive maintenance and monitoring. (e.g., structural health monitoring of the Khair Berth petroleum jetty piles).
- **Low Consequence / High Probability:** Routine maintenance. (e.g., repainting fender panels or minor pavement crack sealing in low-traffic yard areas).
- **Low Consequence / Low Probability:** Run-to-failure or deferred maintenance. (e.g., aesthetic degradation of secondary port buildings).

By implementing RBM, the SSPC can allocate its severely constrained financial resources to the civil assets whose failure would cause the most severe operational and economic disruptions.

7.3 Lifecycle Cost Analysis (LCCA) for Rehabilitation Projects

When capital is available for rehabilitation, civil engineering managers must use Lifecycle Cost Analysis (LCCA) to select the most economically viable design alternatives. LCCA evaluates all costs associated with a civil asset over its design life (typically 50 to 100 years for marine structures), discounted to present value.

For example, when rehabilitating a section of the Northern Berth quay wall, the management team might compare two options:

1. **Option A (Conventional):** Standard reinforced concrete patching with ordinary Portland cement (OPC). Low initial CAPEX, but high maintenance OPEX due to rapid chloride ingress and future spalling.
2. **Option B (High-Performance):** Patching with micro-silica blended concrete, applying a silane sealer to the surface, and installing impressed current cathodic protection (ICCP). High initial CAPEX, but negligible maintenance OPEX for 30 years.

Despite the SSPC's current financial constraints, LCCA will often demonstrate that Option B is more cost-effective in the long run. Civil engineering managers must use LCCA data to advocate for upfront capital investment from the government or international donors, proving that higher initial costs reduce the long-term burden on the national budget.

8. Digitalization and BIM in Civil Port Management

The SSPC report highlights significant investments in electronic management, including the STOWMAN system for vessel planning, the VBN network, and EDITA Xpress for customs. While these are excellent operational tools, civil engineering management requires a different suite of digital technologies focused on physical assets.

8.1 Building Information Modeling (BIM) for Facility Management

The transition from 2D CAD drawings to 3D/4D/5D Building Information Modeling (BIM) is essential for modern port civil management. A comprehensive BIM model of Port Sudan would integrate the as-built drawings of all quay walls, underground utilities (water, power, drainage), and pavement layers into a single, intelligent 3D environment.

For the civil engineering management team, a BIM model allows for:

- **Clash Detection:** Identifying conflicts between new infrastructure projects and existing underground utilities before excavation begins, preventing costly construction delays.
- **Asset Tagging:** Embedding maintenance history, material specifications, and design load capacities into the digital model. When a maintenance crew is dispatched to repair a fender, they can access the BIM model on a tablet to view the exact structural details and previous repair history of that specific quay wall segment.
- **4D Scheduling:** Linking the 3D model to the construction schedule to visualize and manage the phasing of complex rehabilitation projects without disrupting port operations.

8.2 Structural Health Monitoring (SHM) and Digital Twins

To manage the structural integrity of critical assets like the deep-water Green Berth and the Khair petroleum jetty, the SSPC should implement Structural Health Monitoring (SHM) systems. SHM involves continuous, automated monitoring of the structure using a network of sensors:

- **Strain Gauges and Tiltmeters:** Installed on quay walls to monitor lateral deflection and bending moments, providing early warning of excessive earth pressures or structural overstress.
- **Corrosion Probes and Half-Cell Potentiometry:** Embedded in marine concrete to measure the rate of steel corrosion and the depth of the carbonation/chloride ingress front.
- **Scour Sensors:** Placed at the toe of quay walls and breakwaters to monitor the loss of seabed sediment due to wave action or vessel propeller wash.

The data from these sensors feeds into a **Digital Twin** of the port's civil infrastructure. A Digital Twin is a dynamic, virtual replica of the physical assets that update in real-time. Civil engineering managers can use Digital Twin to simulate scenarios, such as the structural response of the Southern Berth if a 70,000 DWT vessel berths during a severe storm, or to predict the remaining fatigue life of a crane rail beam. This shifts maintenance from a reactive, schedule-based approach to a truly predictive, condition-based paradigm.

8.3 Integrating SHM with Operational Systems

The true value of SHM is realized when it is integrated with the port's operational systems. For instance, if the SHM system detects that the lateral deflection of a specific quay wall segment at the Northern Berth is approaching its design limit, this data should automatically interface with the STOWMAN vessel planning system. STOWMAN would then automatically restrict the berth of vessels exceeding a certain DWT or draft at that specific segment, ensuring operational safety without requiring manual intervention. This integration of civil engineering data with operational logistics is the hallmark of a mature, smart port.

9. Strategic Framework for Civil Infrastructure Modernization

To ensure the long-term resilience, safety, and economic viability of the Sudanese port system, the SSPC must adopt a comprehensive strategic framework for civil infrastructure modernization. This framework is divided into four pillars: Structural Rehabilitation, Capacity Enhancement, Sustainable Engineering, and Hinterland Integration.

9.1 Pillar 1: Structural Rehabilitation and Durability Enhancement

The immediate priority for civil engineering management is to arrest the degradation of existing marine structures.

1. **Comprehensive Condition Assessment:** Commission an independent, international marine engineering consultancy to conduct a thorough condition survey of all quay walls, jetties, and breakwaters. This should utilize advanced non-destructive testing (NDT) techniques, such as ground-penetrating radar (GPR) for rebar location and cover depth, and ultrasonic pulse velocity for concrete integrity.
2. **Concrete Rehabilitation Program:** Implement a massive concrete repair program focusing on the splash and tidal zones. This must involve the removal of chloride-contaminated concrete, cleaning and treating the steel reinforcement, and patching with high-performance, polymer-modified mortars.
3. **Cathodic Protection (CP) Installation:** For critical structures like the Khair Berth and the deep-water sections of the Green Berth, install Impressed Current Cathodic Protection (ICCP) systems. ICCP is the most effective engineering solution for halting active corrosion in submerged and buried steel structures.

9.2 Pillar 2: Capacity Enhancement and Geotechnical Upgrades

To accommodate the trend toward larger vessels and heavier cargo, the physical capacity of the civil infrastructure must be enhanced.

1. **Quay Wall Upgrading:** For berths where the structural capacity is insufficient for modern cargo handling equipment, implement structural upgrading techniques. This may include the installation of rear tie-back anchors to reduce the bending moment on the quay wall, or the construction of a secondary relieving platform in front of the existing wall to absorb berthing impacts.
2. **Capital Dredging and Deepening:** Initiate a phased capital dredging program to deepen the Northern Berth from its current maximum of 10.7 meters to at least 13.5 meters. This will allow the berth to accommodate larger general cargo and container vessels, reducing the reliance on the Green Berth and improving overall port throughput. The dredging design must include the installation of new, deeper sheet piles or the underpinning of existing gravity walls.

3. **Fender and Bollard Replacement:** Upgrade the mooring and berthing systems across all ports. Replace aging rubber fenders with high-energy-absorption super cone fenders and install quick-release mooring hooks with load monitoring capabilities to comply with the latest OCIMF safety guidelines.

9.3 Pillar 3: Sustainable and Resilient Civil Engineering

Port infrastructure must be designed and managed to withstand the impacts of climate change and to minimize environmental degradation.

1. **Climate Change Adaptation:** Update the design criteria for all civil structures to account for projected sea-level rise and increased frequency of extreme weather events. This involves increasing the crest elevations of breakwaters and quay walls, and enhancing the drainage capacity of port yards to handle intense, localized rainfall events.
2. **Green Port Initiatives:** Implement "Building with Nature" (BwN) principles for shoreline protection. Instead of purely hard engineering solutions (rock armor), integrate ecological enhancements, such as creating artificial reef structures using eco-friendly concrete mixes that promote marine biodiversity.
3. **Sustainable Materials:** Mandate the use of sustainable materials in all new civil works. This includes the use of supplementary cementitious materials (like fly ash or ground granulated blast-furnace slag) in concrete mixes to reduce the carbon footprint and improve long-term durability against chloride ingress. Utilize recycled aggregates for base courses in pavement construction where structurally permissible.

9.4 Pillar 4: Hinterland Pavement and Multimodal Integration

The efficiency of the port is inextricably linked to the civil infrastructure of the hinterland transport network.

1. **Heavy-Duty Corridor Pavements:** The 1,200 km road corridor between Port Sudan and Khartoum bears the brunt of the 11.5 million tons of trade. The SSPC, in collaboration with the Ministry of Transport and international development banks, must advocate for and co-fund the upgrading of this corridor to heavy-duty, rigid concrete pavement standards. The current flexible pavements rapidly deteriorate under the axle loads of fully loaded bulk and container trucks, creating a bottleneck that causes massive congestion inside the port gates.
2. **Inland Dry Port Civil Works:** To alleviate yard congestion, the SSPC should lead the civil engineering design and construction of Inland Container Depots (ICDs) in Khartoum and other major logistics hubs. These dry ports require the same high-standard civil infrastructure as the seaport, including heavy-duty pavements, efficient drainage, and modern gate complexes, effectively extending the port's operational footprint inland.
3. **Railway Revitalization:** The civil rehabilitation of the railway line from Port Sudan to the interior is a critical national priority. Shifting the 2.8 million tons of cement and 2.8 million tons of wheat from road to rail requires the construction of modern rail-mounted gantry (RMG) crane foundations and specialized rail sidings within the port terminals. The civil design of these interfaces must ensure seamless transfer of cargo between ship, rail, and road.

10. Conclusion

The Sudanese Sea Ports Corporation manages a vital, yet highly stressed, portfolio of civil engineering infrastructure. This paper has demonstrated that the operational statistics of the SSPC—ranging from the handling of 11.5 million tons of trade to the berthing of 70,000 DWT vessels—translate directly into profound structural, geotechnical, and hydraulic demands on the physical assets of the ports.

The analysis reveals a critical divergence between the physical requirements of modern maritime logistics and the current state of civil infrastructure management. The aging quay walls, the extreme loading on port pavements from heavy bulk imports, and the continuous battle against siltation in the navigational channels require a sophisticated, proactive approach to civil engineering management. However, this imperative is severely complicated by the macroeconomic reality of declining real revenues, which threatens to trap the SSPC in a cycle of deferred maintenance and accelerated asset degradation.

To secure the future of the Sudanese maritime sector, civil engineering management must evolve. The adoption of Infrastructure Asset Management (IAM) principles, underpinned by Risk-Based Maintenance and Lifecycle Cost Analysis, is essential to optimize the allocation of constrained financial resources. Furthermore, the integration of digital technologies—specifically Building Information Modeling (BIM) and Structural Health Monitoring (SHM) via Digital Twins—will provide the visibility and predictive capabilities required to manage these assets safely and efficiently.

The strategic framework proposed in this paper provides a roadmap for the physical modernization of the SSPC's infrastructure. By prioritizing the structural rehabilitation of marine concrete, the deepening of navigational drafts, the implementation of sustainable engineering practices, and the critical integration of port assets with hinterland transport corridors, the SSPC can transform its civil infrastructure from a potential bottleneck into a resilient, competitive engine for national and regional economic growth. Ultimately, the success of the Sudanese ports in the Red Sea corridor will depend not just on the efficiency of their cranes and software, but on the structural integrity, durability, and strategic management of their foundational civil engineering assets.

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