Conference Proceedings

Development of a Secure Structural Component to Mitigate Environmental Contamination at Ports During the Transfer of Granular Materials in Global Maritime Logistics: Ecological Port Loading Bunker

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Abstract

This study focuses on the design and production of the 100-m³ "Ecological Port Loading Bunker," which has been built for the first time in our country. The objective is to address the environmental pollution issue stemming from bulk material logistics in ports, which serve as a nexus of the global supply chain in maritime trade, and to guarantee a secure transit procedure by reducing material waste. The research encompasses theoretical computations for the bunker situated near the port of Samsun; many engineering investigations were conducted, and design evaluations were executed utilizing the finite element approach in response to seismic impacts. FEM (Finite Element Method) analyses determined the ground bearing capacity, incorporating the seismic factor of the bunker's location. The seismic loads impacting the structure were assessed through displacement and *irregularity evaluations at the critical values of static and dynamic load combinations anticipated in the design. The study results were validated in accordance with the general steel design code ÇYTHYEDY 2018 (YDKT) [1] and the Turkish Building Earthquake Code (TBDY 2018) [2]. Improvements to the ecological port loading bunker design were implemented based on conclusions and theoretical validations derived from the results, leading to the establishment of a secure structural component inside the port. The undertaken work would enhance the 'Green Port Project for Turkish Ports' established by the Ministry of Transport and Infrastructure of the Republic of Turkey, as it encompasses measures designed to mitigate the adverse environmental effects of ports. The system devised in the study is wholly domestically manufactured and will diminish environmental pollution from dusting by a minimum of 85%, establish eco-friendly transmission zones in ports, and, due to its recovery capability, reclaim approximately 75% of material losses during loading. It exemplifies a solution in addressing environmental and climatic issues within the context of the European Green Deal, which delineates the European Union's objectives for implementing sustainable economic strategies globally.*

Key: Port Bunker, Finite elements, Port Operations, Green Port, European Green Deal

1. Introduction

The global maritime transport market retains growth potential amid economic recovery and increasing demand, however it remains vulnerable to environmental issues. Research aimed at mitigating the environmental impact of maritime trade has revealed that minerals such as coal, iron ore, nickel ore, and phosphate, often transported in powdered and granular forms by sea, are held in bulk at ports throughout transit. These products cause environmental pollution, damage to the natural life cycle of living creatures in the immediate vicinity, and negative effects on ecological resources in the surrounding area by producing large amounts of dust under the influence of wind or during transport. . Air pollution is the foremost environmental issue in ports (ESPO, 2016b)[3]. To reduce the environmental issues arising from ports, specific communities have been formed, and international treaties and environmental regulations have been enacted. Furthermore, the 'Green Port' concept has been established to enhance environmental consciousness [4]. A green port integrates ecologically sustainable methods into port activities and operations, ensuring their efficient utilization. These methods seek to reduce the adverse environmental impacts associated with ports [5].

Numerous studies are being conducted to urgently solve the pollution that has become a serious problem in ports today. Recently, sustainable environmental policies have gained prominence, especially in the context of the European Union's 'European Green Deal.' Effective and sustainable port management has become crucial for ecologically responsible operations. The sustainability-focused transformation in the global maritime sector requires Turkey to invest in environmentally friendly elements in port equipment. Turkey's susceptibility to earthquakes renders safety a critical consideration in investments for sustainable logistics. This initiative has the capacity to modernize Turkey's ports, enhance its international competitiveness, and strengthen the nation's position in global trade.

A review of national and international publications reveals that Yorulmaz et al. [4] emphasised the environmental impacts caused by operations in ports, which are a crucial link in international freight transport, and the need to promote the concept of sustainable green ports to minimise these impacts. In their work, Korucuk and Memiş (2019) aimed to determine and prioritise the performance factors of green port-certified businesses operating in Istanbul using the DEMATEL method [6]. The DEMATEL method was used in the study due to its ability to explain the complex interconnections between criteria and synthesise expert perspectives. The opinions of 13 experts were taken into account in the study, and the most important criteria were determined to be 'Sustainable Environmental Management,' 'Minimum Pollution,' and 'Minimisation of Waste.'

Çağlar et al. [7] stated that many concepts related to efficiency and productivity within port performance, such as infrastructure, equipment, and cargo traffic, are included in the subject, and that efficiency and productivity analyses in ports play an important role in competitiveness and sustainability. They emphasised the need for better port planning and greater efficiency in the use of port equipment with the help of analyses.

Keser et al. [8] presented research and findings on reducing carbon emissions in maritime transport to combat climate change and environmental pollution issues under the European Green Deal. Danışman et al. [9] examined the E-RTG conversion project carried out at Marlport Port Operations and pointed out that the investment made to reduce the carbon footprint was recouped in about three years, along with energy savings.

While supporting the concept of ‘Green Ports’ in the study, the importance of the developed structure's resilience to external impacts such as natural disasters was also considered in terms of both port safety and sustainable logistics. Therefore, the designed ecological port bunker structure analyses were based on dead load, live load, wind loads in the x and y directions, as well as vertical earthquake (Ez(G)) and earthquake loads in the x and y directions. The design analyses were performed using the ideCAD programme.

In the context of port design, Mısır et al. [10] investigated the lateral loads that are generated by wind and wave loads, as well as those that occur during ship berthing and mooring. They employed Plaxis 3D finite element software to simulate the actual lateral load-displacement behavior. The pile lateral load-displacement behavior observed in the loading test was accurately represented by the analyses. A study was conducted by Yılmaz [11] to estimate the wind, Coriolis force, wave, tidal, and density-driven currents in the coastal region of Samsun Bay. He validated the results with physical parameters and measurements and employed the HYDROTAM-3D three-dimensional numerical model for hydrodynamic, turbulence, and transport.

Eroğlu et al. [12] modelled the structure using the ideCAD programme and examined the soil interaction. They investigated the resistance characteristics of different foundation types, such as individual foundations, continuous foundations, and raft foundations, as well as the soil bearing capacity. As a result of their work, they determined that raft foundations are a more suitable foundation system in terms of design because they distribute the building load over a wider area.

Bozer's [13] study calculated and compared the short-period design spectral acceleration coefficient and the design spectral acceleration coefficient values for a 1-second period according to DBYBHY 2007 and TBDY 2018. The calculated results were mapped onto a visual representation of Turkey. A 175% or greater rise was seen in the computed ZE ground class values for ten provincial centers. Azimi et al. [14] evaluated the expenses associated with pre-designed structures versus reinforced concrete load-bearing systems, utilizing ground amplification factors (DBYBHY2007) and design acceleration spectra from the Uniform Building Code (UBC97) and the Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10) standards. Estimates conducted under various regulations noted substantial cost escalations of 15 times or more. The cost escalation approximated 33% for Z4 in 15-floor buildings and roughly 27% for E and SE. Karayer et al. [15] used Idea Statica to analyze the connections between the columns and beams in the structure.

Upon examination of national and international patents in the research, it was observed that patent [16] pertains to an unmanned grain loading system and control technique utilizing a port hopper. This invention utilizes multi-sensor management and processing strategies to boost operational efficiency and digitalization. The patent [17] pertains to a method and apparatus for loading bulk materials into mobile containers. The objective is to ascertain the dimensions of the container with a laser scanner to guarantee uniform loading and to predefine the unloading protocol.

The patent [18] pertains to the mechanization of loading activities. It comprises a dosing apparatus, funnel, and conveyor feeding system for the loading of diverse bulk, granular, and lumpy materials. The patent [19] pertains to a system for the loading and unloading of recyclable powder. The system comprises a silo, a powder sieve, a primary discharge channel, a powder transport conveyor, and much powder collection equipment. The patent [20] features a moveable, double-opening discharge hopper equipped with weighing capabilities. This design addresses the issues of releasing material from a stationary location into a loading truck or the vehicle undergoing a second weighing. The utility model [21] pertains to the technical domain of loading stored bulk grains, specifically an intelligent loading system for bulk grains stored at ports, comprising a storage silo, a discharge apparatus, a dust extraction system, a discharge monitoring device, and a primary control server.

This study introduces an ecological port loading bunker with a volume of 100 m³, elevated on a steel structure approximately 5 m above ground, supported by four pairs of wheels at the base, and equipped with installable dust extraction devices (Figure 1). To account for the influence of wind speed and direction on the material during the crane's discharge of granular substances, wind walls of 2068 mm in height were constructed on all four sides of the bunker model. A discharge conveyor is positioned in a line at the bottom for the expulsion of bulk material. A grid has been built at the top to which flex flaps are affixed. A slanted closing mechanism (Flex-Flap) is implemented to inhibit the escape of dust generated by the pile dropping into the bunker (Figure 2). This system has angled closure mechanisms that activate under the weight of the released material. These mechanisms may consist of rubber or steel, contingent upon the material's density, kind, and abrasiveness. The Flex-Flaps facilitate external air flow into the hopper via the center opening, thereby inhibiting dust recirculation. The angled closure mechanism traps the poured product within the bunker using Hardox and St37 material plates. The Hardox plates, configured with a 30° discharge angle, are stationary, but the St 37 plates are engineered to open and close, with an aperture of up to 150 mm. This machine offers a throughput capacity of 1000 tons per second.

The finalized "Ecological Port Loading Bunker," commercially referred to as "eco hopper," was registered in 2024 [refer to registration no: 2024 006144], installed at the Samsun Tekkeköy port, and commenced operations (Figure 3).

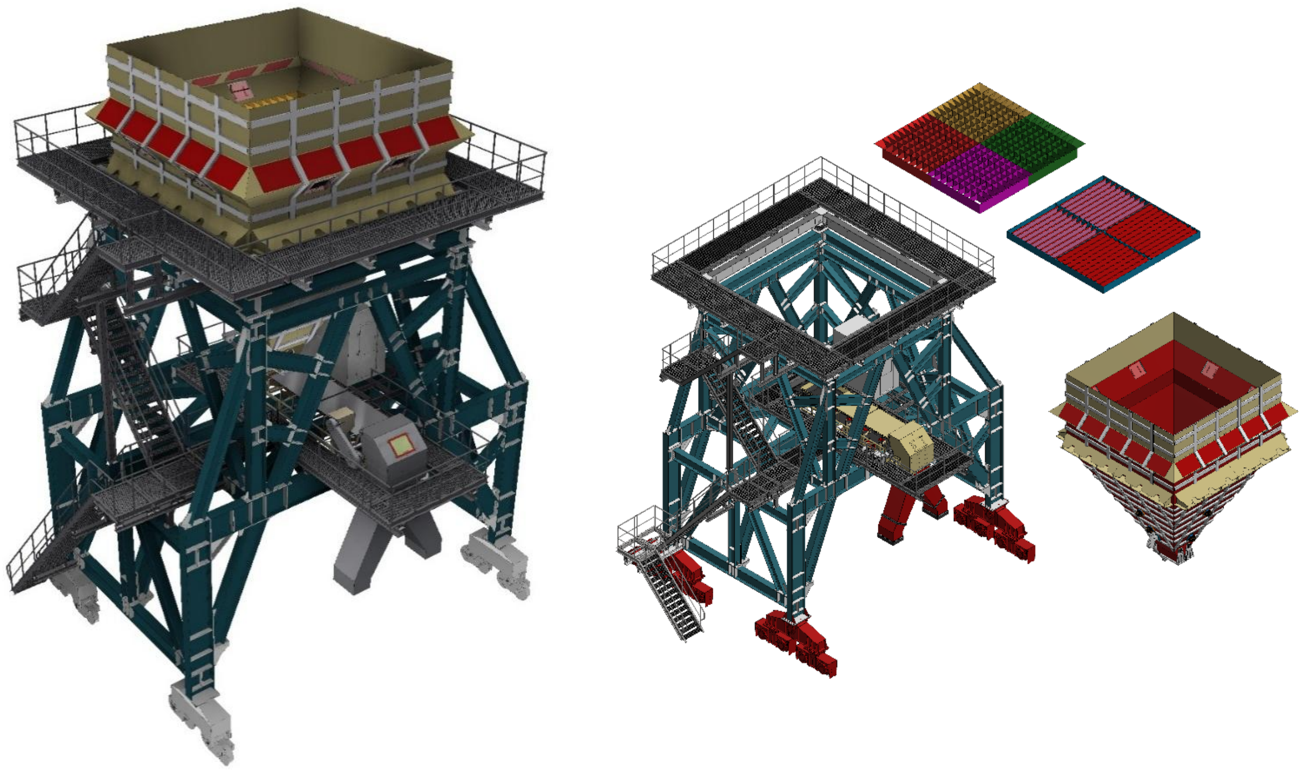

Figure 1: Ecological Port Loading Bunker 3D Design

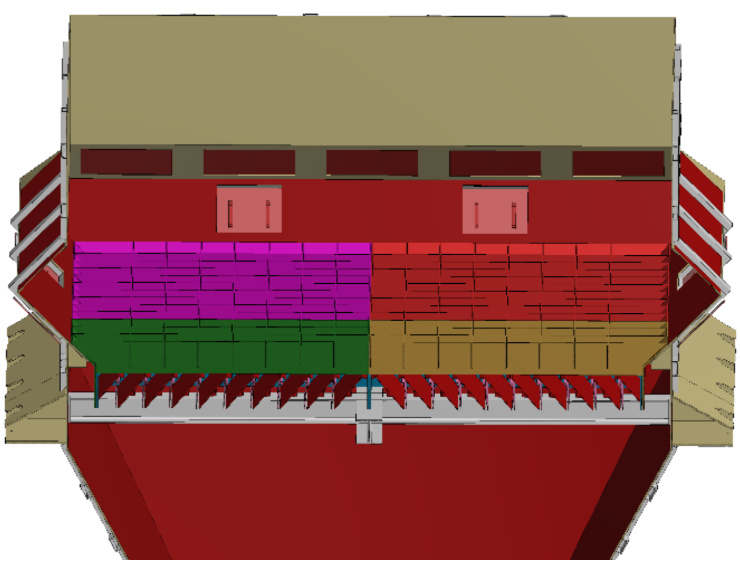

Figure 2: Flex-Flap Design

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Figure 3: Ecological Port Loading Bunker

2. Materials and Methods

This study conducted an earthquake load analysis utilizing ideCAD finite element analysis software to assess the performance of the environmentally built port loading bunker under seismic effects. Appropriate earthquake load calculations were conducted, considering the seismic potential of the area, the design spectrum, and local geological circumstances.

2.1 General Structural Information

The ecological port loading bunker structure analyzed is a 100 m³ bunker supported by a steel frame roughly 5 m above ground level, featuring a frame composed of grating and Flex-Flax at the entrance of the internal chamber. Table 1 presents the design specifications of the ecological port loading bunker. The utilized steel grades are St37 and St44.

Table 1. Ecological Port Loading Bunker Design Parameters

Building Geometric Information	
Number Of Floors	1
Structure Height	11.56 (m)
The Height of the Structure Above the Rigid Basement	11.56 (m)
Rigid Basement Floor	0
Rigid Basement Floor Number	-1
Maximum Floor Height	11.56 (m)
Maximum Beam Clearance	0 (m)
Planned Use	
Number of Rigid Diaphragms	0

The comprehensive analysis of the system delineates the loads impacting it and the possible combinations of these loads, as illustrated in Table 2.

Table 2. Loads and possible combinations

Loading and Combination	
G	Constant load
Q	Moving load
G'	Constant load (Effective section stiffnesses used)
Q'	Moving load (Effective section stiffnesses used)
Ez(G)	Vertical earthquake
WX(+)	Wind loading in X direction
WX(-)	Wind loading in X direction
WY(+)	Wind loading in Y direction
WY(-)	Wind loading in Y direction
Ex	X yönünde dıs merkezlikli deprem yüklemesi
Ey	Y yönünde dıs merkezlikli deprem yüklemesi

2.1 Determination of analysis parameters according to TBDY 2018

The design analysis was carried out in accordance with the General Steel Design Regulations (ÇYTHYEDY 2018 (YDKT)) [1] and the Turkish Building Earthquake Regulations (TBDY 20218) [2]. The general design criteria are given in Table 3.

Table 3 General Design Criteria

General Design Criteria	
Regulation Of The Design Of The Steel Used	ÇYTHYEDY (YDKT)
Earthquake Regulation	TBYD 2018
The analysis Method Used	Linear Static Analysis
The level Of Countinuty	High Ductility
Strength Factor (θ)	0.90

<u>Soil Characteristics</u>

The local geological conditions are the primary determinant influencing the measured seismic intensity. Diverse soil classifications induce amplification over varying time spans within the seismic response spectrum. When the natural period of structures approaches this amplification range, structural damage may escalate considerably. Consequently, local subsurface conditions are crucial in ground motion assessments and the construction of earthquake-resistant structures.

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Establishing an earthquake acceleration spectrum suitable for local ground conditions is the most often utilized input parameter in dynamic structural assessments [9].

Turkey possesses a significant seismic hazard. Consequently, in evaluating the design of the ecological port bunker proposed for Samsun, the Turkish Building Earthquake Regulation (2018) and the Turkish Earthquake Hazard Maps were considered. The earthquake ground motion surface was designated as DD-2 in accordance with the map. The soil investigation conducted at the bunker site identified the soil type as ZE (loose sand, gravel, or soft-solid clay layers). The building use classification was designated as 3, and the building precaution coefficient (I) was set at 1.0.

Soil effects and the computation of SDs (short-period spectral acceleration coefficient) and SD1 (design spectral acceleration coefficient for a 1.0-second period) were conducted in accordance with Equation 1 (Table 3).

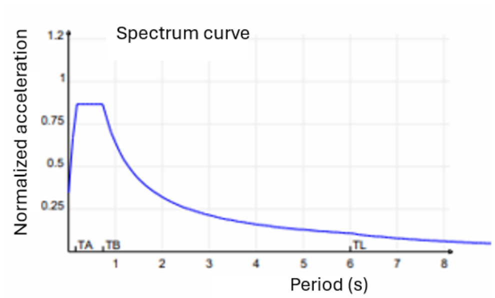
$$SDs = Ss \times Fs$$
$$SD1 = S1 \times F1 \qquad (1)$$

In this equation;
Ss : Short-period map spectral acceleration coefficient,
Fs: Short-period local site effect coefficient,
S1 : Map spectral acceleration coefficient for 1 second period,
F1 is the local site effect coefficient for 1 second period.

As a result of the ground investigations, the ground bearing capacity was calculated as 41,187.93 DaN/m^2 (42000 kgf/m^2). The spectrum curve in the designated soil type is given in Table-4.

"Table 4. Layer Parameters"

Ground Parameters	
Soil type	ZE
Spectral Characteristic Periods	Ta : 0.147, Tb : 0.737
Soil bearing capacity	42000.00 [kgf/m²]
Modulus Of Subgrade Reaction	2500000.00 [kgf/m³]
Earthquake Ground Motion Level	DD-2
Short period Map Spectral Acceleration Coefficient (Ss)	0.519
Map Spectral Acceleration Coefficient for 1-Second Period (S1)	0.187
Short Period Local Site Effect Coefficient (Fs)	1.6696
Local Site Effect Coefficient for 1-Second Period (F1)	3.417
Short Period Design Spectral Acceleration Coefficient (SDs)	0.866522
Design Spectral Acceleration Coefficient for 1.0-Second Period (SD1)	0.638979
Maximum Ground Acceleration (g) (PGA)	0.221
Maximum Ground Velocity (PGV)	15.764



St 44-St 37 has been designated as the material for the bunker structure and additional steel components. During design verification, it was established that the structure was adequately designed when the PMM ratio (the ratio of the capacity demanded by a structural element to the readily available capacity of the cross-section) remained below 0.9 for the most critical load combinations of axial load and bending moments in alternative directions under its own weight (internal forces) (Figure 4).

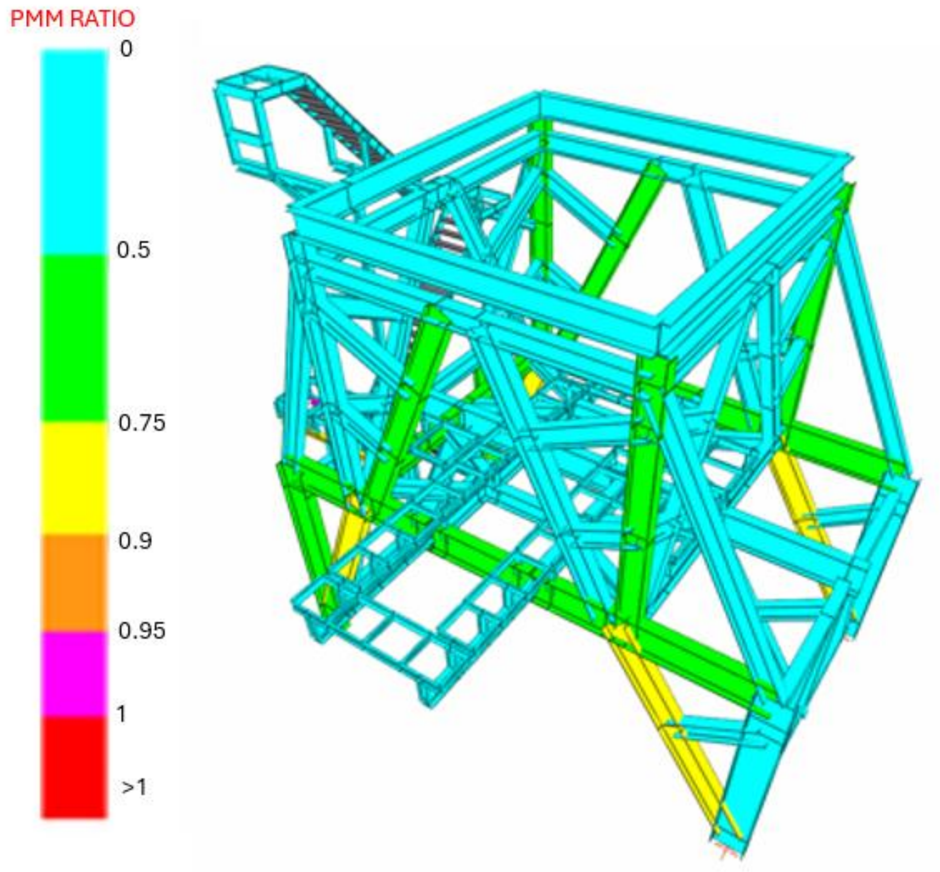


Figure 4: PMM ratios for the designed structure

The eccentric seismic stress in the X and Y directions has been included in the semi-rigid solution utilizing the ASCE/SEI 41-23 standard from the American Society of Civil Engineers. The structural analysis indicated that the cross-sections of all components of the ecological port bunker are satisfactory. The ductility level in the X and Y directions was found to be high.

The seismic performance of structures is assessed by verifying their compliance with the Turkish Building Seismic Code (TBDY 2018) standards. This assessment is termed the design's displacement and irregularity evaluations. The relative floor drift control assesses the extent to which the horizontal displacement of one floor in the design deviates from that of the floor underneath it. It is the variation in horizontal displacement between two adjacent floors. This value must remain within specified limits to avert excessive deformation of the building during an earthquake and to protect non-structural elements (such as construction additions). Relative narrative drift values were calculated for each floor in the X and Y directions, incorporating ± 5% additional eccentricity conditions. The calculated values for the column exhibiting the maximum displacement were compared and verified against the regulatory limit of 0.004. Irregularities that may arise in the structure due to seismic effects include A1-torsional irregularities, A2-slab discontinuities, A3-plan projections, B1-strength irregularities between adjacent floors (weak floor), B2-stiffness irregularities between adjacent floors (soft floor), and B3-discontinuities in the vertical elements of the load-bearing system, as detailed in Table 5.

Table 5. Displacement and Irregularity Checks

Displacement and Irregularity Controls		
TBYD 4.9.1 Limiting Relative Floor Offsets	Relative Floor Displacement Control is Provided in the x Direction	✓
	λδi(max)/hi = 0.0018 ≤ 0.004 – Ground Floor	
	A Relative Floor Displacement Has Been Provided in the Y Direction	✓
	λδi(max)/hi = 0.0014 ≤ 0.004 – Ground Floor	
	Determination of Relative Floor Shift Limits	
	No Flexible Joints or Connections, Fully Adjacent (4.9.1.3.a)	
Second-Order Effects	The Second Order Effects Condition is Provided on All Floors	✓
	ηi (max)/hi = 0.002 ≤ 0.048 – Ground Floor	
A1 Torsional Irregularity	A1 Irregularity Control in the X Direction is Provided on All Floors	✓
	ηi (max) = 0.00 ≤ 1.2 – ()	
	A1 Irregularity Control in the Y Direction is Provided on All Floors	✓
	ηi (max) = 0.00 ≤ 1.2 – ()	
A2 Slab Discontinuities	A2 Irregularity Control is Provided on All Floors	✓
Finding Outputs in the A3 Plan	A2 Irregularity Control is Provided on All Floors	✓
B1 Strength Irregularity Between Adjacent Floors (Weak Floor)	B1 Irregularity Control is Not Applicable in Single-Story Structures. TBDY 3.6.2.3	✓
B2 Rigidity Irregularity Between Adjacent Floors (Soft floor)	The B2 Irregularity Condition Has Been Met on All Floors in the X Direction	✓
	The B2 Irregularity Condition Has Been Met on All Floors in the Y Direction	✓
B3 Discontinuity of Vertical Elements of the Structural System	B3 Irregularity Control Has Been Provided on All Floors	✓

The seismic loads impacting the structure have been calculated for 45 modes. The overall mass of the structure was calculated as presented in Table 6, including the total seismic stresses that may arise in the X and Y directions with an additional eccentricity of ± 5%.

Table 6. Earthquake Loads Acting on the Structure

Calculation of Earthquake Loads Acting on the Structure	
Total Structure Mass	324,65t
	Live Load Coefficient = 0.3000
Total Earthquake Load (X-modal combination +5% and -5%)	Vt=40886.08 [kgf] – Dynamic Method
Total Earthquake Load (Y--modal combination +5% and -5%)	Vt=62623.43[kgf] – Dynamic Method
Structure Natural Vibration Period (X modal , +5%)	Ta=0.15 ≤ Tr=0.55 ≤ Tb=0.74 [s]
Structure Natural Vibration Period (X modal , -5%)	Ta=0.15 ≤ Tr=0.55 ≤ Tb=0.74 [s]
Structure Natural Vibration Period (Y modal, +5%)	Ta=0.15 ≤ Tr=0.55 ≤ Tb=0.74 [s]
Structure Natural Vibration Period (Y modal , -5%)	Ta=0.15 ≤ Tr=0.55 ≤ Tb=0.74 [s]
Spectral Coefficient	S(T) = 0.87
Number of Considered Modes	The Number of Considered Modes is Sufficient

3. Results

In mining, aggregates and ores; in agriculture, grains; and in construction, materials like cement and sand are transported in bulk by ship, thereby making the eco hopper (ecological bunker) a crucial instrument for port logistical operations. Its inventory management capability enhances logistical efficiency, promotes environmental sustainability with its dust extraction technology, and mitigates unnecessary material waste. The studies performed , including the seismicity factor, indicated that the building safety component complied with the Turkish Building Seismic Regulation (2018).

For the most significant load combinations influencing the design, the PMM ratio was observed to remain under 0.9. The relative floor displacement values in the X and Y directions were determined to be below 0.004 during the structural displacement and irregularity assessments. The elements A1-torsional irregularities, A2-slab discontinuities, and A3-projections in the plan have been determined to comply with TBDY (2018). The assessment of B1-inter-floor strength irregularity (weak floor) has not been conducted, as it is not relevant to single-floor constructions. Irregularities, including B2 - inter-floor stiffness irregularity (soft floor)—and B3 - discontinuity of vertical elements of the load-bearing system, were observed in all floors in the X and Y directions.

The conducted work has substantially advanced the principle of sustainable living, encompassing the European Green Deal and the EU's core objectives, including the conservation of natural resources by 2050, while incorporating a logistical component that mitigates environmental pollution and waste in ports.

4: Discussion

In the subsequent phase of the study, a dust extraction system will be integrated, which will utilize an air extraction mechanism to draw air from within the bunker. This system will purify the air volume displaced when it descends into the bulk bunker through a series of external jet-pulse filters. Initial preliminary tasks for this feature have been completed according to the project timeline. The project is amenable to additional expansion and serves as a foundation for future R&D initiatives. One of the developmental objectives to be executed post-project completion is the prevention of 85–90 percent of dust dispersion in a conventional bunker by the installation of a filter-assisted extraction system.

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