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Journées Méditerranéennes de l'AIPCN/PIANC Med days

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25 au 27 octobre 2023 à Sète (Occitanie)
25th until 27th of October 2023 in the city of
Sète (region Occitanie)

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Performance-based design of berthing/mooring dolphin structure considering geotechnical and structural constraints under offshore load conditions

A number of terminals have been extended through the use of berthing and/or mooring dolphins aligned with the existing berth structures. These dolphins allow larger ships to safely moor at the berth. They serve to counteract mooring loads from mooring lines and fenders, restrict the motion of the moored ship, increase the available fender contact length, and absorb part or all of the berthing energy, thus protecting the existing harbor structures. Regarding the design techniques for berthing dolphins, the yield limit has been approached more optimally over the years to make better use of the load-bearing capacity of the dolphins. The present study aims to provide a better understanding of the application of available design methods in engineering practice. This study is conducted within the context of the project assessing the reinforcement of existing harbor facilities and the extension of the “Mole Croisière” cruise berth in Ajaccio, France. The project involves the addition of a berthing dolphin structure located at the end of the existing berth. The optimal design of the dolphin structure was achieved using advanced numerical modeling techniques. These techniques were applied to the structural analysis of the dolphin-fender system, the interaction between the dolphin and the soil it is embedded in, and the fully dynamic mooring analysis. The mooring analysis was used to assess the mooring loads for several design ships under various wind, wave, and current conditions at the site. Several technical aspects were evaluated. The primary structural design challenge was related to the limited load-bearing capacity of the pile foundation at the seabed level, in a water depth ranging from 20 to 30 meters. The optimization of the dolphin structure design was carried out by employing rock-socketed foundation piles embedded in the seabed. Additionally, X-tie-braces were installed at the mid-height of the dolphin's piles to transform bending moments into axial forces (compression and tension exerted on the steel bracing system). A predetermined displacement for the dolphin was set, along with a desired fender performance, to achieve the desired energy absorption capacity of the quasi-flexible system.



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1. Introduction and aims

The berthing and mooring processes are vital operations in maritime and naval activities, necessitating high-capacity, functional, and secure infrastructures to meet current needs and address the growing demands of global maritime transport. As ship dimensions have continued to increase over time, specialized terminals and equipment have been developed to handle specific types of high-tonnage vessels, including containers, cruise ships, tankers, and roll-on/roll-off vessels. In most port terminals, traditional berthing and mooring methods involve the use of docks, wharfs, jetties, or piers equipped with fenders and bollards to facilitate the berthing maneuvers of vessels. However, existing berthing facilities often face challenges in accommodating large vessels due to constraints related to draft limitations and low structural load-bearing capacity. In response to this, alternative configurations can be designed, such as incorporating discontinuous berths or combining berths with dolphin structures to create a unified mooring and berthing line ([1], [2], [3]). A dolphin can serve as either an isolated marine structure or as part of a system, with multiple dolphins aligned or following the ship layout. Dolphin structures have the potential to function as additional protective hardpoints, aimed at increasing the berthing capacity of a port and redistributing the total applied ship-induced loads. Based on this concept, the Port of Ajaccio in Corsica is currently planning to extend their cruise berth, known as 'Môle Croisière,' by installing an additional berthing/mooring dolphin structure at the end of the existing berth. This project aims to achieve three primary goals: 1) To secure the berthing of large vessels by increasing the supporting surface through the construction of the dolphin; 2) To enhance the mooring capabilities of these vessels by adding additional mooring points, particularly through the installation of a 50-ton capacity mooring bollard and a capstan; 3) To reinforce the safety of passenger embarkation and disembarkation at the Cruise Terminal by ensuring a continuous flow between the Terminal and the water structures. This will be achieved, notably, through the construction of a bridge connecting the Terminal to the dolphin. The purpose of this paper is to present conceptual solutions and provide an overview of the conducted analyses.

1.1 Study area

Môle Croisière is situated on the south-western side of Ajaccio Port, France. The structure has a width of 20 m and is aligned at 106°N / 286°N. It consists of a solid blockwork wall stretching 60 m at the western end, while the eastern end features an open-piled quay that spans 188 m. The berth is elevated at +2.8 m. Adjacent to the eastern end of the berth, there are two mooring dolphins supported by piles, measuring 13.6 m in width and 6.4 m in depth, interconnected by walkways. Further to the east of the outer mooring dolphin, there is a mooring buoy connected to a sinker on the seabed via a chain and auxiliary buoy. The port basin is characterized by prominent granite-type rock formations. Figure 1 depicts the proposed structure's location, overlaid with bathymetry contours.

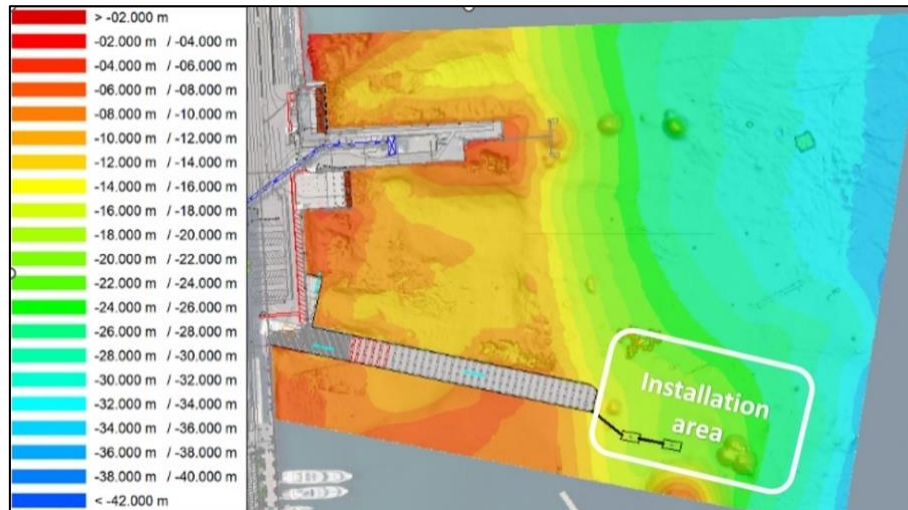


Figure 1 : Projected structure's location, superimposed with bathymetry contours.

The conception and construction of the dolphin had to fulfill numerous constraints and objectives, including minimizing environmental impact, facilitating access to the dolphin through auxiliary structures, ensuring construction and phasing feasibility, meeting structural design requirements, addressing geotechnical constraints, considering environmental factors such as wind and hydrodynamic loads, taking into account local depths and required draft. Additionally, the project aimed to enhance the port's capacity in terms of accommodating a greater number of vessels. Therefore, the location and altimetry of the dolphin needed to be adjusted to effectively cater to the widely varying principal dimensions and side door positions of each cruise ship.

1.2 Environmental conditions

ACTIMAR (2022) [4] showed that the prevailing winds on the west of Corsica are from the north-east, with occasional strong winds from the south-west. Stronger winds are most consistent during the winter months although instances of high winds can be observed at various times throughout the year. The maximum windspeeds documented was 15 m/s.

The prevailing wave conditions in Ajaccio can vary depending on the season and weather patterns. Generally, the region experiences calm to moderate wave conditions, with occasional larger swells during certain times of the year. ACTIMAR (2022) showed incident wave directions of approximately 125°N to 140°N, while significant wave heights can reach values of about 1.2m for the 10-year return period, associated with wave peak periods between 4 s to 15 s. The design site water levels (considering an adjustment for sea level rise) are shown in the Table below.

Parameter	Height above datum (m)
Highest Astronomical Tide Level	+0.7
Mean High Water	+0.47
Lowest Astronomical Tide	+0.21

Table 1 Water levels in Ajaccio, France (Shom, 2019).



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1.3 Soil characteristics

The nature and characteristics of the soil investigated through pressuremeter tests across the site are as follows: Greyish sandy silts were identified, reaching a depth ranging from -20.3 m to -23.7 m below the chart datum (mCD). Below the greyish sandy silts, granitic arenas followed by fractured granite were identified, extending to a depth between -21.6 m and -25.6 m below the chart datum (mCD). Additionally, geotechnical surveys revealed the presence of granite bedrock, which extends to a depth ranging from -26.6 m to -29.6 m below the chart datum (mCD). The geological material properties are presented in Table 2.

Geologic materials	Ménard Rheological coefficient (a)	Pressuremeter modulus (E_M)	Pressuremeter net limit creep pressure (pf^*)	Pressuremeter net limit pressure (pl^*)
Greyish sandy silts (-16,2 to -19,5 mCD)	0.33	1.8	0.22	0.30
Granitic arenas (-20,3 to -26,4 mCD)	0.66	184	3.00	3.00
Granite bedrock (-26.8 mCD)	0.50	600	5.00	5.00

Table 2 Soil properties obtained by pressuremeter tests.

2. Conceptual design

The proposed dolphin comprises a platform supported by 15 piles. Figure 2 offers a top view of the projected structures, showcasing the essential geometric characteristics and layout of the dolphin. Further details regarding the piles' geometry and foundation are depicted in Figure 3. For optimal support during mooring and berthing processes, the dolphin structure was meticulously designed with specific dimensions: a length of 20 meters and a width of 10 meters, with a platform elevation of +2.80 meters above datum. These measurements were carefully chosen to accommodate the needs of berthing 20 high-tonnage cruise ships effectively. The planned location for the dolphin is set to be 30 meters seaward from the end of the existing berth. To provide access to the structure, an auxiliary bridge was conceptualized.



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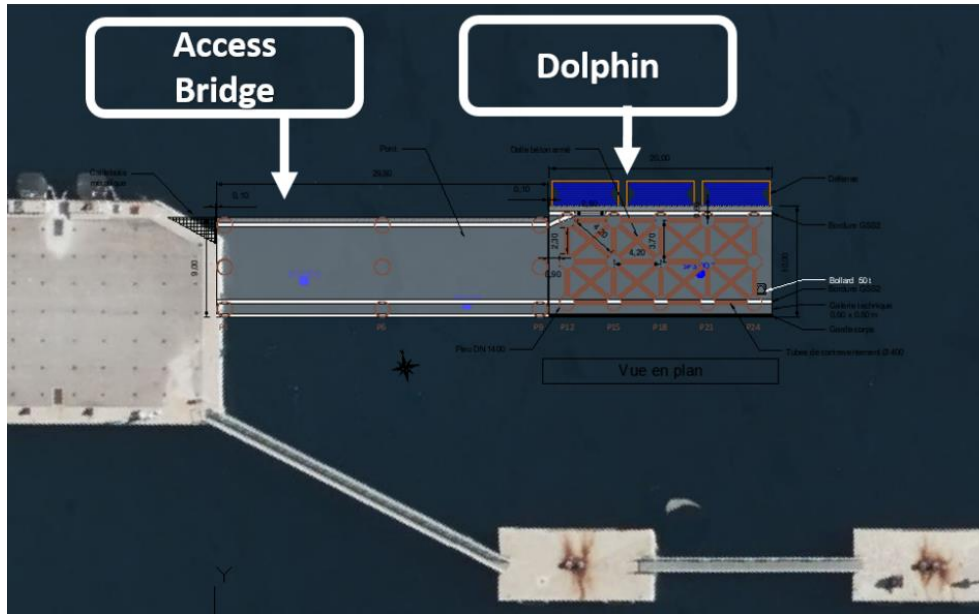


Figure 2 : Projected structure's location, superimposed with bathymetry contours.

To ensure the dolphin's optimal bearing capacity, a novel design was proposed and validated through comprehensive 3D numerical analyses, as described below. The construction of the dolphin will involve using tubular steel piles, with a diameter of 1400mm and a thickness ranging from 30 to 36mm. To address the specific site foundation and construction constraints, two distinct design schemes were meticulously chosen.

Under the first scheme, rock-socketed foundation piles will be utilized, filled with concrete along a 6-meter length, with 3 meters extending below and above the interface between the bedrock and the soft bottom (see Figure 3). To bolster stability further, X-tie-braces will be integrated at the mid-height of the dolphin's piles. This addition will effectively reduce displacements and mitigate bending moments along the piles, ensuring enhanced structural integrity. The superstructure comprises a concrete slab with a thickness of 2 meters.

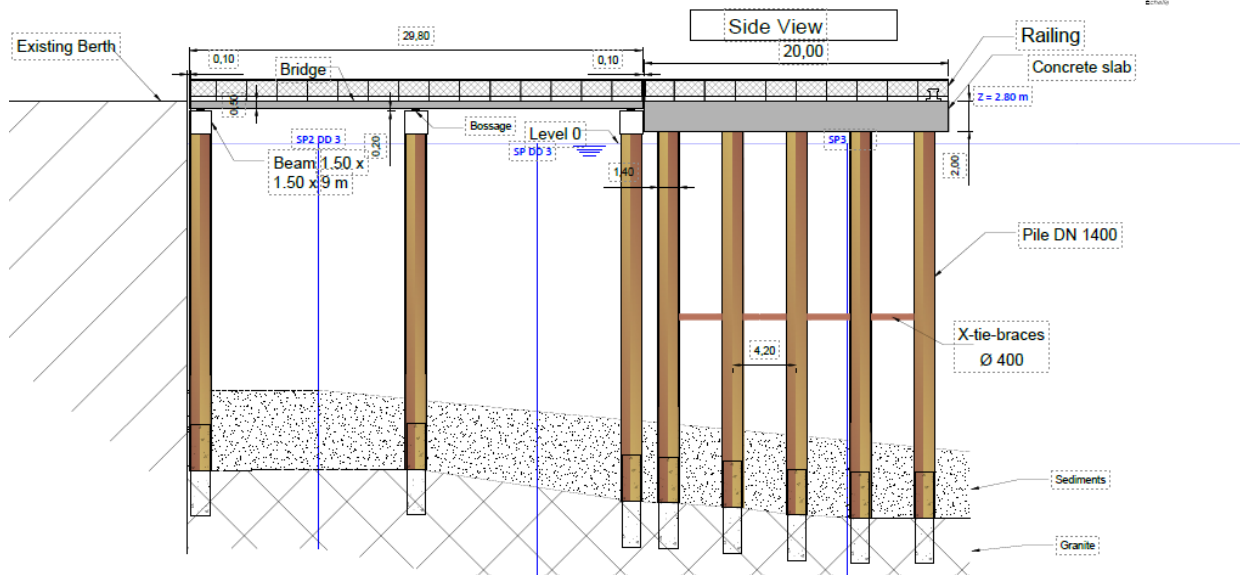


Figure 3 : Longitudinal section of bridge and dolphin structure.

Contrasting the first scheme, the second scheme involves incorporating a group of four micro-piles for each main pile. These micro-piles, measuring 250mm in diameter, will reinforce the main piles and allow for penetration into the rock layer. Each micro-pile will be drilled 3 meters into the bedrock while extending an additional 3 meters upward within the main pile (see Figure 4). Notably, for this configuration no tie-braces were considered. The advantages of this scheme lie in its ability to provide adequate support while minimizing additional components. Furthermore, a more flexible superstructure/platform was implemented to complement the overall design. The superstructure consists of a 300mm concrete slab supported by beams measuring 1.2 meters in width and 2.0 meters in height. This thoughtful configuration enables displacements in the head of the structure, which in turn significantly reduces bending moments in the toe of the piles.

3. Calculations and numerical simulations

The numerical analyses were conducted using Autodesk Robot Structural Analysis (FEM) Professional v2022 software [5]. The two distinct design schemes underwent analysis while considering various designed loads, including dead loads, live loads, berthing forces, mooring conditions, hydrodynamic forces, moving loads (a 60-ton truck crane was considered), thermal loads, and construction loads. Furthermore, the potential effects of corrosion were also taken into consideration. To model the elastic behavior of the soil surrounding the piles, we defined supports with horizontal elasticities corresponding to the specific soil properties.

The structural design was meticulously executed following Eurocode standards, carefully considering action safety factors and load combinations. Special care was taken to ensure that the load combinations used in the analysis accurately represented 'real' scenarios. For this purpose, we thoroughly assessed various load combinations to capture the most realistic conditions that the structure may encounter during its operational life. To exemplify, we intentionally avoided combining



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berthing and mooring loads simultaneously in the analysis. Consequently, a total of 83 load cases were thoughtfully considered to encompass a wide range of potential operational scenarios.

The berthing loads were calculated following the guidelines set forth by PIANC (2002) [6], taking into consideration no tug assistance. The design ship's characteristics used for this computation were as follows: length of 361m, width of 47m, height of 65m, and a displacement of 106,946 tons. The total berthing load was determined through the assessment of fender reaction resulting from the kinetic berthing energy, ultimately amounting to 4075 kilonewtons. This load stands as one of the most critical design parameters, as it encompasses the forces that the dolphin must withstand during berthing operations.

It is worth emphasizing that, in this conceptual design phase, we have intentionally chosen not to approach the structure's yield limit ([7], [8], [9]). This decision is driven by the understanding that the projected dolphin structure serves a multifunctional purpose beyond merely absorbing ship kinetic energy. In addition to that, it will be responsible for accommodating passengers, vehicles, trucks, and construction engines. Consequently, to ensure safe and efficient functioning, significant displacements, typically associated with high elastic structure's behavior, are not allowed. Thus, by maintaining structural rigidity and minimizing excessive deformations, we can guarantee the dolphin's ability to fulfill its various roles effectively and with enhanced reliability.

The results obtained from the 3D Finite Element Method (FEM) analysis for each geometrical configuration/scheme were compared to identify the most suitable solution that best aligns with the technical project constraints. Figures 4 and 5 illustrate the maximum calculated deflections in the two horizontal directions (U_x , U_y) at the top of the structure under a load case combining the effects of dead, live, berthing, and thermal loads.

Notably, the maximum computed deflections for scheme 2 are significantly higher ($U_{max} \sim 53$ cm), whereas scheme 1 exhibits much lower deflections ($U_{max} \sim 3$ cm). These numerical findings indicate that scheme 1 presents a more rigid structural system. This enhanced rigidity can be attributed to the X-tie braces, which effectively constrain lateral displacements, and the presence of a thicker superstructure with a width of 2 meters, effectively limiting deflections at the top.

Regarding the foundation solution for schemes 1 and 2, the implementation of a 4-micropile group (in scheme 2) was found to be inadequate in supporting the applied loads, which significantly exceeded the bearing capacity of the 250mm diameter micropiles. The micropiles' elastic critical moment ($M_{cr} \sim 190$ KNm) and plastic shear resistance ($V_{pLRd} \sim 1640$ KN) were lower than the corresponding maximum design bending moment ($M_{ed\ max} = 5530$ KNm) and shear force ($V_{ed\ max} = 7068$ kN).

In contrast, the 1220mm foundation rock-socketed piles of scheme 1, drilled into the granitic bedrock, are associated with higher values of resistance, an elastic critical moment M_{cr} of about 8390 KNm and a plastic shear resistance V_{pLRd} of 8111 KN, which are sufficient to withstand the design loads.

In conclusion, the geometrical configuration of scheme 1 offers superior structural stability and performance compared to scheme 2, meeting the project's technical requirements more effectively.

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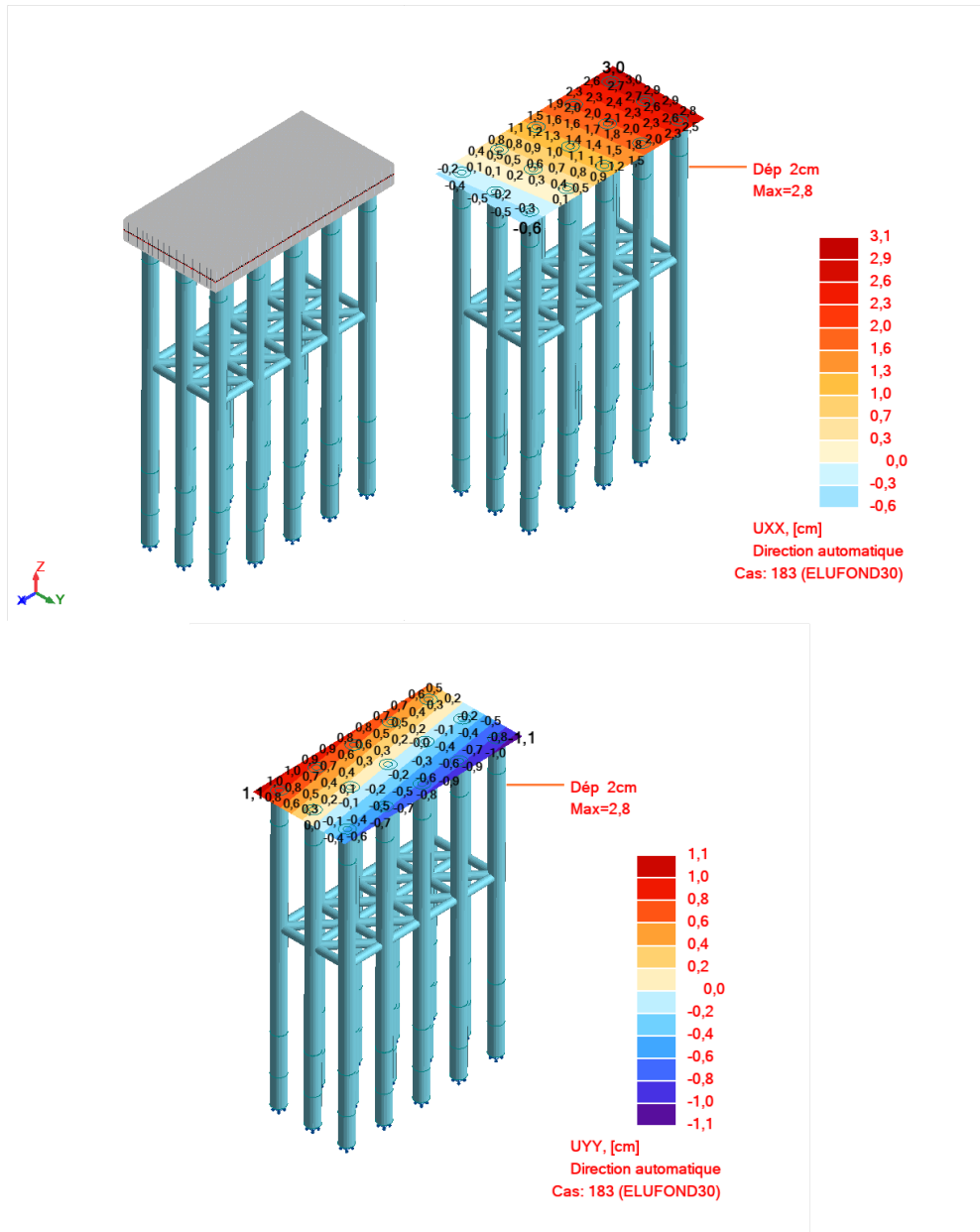


Figure 4 : Scheme 1- Initial unloaded state (up-right) and Maximum deflections at the top of breasting dolphin in x direction (up-left) and y direction (down).

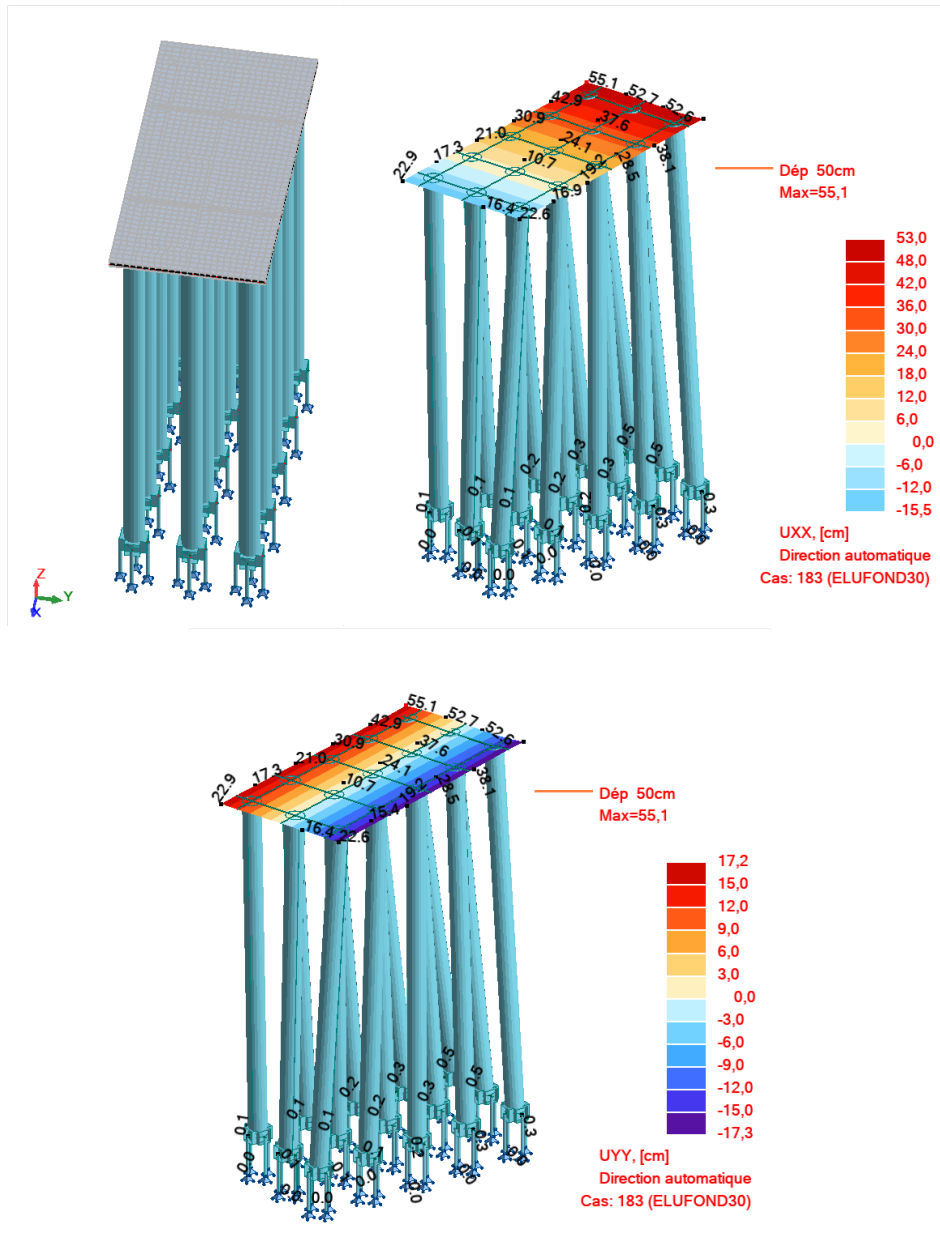


Figure 5 : Scheme 2- Initial unloaded state (up-right) and Maximum deflections at the top of breasting dolphin in x direction (up-left) and y direction (down).



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4. Conclusions and perspectives

In conclusion, the study underscores the critical significance of optimizing dolphin design to effectively meet the future berthing and mooring requirements. The environmental conditions in the study area, such as prevailing winds and wave patterns, were thoroughly considered to ensure the feasibility of the design. Extensive analyses of geotechnical constraints, soil characteristics, and foundation options were conducted to enhance the accuracy of the dolphin's performance while minimizing its environmental impact. The conceptual design of the dolphin involved a platform supported by 15 piles, and two carefully selected design schemes were subjected to detailed 3D numerical simulations for performance comparison. Scheme 1, incorporating rock-socketed foundation piles and X-tie-braces, exhibited superior structural stability and reduced deflections in comparison to scheme 2, making it the more suitable solution. The structural design adheres to Eurocode standards and takes into account various load combinations, ensuring the dolphin's efficiency without approaching yield limits. These comprehensive analyses and findings contribute significantly to the successful design and implementation of the dolphin structure at the Port of Ajaccio, Corsica. For future research, additional schemes can be explored and implemented to further enhance the effectiveness of the dolphin's design and overall port capacity.

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