Monaco semi-floating dyke
A 352 metre long concrete caisson

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Summary

Built in a dry dock at Algesiras in Southern Spain, the massive 352m long and 163,000 tonne semi-floating dyke is the key element of the extension project of Condamine harbour at Monaco.

The highly pre-stressed reinforced concrete structure has a design life of 100 years. Upon completion in Algesiras, it has been towed up the Mediterranean sea to the Principality of Monaco where it has been attached to an abutment by means of a 770 tonne steel ball-joint system and, at the other end of the caisson, to mooring chains connected to piles driven into the seabed.

This exceptional project is a mix of building techniques, mechanical engineering, public and offshore works : it includes several world records and, particularly, the spectacular connection of the ball joint system to the land abutment which took place on 3rd September 2002.

1. The need : the extension of Condamine harbour

The Principality of Monaco has been always looking at the sea in its search for economic development and prosperity. Today, the completion of the extension of Condamine harbour will provide moorings for yachts and a berthing capacity for large-sized luxury cruise liners.

La Condamine harbour *before extension*

The goals of the project

The extension of Condamine harbour was decided to meet three main goals:

- to almost double the berthing capacity for yachting,
- to create a berthing area dedicated to luxury cruise liners up to 200 m,
- to effectively protect the harbour from the easterly waves. Indeed, when Condamine harbour was first constructed over a hundred years ago, the depth of the water in the bay was such that

engineers were not able to build a standard over-lapping jetty and counter-jetty system. As a result, the harbour was left open to the most frequent swells blowing in from the east.

The solution finally retained to meet the project goals presents several other interesting features including a car parking space, a large storage area for boats, a maritime terminal and a shopping mall.

The constraints

Although several successive projects for the extension of Condamine harbour had been in the pipeline for many years, the bathymetric and geotechnical conditions of the site were such that, technically speaking, the construction of a standard breakwater would have been very difficult :

- water depth is 55m at the end of the breakwater,
- the seabed is covered with a thick layer of mud and the quality of the underlying sediments only increases very slowly with depth.

Besides these natural constraints, the owner was also concerned about the protection of the marine and urban environments. This latter concern meant that it was essential that the construction works in Monaco be minimised.

2. The solution : a semi-floating dyke

As a result of all these constraints, a standard approach based on dumping of earthfill into the sea was totally out of the question. The project for the harbour extension, therefore, only got under way when the engineering division of the Principality (Services Techniques des Travaux Publics) came up with an entirely new and unprecedented technical solution known as the "**fixed-water wall**".

The idea is to block the upper layer of the water where one finds the bulk of the waves' energy by means of an obstacle designed specially to mobilise the inertia of the water located below.

It is this innovating "floating dyke" technique that was retained, making the extension project of Condamine harbour the first on site application of the "fixed water wall" patent.

The other advantage of the floating dyke principle is to resolve the geotechnical and environmental problems associated with the construction of a fixed berm or a structure erected on piles. In the present case, the wave forces applied along the dyke are transferred to an abutment seated on a sound seabed.

3. The project

Project basic requirements

During the course of the feasibility and basic engineering studies, the considerations aforementioned led to the development of a project consisting in the construction of the different components of the harbour extension outside the Principality, then towing them and setting them in place, limiting the works at Monaco to the preparation of the foundations and moorings.

The owner requested that the following specifications be taken into account for the design:

- Protection of the harbour: the transfer coefficient of the swell i.e. the relation between the height of the in-harbour swell and the height of the offshore swell had to be under 0.2. At Monaco, project swell heights are: Hs = 4.90m and Hmax = 7.90m.
- Design life of the structures: 100 years with no major maintenance.
- Safety of the structure against flooding ensured by partition of the dyke.

It should be noted that the choice of concrete as the construction material of the dyke is the result of the specified design life.

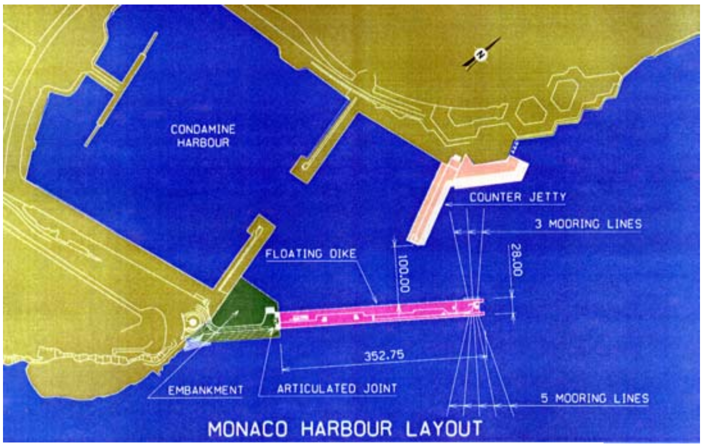
Existing references of off-shore works and particularly construction of floating oil production and storage barges (FPSOs) have paved the way for the construction of this large-sized floating prestressed concrete structure.

Overall description of the structures

Condamine harbour extension includes three distinctive parts :

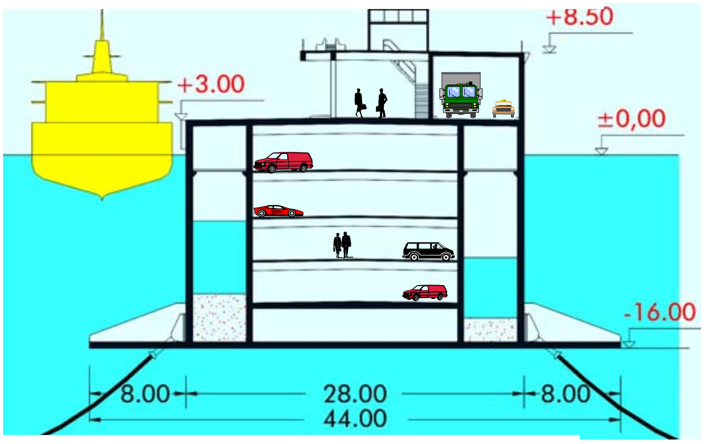
3.1.1. The dyke

Among the different pieces of the huge puzzle forming the extension project of the harbour, the semi-floating dyke looks like a massive, double wall, post-tensioned concrete ship shaped like a parallelepiped (352m long, 28m wide, with a total height of 19m and a draft of 16m). At its base (-16m), the box described above is fitted with two 8m wide horizontal fins designed to ensure both hydraulic efficiency ("*water wall*" effect) and hydrodynamic stability.



Overall description of the harbour project

The interior of the concrete floater is divided into two sections, one providing parking space for 360 cars on four different levels and the other, a 25 000 m^3 storage area for 6 to 14m long boats. Upon the main deck (3m above water level), superstructures include a lighthouse, a maritime terminal, shops and promenades. The onshore end of the dyke is attached to a land abutment by means of a ball-and socket joint allowing rotation in all three directions and designed to withstand a global shear force of about 10,000 tonnes in extreme conditions. At the other end, the movements of the structure are limited by a set of conventional mooring chains – 5 on the sea, 3 on the land side – linking the extremity of the dyke to piles driven into the seabed.



Cross section of the dyke

In the event of a severe earthquake, the dyke is designed to disconnect itself from the land abutment thanks to fusible bolts fitted on the axis of the socket-and-ball joint. The dyke would then be held in place by two emergency mooring chains fitted on either side of the shore end of the structure.

Basically the dyke consists of a 352m long "tube". In order to ensure the safety of the public who has access to the dyke (upper deck and inner compartments dedicated to car parking and boat storage space), the immersed part of the dyke includes a double hull structural system.

In order to rigidify the structure, the available annular space located between the two walls and the two base slabs is divided into compartments every 8m by way of U-shaped transversal diaphragms. Some of these diaphragms are watertight so that the structure remains stable even in the event of accidental flooding in two contiguous compartments.

In order to ensure an optimum longitudinal and transversal distribution of the masses which minimises the longitudinal bending moment under static loads, much of this annular space is occupied by liquid ballast (fresh water) and solid ballast (gravel). It should be noted that the ballast is installed once and for all and no further adjustments are required throughout the life of the structure.

The secondary structures (car park floors, staircases, superstructures) are dissociated from the dyke main structure. Considered solely as applied loads, they do not contribute to the structural resistance of the ensemble.

Main quantities of materials

Concrete volume: 44,000m^3

Reinforcing steel: 10,500 tonnes

Pre-stressing steel: 3,200 tonnes

Weight prior to ballasting: 130,00 tonnes. Total in service weight: 163,000 tonnes.

3.1.2. The land abutment

Serving as a transition between the floating dyke and the natural shoreline, the land abutment consists of four reinforced concrete caissons seated at depths ranging between 10 and 30m under sea level, on earthfill platforms that have undergone various sophisticated soil compaction and solid injection treatments. Amounting to approximately one hectare, the area outlined by these caissons has been designed for future property development.

Seated at a depth of 30m, the largest of these caissons (80m x 40m) is fitted with the support of the socket-and-ball joint system designed to attach the floating dyke to the shore.

The aim of the various soil treatments undertaken on the foundations was to perfectly control the earthfill settlements during construction and during the life of the structure. Achieving this goal was a prerequisite for a satisfactory behaviour of the socket and ball joint system.

3.1.3. The counter jetty

Enclosing the outer harbour, the counter jetty (145m long, 30m wide) looks like a pre-stressed concrete underwater bridge. It lies 9 metres under sea level on a land abutment and a double concrete pile connected to a caisson seated at - 40m.

4. The main contributors

Owner: Service des Travaux Publics de la Principauté de Monaco

Engineering and project management: DORIS Engineering

Certifying authority: Bureau Veritas.

The main civil construction works were divided into two contracts:

Contract n° 1 included the caissons and the earthworks for the land abutment and the counter jetty. The works were carried-out by a consortium of companies: Bouygues Offshore-Saipem (leader), Bouygues, GTM, Dumez and Impregilo. The caissons were constructed in a dry dock at La Ciotat up to a height of about 10 metres then, due to draft limitations, completed afloat either in La Ciotat or, in the case of the higher caissons, in Marseilles.

Executed by a consortium of companies: Bec (leader), Dragados, FCC, Triverio, SMMT, contract n° 2 included the construction and installation of the semi-floating dyke. The monolithic caisson was entirely constructed in a purpose built dry dock in Spain in the bay of Algesiras.

5. Design studies

Several somewhat unusual points were included in the basic engineering design studies carried out by DORIS. Among these :

- the hydrodynamic studies and basin model tests,
- the establishment of a specific set of rules in order to take into account the specified life design of this concrete structure in a marine environment,
- the development of a detailed finite element model.

Hydrodynamic studies

The hydrodynamic studies aimed at assessing the movements and the internal structural forces of this massive "ship" whose dimensions and mooring conditions were unusual.

These studies also enabled engineers to finalise the forces supported by the socket-and-ball joint system and to calculate the tensions in the mooring lines.

By testing a 1/60th scale model in the Oceanide tank at La Seyne-sur-Mer (France), engineers were able to calibrate the hydrodynamic calculations which could not directly integrate the effects of bathymetry.

The maximum overall first order movements of the dyke under waves action are as follows:

	100-year swell	1 - year swell
Swell Hs / Tpic	4.9 m / 12.0 s	2.8 m / 7.2 s
Roll	± 1.12 d°	± 0.20 d°
Heave (sea end)	± 1.81 m	± 0.11 m
Yaw (offshore end)	± 2.73 m	± 0.75 m

These theoretical values were satisfactorily compared with the values measured in April 2003 during a storm close to the 10-year conditions.

Durability, a major concern for the design of the structure

Project specifications required that the structure has a design life of 100 years in spite of its location in an aggressive marine environment where it has to remain watertight and stable in any event.

Durability, therefore, was a major concern throughout the designing stages of the project and when drafting the specifications.

In order to meet the demands of this long design life in a hostile environment, the standards and norms used for offshore constructions – Norwegian NS 3473design code – were combined with the usual standards (BAEL and BPEL) retained for civil works in France.

The following rules and dispositions were established in the domain of the engineering and design studies:

- replacement of the standard stress limit criteria in the reinforcing steels by crack opening limit criteria : basically, 0.2mm in tidal zones and 0.4mm in the other sections of the structure. Moreover, due to the watertightness requirements, the minimal height of compressed concrete is equal to the maximum of the two values – 0.25h and 100mm,
- systematic research of the most penalising stress combinations and of the most unfavourable state of pluri-axis stresses,
- thick concrete cover (55mm on the re-bars in walls in contact with sea water and 100mm for pre-stressing ducts),
- installation of a cathodic protection by sacrificial anodes, with electric continuity ensured of pre-stressing ducts,
- systematic fatigue calculations.

As regards to the construction of the structures, the following specifications can be noted:

- non-alcali reaction control for all concrete constituents,
- concrete compactness obtained by means of a ternary mix of hydraulic binders (cement, pouzzolanic materials, silica fumes) dosed at 425kg/m^3,
- limitation of mixing water W/C< 0.35 and use of superplastisizer,
- use of rigid pre-stressing steel ducts,
- careful treatment of casting joints : high pressure water jetting, systematic use of re-injectable FUKO joints,
- particular attention to the grouting of pre-stressing cables,
- no crossing bars allowed in the watertight walls to fix formworks.

Basic engineering calculation model

The general definition for the pre-stressing and reinforcement of the dyke was established by producing a finite element model of the structure in service conditions (excluding towing phase). Consisting of over 100,000 knots and 126 elementary load cases, this model, established at the basic engineering design stage, was sufficiently detailed to be used again at the time of the execution studies for the establishment of all statutory combinations and for all the justifications of the structure in operation.

6. Execution calculations

The dyke was designed and sized at the time of the basic engineering design study for 100-year service conditions. However, before being installed in its definitive configuration, the structure had to get through several temporary stages implying different stress conditions, namely:

- construction on the ground, in dry dock at Algesiras,
- setting afloat and exit from the dry dock,
- towing from Algesiras to Monaco and connecting of the ball joint system,
- completion at Monaco of the superstructures and ballasting operations.

For each of these different stages, the behaviour of the dyke, checking criteria and applied loads changed and were checked within the execution studies.

Methodology

A precise analysis of the pre-stressed concrete hull called upon the use of special calculation tools developed by SETEC TPI:

- A calculation program capable of analysing the overall functioning of a pre-stressed concrete structure constructed in different stages. The program was able to calculate the evolution of stresses in relation with the casting of the different elements, the shrinkage and creep of the concrete, tensioning of the pre-stressing cables and the setting afloat of the structure. The floating dyke is an extremely long and slender structure (L/H = 1/18.5). The variations of Archimedes thrust created by the deformation of the structure were taken into account at each of the above construction stages.
- A post processor of the finite element model calculation which analysed, point after point, the local behaviour of the pre-stressed concrete. This program can be used either for reinforcement area checking (in this case, reinforcement is an input data) or in an automated reinforcement calculation mode: the four passive reinforcement layers, in this case, are established so as to meet the different limit conditions specifications (SLS or ULS).

Weight distribution in the floating structure : a permanent concern

The equilibrium of a floating structure depends on the action of two types forces:

- the action of permanent loads and ballast weight,
- the action of hydrostatic pressure.

When these two forces are perfectly balanced, in each individual section, the floating structure remains flat and is not submitted to internal stresses. In the present case of the floating dyke, due to its architecture, the permanent weight distribution is irregular. In addition, possible ballasting adjustment is limited. A perfect balance, section by section, is therefore not possible, resulting in bending moments under permanent loads.

Main dispositions

6.1.1. Passive reinforcement

The mean rate of passive reinforcement averaged 238 kg/m^3 but, in certain sections, reached 400 kg/m^3. The combination of this re-bar and pre-stressing cables density left very little tolerance for placing them within the thickness of the walls.

Spacing of the passive reinforcement was limited to 150 mm for crack width limitations in order to reduce the diameter of the passive reinforcements as much as possible.

In all the critical areas, extremely detailed studies on the placing of reinforcement steel were undertaken, particularly at wall crossings.

Due to the amount of pre-stressing steel in the lower longitudinal walls (31T15), to the large number of vertical U-shaped cables (12T15) and to the sections of the passive steel (layers of 32mm diameter bars), some walls were thickened.

6.1.2. Active pre-stressing reinforcements

BBR pre-stressing system was used for the construction of the dyke. The structure is pre-stressed in three directions: longitudinally, transversally by means of horizontal cables and vertically by means of U-shaped cables.

Due to the alternate swell forces to which the structure is submitted, longitudinal prestressing was more or less centred. Mean longitudinal pre-stressing compression attained 13MPa while mean transversal pre-stressing was about 2 MPa.

The overall rate of active reinforcement is 74kg/m^3, a ratio which corresponds to the fitting of 2,250 tonnes of longitudinal pre-stressing cables, 730 tonnes of transversal cables and 250 tonnes of vertical cables i.e. a total of 3,230 tonnes including 110 tonnes of Macalloy rods.

Interferences between longitudinal, transversal and vertical cables were such that, prior to any other detailed study, it became necessary, in order to avoid conflicts, to establish the overall position of the cables from the base slab up to the top slab.

Concerning the longitudinal cables, overlapping areas were designed in the three slabs and the four main walls to ensure that the cables were not too long and inefficient. In these overlapping areas, the density of the pre-stressing reinforcement was doubled which increased the problem of low placing tolerance already encountered in standard sections.

6.1.3. Socket-and-ball joint anchoring area

The junction area between the steel socket-and-ball-joint system and the dyke structure had to deal with the interface between the two designs: the concrete structure execution studies and the socket-and-ball joint studies. A specific element model was developed to establish interface strains.

The ball joint system is attached to the dyke through a 8.5m side concrete cube. The cube is highly strengthened by thick walls and slabs ranging from 80cm to 1m.

The main stresses resulting from the finite element calculations were analysed in direction and amplitude. Traction forces were used to establish the size of the required steels reinforcement.

Steel ratio in the cube was approximately 340kg/m3.

6.1.4. Studies completed in view of maritime transportation

The required solid and liquid ballast was established for the different maritime stages of the floating dyke, from setting afloat within the dry dock at Algesiras to the connection of the structure to the land abutment at Monaco. Ballast calculations were performed using a stick model of the dyke lying on hydroelastic supports by taking into account the weight of the dyke, section by section.

The effect of swell during towing was established by HYDRATEC. The purpose of the study was to establish the oscillatory movement amplitude and related internal stresses under extreme wave conditions the towing route (Hs = 6.70m, associated period = 12-14 seconds).

The studies were completed in three stages as follows:

- hydrodynamic study of the dyke behaviour in swell,
- assessment of the global forces in the ship shaped beam,
- calculation of local hydrodynamic pressures along the length of the dyke.

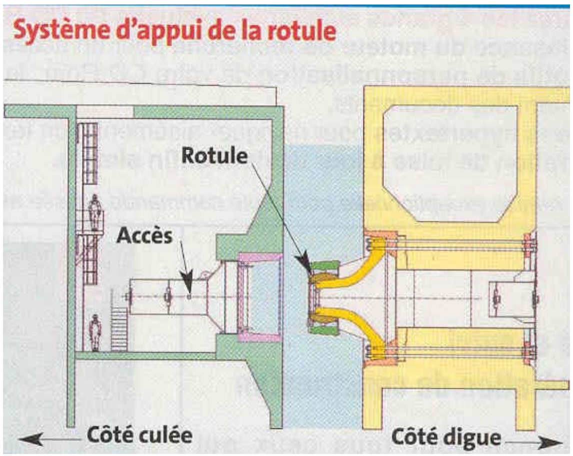
The results obtained from these calculations were then checked against basin model tests.

7. Construction and installation of the floating dyke

The exceptional features

7.1.1. The socket-and-ball joint system

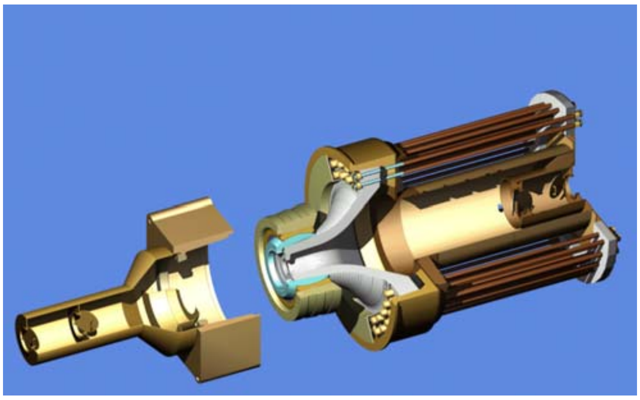
Attachment of the floating dyke to the land abutment is ensured by means of a support system allowing a rotational movement of up to 3° around a socket-and-ball joint. The socket-and-ball joint is a complex cast steel structure with a total weight of 770 tonnes. The axis of the socket-and-ball joint coincides with the longitudinal axis of the dyke. It is located at – 8,00 metres, a depth established on the basis of basin model tests and hydrodynamic calculations carried out within the basic engineering studies, to optimise the dyke motions**.**



Support system of the socket and ball joint

As such, the socket-and-ball joint consists of a spherical cast steel piece with a diameter of 2.60 metres. It is firmly attached to the floating dyke by means of a massive bell shaped support and to the land abutment by means of a large conical sleeve. Sliding surfaces are made of chrome carbide-nickel chrome coated steel / PTFE based composite material (SKF supply) with a friction coefficient of about 5%.

The socket-and-ball joint support is attached to the dyke concrete hull through a large-sized flange 7,30m in diameter, by 60 tensioned bars, 120mm in diameter.



The socket-and-ball joint system

Transportation of the « tulip »

On the shore side, a large cast steel box was set into the concrete of the abutment caisson. The box contains the cone-shaped female section of the support system into which the ball joint support was encased. The studies and the manufacturing of this steel part were completed in France by N.F.M. at their plant of Le Creusot, near Lyon.

7.1.2. The concrete

In line with the technical specifications of the project and, particularly, the 100-year design life of the structure in a marine environment (cf. 5.2), the utmost attention was given to the preparation of a high performance concrete for the construction of the dyke. Its specified characteristic strength was > 54MPa.

It was also necessary to ensure that the workability of the concrete was such that it could be pumped and poured on the work site within one hour after mixing, with very low bleeding and segregation.

The following mix was retained:

Cement + micro silica	425 kg/m^3	sand 0/2	341 kg/m^3
Water	148 kg/m^3	sand 0/5	497 kg/m^3
Super-plasticiter	6,4 kg/m^3	gravel 5/10	411 kg/m^3
Retarder	0,85 kg/m^3	gravel 10/16	617 kg/m^3

Note: A micro concrete mix following the same specifications but with aggregates measuring less than 10mm was used in areas of the structure where the reinforcement density was particularly high.

The cement used was a CEM II A-S 42.5 SR supplied by the Holcim group at Jerez de la Frontera. It consisted of 77.5% clinker, 11.3% slags, 5.2% plaster and 6.0% silica fumes. Amongst the numerous laboratory tests carried out on concrete samples taken from the batches, the permeability tests to chloride ions (AASHTO test) and oxygen and mercury porosity tests were performed in order to monitor the compactness of the concrete, a factor tightly linked to its durability.

In order to account for the exothermal process of concrete setting and considering the environmental and formwork conditions, the CESAR finite element calculation program designed by the French Laboratoire Central des Ponts et Chaussées (LCPC) was used to predict the thermal and mechanical evolution in the different sections of the structure. Numerous tests and checks were carried out on the different materials of the concrete mix and particular attention was given to the cement : resistance to compression (> 35 MPa at 7 days), start of setting > 60 minutes, volume stability < 5mm, fineness (Blaine test), grout fluidity time, sulfate content between 2 and 3% and micro-silica between 5 and 8%.

Concrete characteristics were checked by means of more than 10,000 cylindrical 16 x 32 cm test samples. Resistance to compression was measured at 7 and 28 days and indirect traction (Brasileño) was measured at 28 days. Mean values obtained were as follows:

- DIN table: 59cm at the batching plant, 56 cm at the pump
- Compression strength at 7 days: 60,0 MPa ; at 28 days: 76.9 MPa ; tension strength at 28 days: 5.54 MPa
- Permeability to chloride ions: 405 Coulombs
- Density : 2.445 kg/m^3

It emerged from these tests that the mean actual compression strength at 7days was higher than the value required at 28 days (54 MPa) by the Specifications. It is also worth noting some compression strength values exceeded 90MPa.

Construction of the floating concrete caisson in Spain

7.1.3. The dry dock

Subject to minor re-development works – including the sealing of a watertight wall and the excavation of a further 420 000 m^3, a dry dock which had been partially excavated in the 1970s in the bay of Algesiras provided the required 14.50m draft for the construction of the caisson in one single stage. The overall size of the dry dock was 380m x 75m which allowed for the installation of longitudinal crane lines and access ramps on either side of the structure.

The dry dock in Algesiras at the foot of Gibraltar rock

7.1.4. Work site installations

Two 2m^3 vertical axis retro-flux batching plants capable of producing 60m^3/hour each were installed on the site. Both plants were equipped with two 250 tonne cement silos and backed by two additional silos with a storage capacity of 500 tonnes each. In order to avoid excessive variations in water content of the mixes, a weather protected warehouse was constructed for the storage of the finer sands. Reinforcement production capacity was 600 tonnes/month split into two production areas, each one fitted with its own tower crane and equipped with all the necessary equipment required to manufacture the reinforcement.

The formwork workshop was equipped with its own carpentry, several storage and assembly areas for 33,000m^2 of formwork and associated equipments. The service of these different working areas was ensured by 8 tower cranes installed upon the bed of the dry dock with a capacity of 200 tm and a radius of 42m.

7.1.5. Temporary foundations

In addition to the standard function of carrying the weight of the structure without suffering any differential settlement, the foundation platform was required to meet two other major constraints:

- allow a sliding between the under side of the base slab and the foundation when the longitudinal pre-stressing was applied, so that the shortening of the dyke (forecast 17 cm) occurred gradually and not suddenly upon setting afloat of the structure;
- ensure a smooth lifting of the dyke from the foundation thanks to a satisfactory distribution of hydrostatic pressure on the under side of the base slab at the time of setting afloat and avoid the possible occurrence in places of suction problems.

The structure was therefore supported by means of 45 concrete cross-beams (one for each transversal wall) through two superimposed, grease coated, steel plates upon which the structure was actually in contact. For construction of the slab, a layer of sand was compacted between the cross-beams. Prior to the first pre-stressing phase, the sand and the formwork were removed laterally. After completion of these two operations, the dyke then rested solely on the 45 cross-beams, thereby easing its lifting from the foundation at the time of setting afloat.

The foundation platform

7.1.6. Construction stages

With the exception of the 16m long section bearing ball joint system, construction of the dyke was staggered into 48m long sections. Each of these blocks was completed according to the same sequence as follows:

Aerial view during construction

A staggered construction

The base slab was constructed first, followed by the first longitudinal walls, then the fins located on either side of the base slab, the ballast compartment walls and, lastly, the intermediate slab at elevation – 12m. After completion of this first stage of works, the longitudinal and transversal walls were constructed up to the top of the dyke in four 3.50m high lifts.

All intermediate floors for the car parking and boat storage areas were constructed by means of 191 pre-cast, pre-stressed, cross-beams resting on corbels and topped with pre-cast concrete slabs and cast-in-place slab, the interior elements such as lift shafts, staircases, air ducts, etc. being constructed simultaneously. The upper slab was concreted on formworks supported by scaffoldings. The superstructures (access tunnel, wave breaker, maritime terminal, etc.) were constructed upon completion of all the former operations.

Internal works

Encasement of the socket-and-ball joint

The ball joint system was mounted in several stages. The metal parts and the pre-stressing rods were set in concrete in successive phases. The 120 tonne flange was mounted when the construction of the caisson was already partially completed. The 450 tonne ball joint support itself was raised by hydraulic jacks supported by a large, specially erected granty.

7.1.7. Placing of the reinforcement and pre-stressing ducts

The specific constraints of the project had to be taken into account for the placing of the reinforcement : high ratio of passive and active reinforcement, strict respect of concrete cover, pre-determined wall thicknesses in order to respect planned weight distribution, appropriate sequencing of pre-stressing operations. As a consequence, placing tolerances were extremely tight.

The diameters of stirrups varied between 12 and 14 mm whereas the diameter of the other re-bars - FE 500 according to NFA 35-016- was between 25 and 40mm. Pre-stressing rigid ducts diameters ranged from 60 to 141mm.

Reinforcement details

In addition to the difficulty of fitting operations due to the high steel ratios, a large number of coupling sleeves were used (either to avoid bending re-bars at casting joints or to avoid overlappings in the very dense areas) and a large number of pins were also incorporated. Re-bars prefabrication was extensively used. In total, over 1,000 cages and 3,000 beams were constructed.

In the end section of the dyke where the ball joint system was to be attached, the re-bars and ducts were fitted entirely on site. Due to the complex disposition of the reinforcement and pre-stressing rods, a sequenced fitting plan was realised by means of 400 drawings. A total of 10,000 coupling sleeves was used in this zone.

Re-bars details in the ball joint system area ➤

Post-tensioning of the structure includes three main groups of cables:

- 1,834 units (12T15 to 31T15), 30 to 40m long, for the transversal prestressing. Phasing operations required that the difference of pre-stressing state in two contiguous compartments do not exceed 30%,
- vertical pre-stressing includes 705 units (6T15 to 31T15), 38m long. Tensioning was performed after completion of the upper slab, ensuring that pre-stressing difference between two contiguous compartments does not exceed 50%,
- longitudinal pre-stressing included 436 units (20T15 to 31T15), 100 to 258m long. Tensioning of the upper areas was performed after completion of the entire upper slab.

Pre-stressing production rate amounted to 650 tonnes/month.

7.1.8. Filling the dry dock and setting the dyke afloat

The dry dock was filled in two stages : first, to a height of 11m in order to check the hull's outer walls for leaks prior to floatation, an operation considered to be irreversible ; then to a height in line with water level outside the dry dock. At this stage the watertightness of the walls of the dyke was inspected again.

The earth closing berm of the dry dock was then opened and an 80m wide channel with a depth of 15m was dredged. This operation meant excavating 20,000m3 of earth by means of land equipment and dredging 80,000m3 including blasting 15,000m3.

Dredging of the canal

Four tugs were brought in to tow the dyke out of the dock. The dyke's course was maintained by means of 6 capstans, the biggest of which were equipped with a double 100 tonne tow drum. Before setting out to sea the dyke was berthed alongside an auxiliary pier in order to add a further 16,000m3 ballast of fresh water and bring the dyke down to a 15m draft as required for towing and navigation to Monaco.

Towing out of the dry dock

7.3. Installation of the anchor lines

The dyke's mooring lines consist of steel chains with links made of 95 or 152mm diameter rods. Each chain is connected to a pile driven into the seabed and, at the other end, to a fairlead attached to the dyke. The length of the offshore chains is 520m ; the lengths of the steel piles vary between 20 and 25m with a diameter of 72, 60 or 42 inches. Steel thicknesses vary between 38 and 63mm.

The 182m long crane ship driving piles inside the harbour

Installation works of the anchoring system were completed in two stages. In the first stage, the piles were driven into the seabed. The chains, which were already attached to the piles, were then positioned and pre-tensioned. The second stage was undertaken once the floating dyke had arrived in the harbour.

The chains were attached to the dyke and tensioned up to nominal values.

In order to drive the piles into the seabed, it was necessary to mobilise the crane ship Stanislav Yudin, 180m long, equipped with a crane having a load capacity of 2,500 tonnes at 35m. Using a pile extension socket so that the beating could be performed above water, the piles were then driven by means of a IHC S-500 hammer boasting a nominal energy of 500kJ.

7.4. Transportation and installation of the dyke in Monaco

Two open sea tugs were used to tow the dyke up the Mediterranean sea to Monaco. The larger of the two (75m long, 22,000bhp, 180 tonne pulling capacity) was used to actually tow the dyke whilst the smaller one (48m long, 14,000bhp, 120 tonne pulling capacity) served as an escort and watchdog, ready to intervene in the event of a breakdown of the main tug.

Whilst on tow the tug and the floating dyke formed a convoy of 1,100m which, when in transit, was too long to enter any port along the coast. However, a number of sheltered coastal areas were spotted along the route and sea routing assistance was used during the trip. The distance from

Algesiras to Monaco is 816 nautical miles, i.e. approximately 1,500 km. Towing of the floating dike took 12 days at an average daily speed of 3.02 knots.

Route from Algesiras to Monaco

Aerial view of the convoy

Movement and deformations were monitored by means of extensometers and servo-inclinometers in order to check that no damage was caused to the structure as a result of the towing and installation operations. The wave effects were recorded by static pressure sensors and hydrodynamic pressure measurements in the top deck. Ballast water levels were monitored in all twelve compartments. Transferred by radio to a computer installed aboard the escorting tug, the data was processed using a specific software and then relayed to land by way of Internet. In the event of a structural risk for the dyke, the convoy's route could have been changed to reach a sheltered zone.

Upon arrival of the convoy in Monaco, four tugs were used for the approach operations. After attaching and tensioning the anchor chains, the dyke was safely moored thanks to these chains and two extra capstan cables drawn from a barge moored outside the harbour. In this position, the dyke was located at approximately 10 to 15m from the land abutment. It was then a matter of waiting for extremely favourable weather and swell conditions before launching the manoeuvre whereby the structure would be connected to the land abutment.

Final position of the dyke prior to the installation manoeuvre

3rd Sept 02 – Connection of the dyke

In order to guide and prevent the slightest drifting of the dyke during this final operation, two large sized steel girders weighing 110 tonnes were placed laterally to control vertical movement and a third girder weighing 80 tonnes was placed in the centre to control horizontal movements. Vertical and horizontal movements of these two sets of girders linked to the floating dyke were, in fact, controlled by batteries of 500 tonne, 850mm stroke, hydraulic jacks located on the land abutment.
Connecting the dyke to the land abutment was a matter of getting one cone that was fixed to the dyke to coincide and penetrate a female cone built-in to the land abutment.

The positions of the dyke and the ball joint system were controlled by installing three fully motorised monitoring stations and a GPS reference station on the land abutment, two stations on the dyke, one at the bow, the other at the stern, and an accelerometer. With regard to the ball joint system, guidance apparatus included four video cameras and two sonar units. Two laser beams were also targeted on the cone-shaped recipient. Relative position data between the ball-joint system and the abutment recipient cone were transferred to a three-dimensional computing model allowing a surveillance of the relative positions and contacts between the parts. Admissible tolerance during the operation was +/- 2cm.

Using two 800 tonne winches, it took nine hours for the dyke to be pulled into place and reach its final location.

8. Future projects

With the completion of these works in which offshore oil and gas engineering methods were applied for the first time to environmentally respectful maritime structures, a doorway has been opened for the development of other urban development projects at sea.

With regard to the Principality of Monaco, studies for further land reclaims and development of the shoreline up to Larvotto beaches are currently underway.

In the longer term, it seems possible to envisage the construction in dry dock of entire areas of a town and, then, to tow and assemble them on site, according to a pre-established urban development plan.