APPLICATION OF INNOVATIVE METHODS FOR DESIGN AND CONSTRUCTION OF OFFSHORE STRUCTURES

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ABSTRACT

On-shore and off-shore maritime works are generally complex and demand from the designer a considerable expertise for the development of structural analysis, detailing and construction methods. In fact, in most cases the design of such structures shall take into account not only operational aspects, structural safety and ultimate limit states but also a sort of construction issues which can guarantee the feasibility of the work. In this way, this paper presents two cases in which design and construction methods are put together, mixing well-known methods and innovative elements and procedures. Both projects are located in the coast of Peru: the Melchorita LNG Terminal, with a solution using steel structures, used for export of natural gas, and the Callao Container Terminal, a concrete deck on steel piles solution. Relevant aspects of the project development are discussed and the construction methods are also presented for each case in order to highlight the challenges and adopted solutions.

Keywords: design, construction methods, structures, technology, innovation

1. INTRODUCTION

The modelling or conceiving of a civil structure is usually started with no major concerns regarding the construction methods, mainly because the construction techniques of usual buildings (using steel, concrete, or mixed systems) are well-known. Saying in other words, generally the construction methods are adapted following the structural project.

This aspect do not applies to special projects, like maritime structures - to cite one, subject of this paper. For the Project of such structures, specifically, the definition and earlier knowledge of the construction method has a huge impact – and an extremely important role – in the structural definition and detailing, even becoming sometimes a commercial advantage, once it brings also impact on the construction planning and schedule.

This last affirmation has it basis in the fact that the Project as a whole cannot take into account only the conceiving of a safe and operational structure, but also it may guarantee that the structure can be feasibly built, respecting the local conditions where it will be implanted and the construction planned schedule.

In terms of costs, this aspect also means that it is not always valid the usual idea which says that the best structure will be the cheapest one, the one which will spend less material. This is because structural optimizations can lead sometimes to the increase in construction costs due to the use of complex procedures, more expenses with equipments and excess of temporary or auxiliary structures, among others. One may note that this represents a paradigm in the Project development, since lighter structures are typically supposed to be better ones.

Based on the aforementioned context, two case studies are presented herein, related to the development of the Project. These Projects will be used, along this text, to show the interface between detailing and construction methods and to highlight relevant aspects of the structural modeling and design criteria.

Figure 1 shows the location of the two Projects, both in the coast of Peru, South America. The Melchorita LNG Terminal is located near to the city of Cañete, 170km to the south from the city of Lima. The Callao Container Terminal is located in the city of Lima.

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Both Projects are being built nowadays, in the final phase of construction, and both had used constructions techniques involving a steel wheeled platform applied to position and drive steel piles and to assemble the superstructure in conjunction with auxiliary cranes. This construction method and temporary structures, usually known as “Cantitravel”, is well-known. The innovations arise from the development and use of the methods conjugated with the specific detailing of the structural elements, in order to optimize the construction cycles, manpower and to increase the productivity in construction.

2. MELCHORITA LNG TERMINAL

2.1 General view

The Melchorita LNG Terminal is part of an industrial complex used to export of liquefied natural gas. It is located at the Pampa Melchorita, at the coast of Peru, between the cities of Cañete and Chincha. The access is provided by the Panamerican freeway, 170km from the south of the Capitol, Lima, and 60km from the north of the city of Pisco. 

The Project is owned by PLNG – Peru Liquefied Natural Gas, a joint-venture formed by the U.S. company HUNT OIL, the Korean company SK and the Spanish company REPSOL and it is part of wide public Peruvian government project named CAMISEA.

The maritime works for the Project comprises:

- Quarry exploitation for 2,900,000 tons of rock for the construction of the breakwater;
- Construction of an Access Trestle, 1,350m long, to be used as a pipeway, for maintenance traffic (operational) and heavy traffic during breakwater construction;
- Construction of an Utility Dock and a Loading Platform, at the continuity of the Access Trestle, for loading of tanker vessels up to 260,000 cubic meters, 54m total length;
- Construction of breasting and mooring dolphins;
- Construction of interconnecting walkways;
- Construction of a RLOF – Rock Load Out Facility to be used during the construction of the breakwater and adapted to serve as a mooring facility for tug boats during the Terminal life-time;
- Construction of the Breakwater, 760m long;
- Dredging at the berthing area and vessels access;
- Construction of a temporary bridge for the construction of the Breakwater, 324m long, used as an auxiliary structure during construction.
The project development was started in 2006 and the construction in the middle of 2007, being nowadays at conclusion stages. In figure 2 a general layout of the Terminal is presented, with main structures and facilities.

Figure 2 – Melchorita LNG Terminal – Layout General View
The construction was developed by a joint-venture formed by ODEBRECHT PERÚ INGENIERIA Y CONSTRUCCIÓN, SAIPEM S.p.A. and JEAN DE NUL. Detailing Engineering for the maritime structures, except breakwater, were developed by EXE Engenharia LTDA.

2.2 Structural concepts and design criteria

The structural system chosen for the Access Trestle, Utility Dock, Loading Platform and RLOF is composed by a foundation in steel API pipe piles with OD1219 and WT varying from 32mm up to 38mm, connected to a steel ASTM A572 girder forming the superstructure.

The Access Trestle will be treated here as a reference for all the structures, since it had demanded major effort on the Project definition and for the typical construction cycles. The Access Trestle is approximately 1,350m long and it was formed by 6 segments, the first with 216m, 4 segments with 252m and a last part 126m long before the Utility Dock. Typical spans are 18m long and widths alternate between 15.6m and 30m depending on the Trestle section, respectively for the typical one (roadway and pipeway) and for the expansion loops.

Figure 3 shows a typical section of the Trestle. The concrete roadway was detailed to work as stand-alone structure, only contributing as a rigid panel to distribute vertical loads and horizontal displacement into the steel girder. In this way, roadway was built using 3m long precast concrete panels, joined to the steel beams by means of a scarce mesh of stud bolts.

In general, the structural definitions were made for regular operational and constructional loads from dead, pipe and traffic loads. All structures were also designed to withstand thermal effects and horizontal loads coming from wave and wind action – with a minor effect – and for seismic loads, which impacts with major significance due to the risks related to the transportation of gas.

This last aspect had a great influence on the entire structural definition process. The structure is located in a region with frequent seismic events. For the Project, the frequent seism was taken as the Peruvian Earthquake, with a ground acceleration of 0.24g for a period of return of 75 years. This seismic event was transformed to take into account, into the design criteria, extreme seismic events. In this way, the ground acceleration for operational conditions took into account seismic events with 0.4g – which corresponds to a seism with 475 years of return period. For survival conditions, 0.65g was considered as PGA for 2750 years of return period.

These criteria, together with restrictions in displacements (due to the pipeway), the required elastic design imposed by owner for main elements and the high free length of piles (up to the level of +20m for the deck level) led to the adopted solution in rigid frames, braced horizontally, with the inclusion of special fixed-points to control the structural behavior during extreme events.
As a point of interest, the first segment, named as Trestle 01, 216m long, was detailed using all the aforementioned aspects including two further characteristics: the first one is related to the abutment, since some special details were considered to allow the interface with the onshore area and startup of the construction. The second one is related to a special event which was expected to occur during extreme seismic events: a vertical uplift of approximately 250mm in the first 160m of the segment due to a significant slip failure of the slope behind the Trestle. Figure 4 shows a plan view of the first segment, Trestle 01, with the indication of a high strength fixed point which separates the segment into two parts regarding the detailing of superstructure.

The loads generated by the uplift made unfeasible the solution using a full-restrained superstructure since it could be hard or impossible to detail full-restrained connections to withstand such loads. In this way, a variation of the braced frame concept was used with the separation of the superstructure in two parts: one connected to the pipe piles forming a bottom layer rigid panel and other composing an overlay formed by continuous beams supporting the roadway and pipeway, as shown in figure 5.
All beams at the top layer were simply supported by the bottom frames. The supports were detailed with stainless steel to allow free displacement in the longitudinal direction with free rotation along the beams major axis. All beams were restrained laterally using steel guides stiffened and welded to the bottom frames.

This solution allowed a significant relief on the bending moments and it also guaranteed that achieved displacements would be kept below the maximum allowed for the Trestle and the pipeway. The fixed point played an important role while minimizing the loss of overall stiffness due to the detailed of more flexible connections. Just for information, the fixed-point presented herein was formed by the typical section piles plus 12 battered piles – slope 1/6 - placed 6 by 6 symmetrically in the longitudinal direction.

The positioning of expansion loops was chosen strategically to account for pipe thermal effects. The structural expansion joints were positioned following the expansion loops and they account not only for thermal effects but also to guarantee a gap for displacements generated in seismic events. Figure 6 shows a typical section at the expansion loop. In the detail there is an indication of the pipeline path.

![Figure 6 – Expansion loop typical section](image)

The split of the superstructure was detailed up to the fixed-point. The remaining segments kept the typical section, varying only the deck elevation which begins in level +20m in the abutment, finishing at level +8m at the Loading Platform.

The detailing of all remaining structures followed similar concepts. For the Dolphins detailing, steel structures were also used with a deck in concrete. The pipe piles were interconnected by a steel jacket forming a bracing system. All points of support for equipments were detailed using steel base plates with a planned interface with the concrete deck. In this case, it is interesting to comment that all decks were built in two phases, using precast concrete elements as a formwork to a second phase of in-situ concrete. This method is similar to the one used to built the quay structures for the Callao Container Terminal, presented herein in item 3.

The details and aspects commented herein for this Project were developed in conjunction with the construction method which will be briefly treated in the following item.

2.3 Construction methods and auxiliary structures

As already mentioned herein, the construction methods have significant impact in the structural detailing. In this case, they also require the development of auxiliary and temporary structures for the construction of the main structure. Those special projects refer to the detailing of a structure called Cantitravel, composed by a steel wheeled platform – which is used to support a crane and equipments – and trussed guides used to locate, drive and cut piles, and also to the finishing of connections between foundation and remaining structural elements.

Figure 7 illustrates the general arrangement of the Cantitravel system used for the construction of the Access Trestle of Project Melchorita. The complete system was designed and planned to allow the construction of all elements of the Trestle, including the full assembling of the superstructure. The
same structure was used at the Loading Platform and Temporary Bridge to the breakwater, with adaptations on the trussed guides and movement systems, but keeping the entire SWP (Steel Wheeled Platform) unchanged. A second structure was detailed to built the RLOF, using same concepts.

The construction process uses the SWP on the top of longitudinal beams named “rail-beams” which have rails on the top flange to guide the SWP. This is a well-known system.

However, innovative elements and procedure are present in the way project is developed to account for the detailing process while taking care of all interfaces with the construction methods and the points that influences the overall development process.

The construction methods are developed together with the structural detailing to give optimal solutions on cycles based on the total span length, cantilever length of the trusses, cranes rigging (influenced by weight of the structural elements and capacity of lifting) and geometrical restrictions given by the structures, all variables that are connected one to each other. Those aspects refer to the choice of using 18m regular spans, steel elements for the superstructures, steel pipe piles for the foundation, and so on.

The process starts up with the pile driving. In the sequence, transverse cap beams are assembled, followed by the girder formed by longitudinal beams and braces. For each complete cycle, the SWP is moved forward to the completion of assembling and to start a new cycle, with the repositioning of the rail-beams. A temporary bracing system is also used to guarantee stability on the front spans.

Figure 8 presents a group of pictures which show the assemblage of the SWP and details of the wheels and trusses. The construction methods are illustrated briefly in the sketches of figure 9. The developed cycles for the Access Trestle using these methods, except for the start up, achieved an average productivity rate of one complete span (foundation + superstructure) at each 1.8 days, which represents significant gains in construction schedule and use of manpower.
Figure 8 – Assemblage of the SWP and trusses – Start up of construction process

Figure 9 – Typical construction cycle for Access Trestle – Illustration of assemblage
Figures 10 and 11 show, respectively, the first pile driving at startup and the SWP operating in the typical span at the beginning of Trestle construction.

**Figure 10 – Cantitravel at the startup – Pile driving**

**Figure 11 – Cantitravel in the typical sequence – Access Trestle**
The sequences presented herein have the purpose of showing general aspects of the construction methods and also some general details about the structural elements used in the development, both elements of the main structures and auxiliary elements.

The sequences applied for the construction of the RLOF follows exactly the same procedures, with adaptations to the specific details of the related structures. Just to illustrate the second Cantitravel used in the Project and some other details, figure 12 presents a general view of the temporary structures assembling the RLOF.

![Figure 12 – Assemblage of the RLOF structure](image)

The movement system for the SWP uses winches and a group of pulleys and sheaves as part of a cable system that is restrained in the superstructure. Especially for the RLOF structure, the segment is divided into 3 parts with different levels. To account for this change in slope, special rail beams were designed to leveling the SWP during the movement, allowing for the adjustment in the wheels and keeping guides horizontal. In figure 13 a general view of the maritime works can be seen just during the final phase of Breakwater construction. In this view, one may note the entire Trestle structure, the Temporary Bridge still serving the heavy traffic to the Breakwater and the complete RLOF with the RLOF Breakwater. Figure 14 shows a general view of the Loading Platform after completion of work and disassemble of the Temporary Bridge.

![Figure 13 – General view of maritime works – RLOF, Breakwater and Temporary Bridge](image)
As a final note, a Jack Up Barge was also used to drive piles and to assemble Dolphins and Catwalks. Special trussed guides were developed and incorporated on the JUB structures to allow the assemblage, including positioning of jackets.

3. CALLAO CONTAINER TERMINAL

3.1 General view

The Callao Container Terminal is located in the city of Lima, Peru, and was designed to be the most important and modern Container Terminal of South America. The Project is owned by DPWC – Dubai Ports World Callao.

Maritime works for the Project comprises:

- Demolition of the unusable quay;
- Dredging of the area until level -16.5m;
- Construction of 650m long quay foundations, superstructure, retaining dyke and wall, quay furniture, slope and scour protection.
- Recovery of existent breakwater;
- Fill of stock area with approximately 100,000m²;
- Construction of administrative buildings, parking, electrical installations, hydraulic installations and substations.

The project development was started in September 2007 and the construction at the beginning of 2008, being nowadays at conclusion stages. In figure 15 a general layout of the Terminal is presented.

The construction was developed by a joint-venture formed by ODEBRECHT PERÚ INGENIERIA Y CONSTRUCCIÓN, SAIPEM S.p.A. and JEAN DE NUL. Detailed engineering for the maritime works, were developed by EXE Engenharia LTDA.

3.2 Quay

The quay has designed to accommodate portainers with 30.48m gauge and is approximately 650m long. The transversal section of the quay is 35.88m wide. The structural system conceived for the quay is formed by a concrete deck on steel pipe piles, partially filled with concrete.

The quay slab is formed by precast concrete elements shaped like domes and used as a formwork to “in situ” concrete. The domes were previously assembled on concrete sleeves fixed on the piles. Figure 16 shows the typical cross section of the quay.
3.3 Construction Methods

The structures presented herein were designed adjusted to local conditions, not only related to environmental ones but also to the availability of special equipments and skilled labour. The main components of the structure were designed aiming to minimize quantity of formwork, which consumes a great amount of manpower. In this way, the precast slabs allowed to increase productivity, bringing significant savings in the schedule.
Activities had started with the installation of the fabrication yard for piles and precast concrete elements, allowing the production in advance of such elements as anticipation of construction activities for foundation and superstructure. Figure 17 shows reinforcement of one precast.

Figure 17 – Callao Container Terminal – Precast fabrication

All the structures were designed to accommodate the execution system also developed for a Cantitravel system, adapted and designed to account specifically for this Project. A plan view of this Cantitravel can be seen in figure 18.

The system allows the execution of all related works without use of floating equipments, minimizing risks of stoppages and interference with local navigation, among others benefits as follows:

- It eliminates interferences and interruptions due to environmental condition, as tides, waves and currents;
- It makes possible the optimization of the use of equipment, eliminating the need of using floating equipments;
- It concentrates the activities of construction in only one work front, reducing the need of specialized labour;
- It simplifies the activities of internal logistic of the site, mainly regarding to the transportation of elements (piles and pre-casts) for the fronts of application.

The rail beams, auxiliary structures and movement system are similar to the one applied in the Melchorita Project, already treated herein. The pile leads are strategically positioned to locate and keep positioned the piles during driving, following the piling layout detailed in the Project. Trussed beams, positioned in the front and laterally in the SWP support the pile leads.
Figure 18 – Callao Container Terminal – Cantitravel (SWP) - Detail

After driving, the piles are cut off in a temporary level, allowing moving and assembling the rails beams and the SWP displacement to the next span. Figure 19 shows a general view of the SWP assembled and at the quay startup.

The superstructure spread, behind 2 spans from the Cantitravel position, has its activities connected with the activities of the SWP, being responsible to the feed of structural elements and materials to the Cantitravel front. This spread also is in charge of assembling the superstructure, listed in the following sequence and illustrated in figure 20:
• Assembly of “domus” precast;
• Reinforcement preparation and filling of the 1st phase of “in loco” concrete, forming the longitudinal beams (this spread is to give partial strength to the entering of the auxiliary crane into the span);

• Reinforcement preparation and filling of the 2nd phase of “in loco” concrete, one span before;

• Cure of concrete.

The precast are supported by the concrete sleeve, which is assembled on the piles already driven. The concrete sleeve is used to support the “domus” precast, but also has the function of protecting the steel pipe piles against corrosion due to the variation of tides, eliminating painting on this region. Figure 21 shows a detail of a sleeve already positioned with placed precast slab elements.

![Figure 21 – Callao Container Terminal – Concrete Sleeve Detail](image)

4. APPLIED TECHNOLOGIES IN STRUCTURAL MODELING

The structural modeling has been widely used in the last few decades in an increasing effort to capture the structural behavior with accuracy, representing complex structural details, the interaction between elements and responses to complex load patterns.

In this way, a sort of analysis codes were produced, allowing the use of engineering techniques together with powerful tools to optimization, mainly with the use of finite element methods, known as F.E.M.

The analysis and checks made for the Projects described herein were developed using all this techniques and codes, in order to account for operational and extreme loads and to observe the structural behavior under seismic events or check stress distribution in localized elements, like connections.

In terms of analysis and following the design criteria for both Projects, seismic events generate the most time-consuming analysis, which can be treated in several ways. For the Melchorita Project, the design was made keeping elements in an elastic range of stresses, in accordance with the design criteria. In this case, response spectrum analyses were made to account for the structural behavior and load combinations, based on the modal effects and seismic spectral acceleration curves taken directly from statistical treatments.
Figure 22 shows, as an example, the spectral curve that defines the structural response spectrum based on the ground acceleration of 0.65g which corresponds to a seismic event with 2750 years of return period, a survival condition for the structures. This curve was obtained following the Peruvian Code E.30 with specific parameters that took into account the PGA, soil condition and adopted structural system.

![Figure 22 – Response spectrum curve – seismic analysis for Melchorita Project](image)

Figure 23 illustrates the model used to analyze segment 1 of the Access Trestle. Modeling includes all relevant characteristics, including soil reaction, modeled by means of P-y and P-z springs.

![Figure 23 – Structural model – Access Trestle – Segment 1](image)

For the analysis of the structures of the Callao Project, a different approach was used, taken into account damage levels and push-over analysis. In this case, the structural system was checked for elastic and plastic ranges with controlled moment-rotation curves for the connections between piles and concrete deck. All models were developed using the SAP code, Computer & Structures, Inc.

Time-history analysis were also performed using soil conditions to check the slope protection, the pile embedment, soil liquefaction and residual displacements of structures after extreme seismic events.
5. GENERAL REMARKS

In this work, two cases were presented in order to show aspects related to the development of the Project, mainly focusing on the definition of construction methods and the integrated conceiving of the maritime structures.

All the approaches related herein concerns with the development of safe and economical structures, meeting the requirements of the design criteria and planned schedules for the construction.

References


