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Medium-term life-cycle monitoring of random behaviour components of in-service pile-supported wharves

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ABSTRACT: In the Nantes Harbour, France, two recently built pile-supported wharves have been instrumented in 30% of the cross sections where tie-rods have been installed. Tie-rods are identified by a risk analysis as fundamental components for two main reasons: the first being that their behaviour is very sensitive to building conditions and secondly they support a significantly great portion of horizontal loading due to ship mooring or wind loading on container cranes. This paper aims to assess the structural health from the information acquired by monitoring and its probabilistic analysis during post-building step but before complete service loading (no ship mooring). A decomposition of measured loads in tie-rods on polynomial chaos is selected. Response distribution leads to assess both the probability of failure (considering a limit state design criterion) and the medium-term evolution of steel corrosion (considering an acceptable corrosion level).

1 INTRODUCTION

Harbour structures are subjected to great hazards during their building due to the long period of construction (at least one year) and the wide set of available techniques to install their various components. Respecting the mechanical design hypotheses during their construction is a key-point for ensuring safety, availability and durability. However due to weather or non-foreseen situations, it is necessary to carry out a review of incidents. This and the knowledge of observed or predicted events during construction and exploitation of a structure allow updating the model and for an optimization of its survey, leading to an improvement of the inspection, maintenance and repair programs. The monitoring is then the only way to improve models and update assumptions. It has been shown that the real state of the structure after building can be far from the design one (Yáñez-Godoy et al., 2008a).

In this paper we present two recently built pile-supported wharves in the Nantes Harbour, in France. They have been instrumented in 30% of the cross sections where tie-rods have been installed. Data collected from 2003 to 2006 are available. An original instrumentation strategy has been achieved: it aims to follow the global behaviour of every wharf during at least the first 5 years after building with a view to setup prediction models. These validated models will allow basing the maintenance policy on a better understanding of the in-service behaviour. Indeed, the large

dimensions of these structures, the building hazards and the soil behaviour induce the choice of conservative and too theoretical hypotheses at the design stage that make the design easier but the re-analysis more difficult.

A risk analysis is performed on the design phase. It highlights tie-rods as key components of the structure. We monitor these components which are hardly accessible after the building period and the sensitivity of which can be measured with the present accuracy of available sensors (Verdure et al., 2005).

In this paper, we focus mainly on the tie-rods during service loading but without ship loading in order to identify first the behaviour of the structures with basic loading. The polynomial chaos decomposition of measured loads in the tie-rods is selected. Response distribution leads to assess both the probability of failure (considering a limit state design criterion) and the medium-term evolution of steel corrosion (considering an acceptable corrosion level).

2 CONTEXT

The two in-service monitored pile-supported wharves presented here are located in the estuary of the river Loire, in the west of France. They are managed by the Port Authority of Nantes Saint-Nazaire (PANSN). These studies deal with the extension of the timber terminal of Cheviré, the station 4 (so called Cheviré-4

wharf) and the extension of the containers terminal of Montoir (so called TMDC-4 wharf). Their detailed description is available in (Yáñez-Godoy et al., 2008a). A sketch of a typical cross section is represented on Figure 2. Collaboration with the PANSN permitted the survey of the structures.

3 RISK ANALYSIS

Risk analysis can be used in design stage but also during operation of infrastructures (Billard et al., 2007). The aims are to provide the owners with formal and objective maintenance decision-making indicators based on technical and financial aspects. In this study, FMECA (Failure Mode Effects and Criticality Analysis) is applied on two pile-supported wharves during design stage. The expert approach is shown in Figure 1. This is a very common method that has been shown to be very efficient when studying coastal structures (Billard et al., 2006, Billard et al., 2007, Crouigneau et al., 2008).

3.1 Functional analysis

The first step of the study consists in system decomposition according to environment, loadings, geometry or material. In case of pile-supported structures, six main components are identified (see Fig. 2).

Main functions filled by wharves are: (1) ship support for berthing and mooring; (2) connection between ship and open area: support for operational charges and discharges from ships; (3) ground support. Each

Figure 1. Risk analysis methodology applied to pile-supported wharves.

Figure 2. Decomposition of “pile-supported wharf” system.

component plays a specific role in the functioning of the pile-supported wharf in a functional context.

3.2 Failure modes identification and assessment

The exhaustive list of potential failure modes is obtained thanks to a crossing between the components and the expected functions of the pile-supported wharves. For each component, an analysis of the different causes which could lead to a failure of the associated function is carried out.

For example, the components “platform”, “piles” must resist mechanically to vertical loading due to both overcharges (container cranes, goods traffic, etc.) and dead loads. The component “anchoring” must support a significantly great portion of horizontal loading due to ship mooring or wind loading on container cranes. If they couldn’t resist to loadings, because of a resistance decrease due to both building conditions and infrastructure ageing or of an increasing stress with traffic evolution, failures could lead to consequences like loss of human life, interruption of traffic, and damage to environment. The component “cut-off (sheet-pile wall)” must prevent leakage of particles from the back-fill to the river. Failure can be caused by holes in the sheet-pile wall due to corrosion and could damage the open area.

Criticality (C) is affected for each failure mode. The criticality assessment allows ranking identified failure modes. In the present methodology, criticality is calculated with three parameters:

- the frequency of failure mode (F) (occurrence probability). Frequency is estimated with experience feedback capitalised in tools such as SIMEO™ Consulting (software that takes into account the ageing mechanisms), but also by experts when mechanisms simulations are complex or in case of missing information;

Component	Mode failure	Design stage			
		F	G	D	C
Platform	Lack of mechanical resistance	1	5	0	5
Platform	Loss of mechanical resistance	1	5	0	5
Piles	Lack of mechanical resistance	2	6	1	12
Piles	Loss of mechanical resistance	1	6	1	6
Embankment	Loss of the passive earth pressure and pile-soil adherence	1	6	1	6
Embankment	Leakage of particles from the backfill	1	4	1	4
Back-quay wall	Lack of mechanical resistance	2	6	0	12
Back-quay wall	Loss of mechanical resistance	1	6	0	6
Anchoring	Lack of mechanical resistance	3	6	2	30
Anchoring	Loss of mechanical resistance	1	6	2	12
Cut-off	Leakage of particles from the backfill	1	4	2	5

Figure 3. Results of pile-supported wharves risk analysis.

- the gravity of failure mode (**G**), which means the consequence level on the owner's stakes (safety and availability of wharves' operations);
- the detection means of signs that a failure mode is on the way (**D**). This parameter is defined according to conditions of access to components.

3.3 Results

The results of failure modes assessment are presented in Figure 3. Tie-rods are identified by risk analysis as fundamental components. Their behaviour is very sensitive to building conditions and their structural health can only be identified from the information acquired by monitoring. That's why in a logic of risk management, this action must be anticipated from the design stage.

4 STRUCTURAL INSTRUMENTATION

Each wharf has been instrumented on twelve tie-rods (regularly distributed along the length of the structure) in order to measure the normal load in the tie-rods. These tie-rods are cylindrical steel bars. In the case of the TMDC-4 wharf, some sets of two vibrating wire strain gauges diametrically opposed and clamped by means of flanges screwed on each tie-rod have been used. In the case of Cheviré-4 wharf, resistive strain gauges have been used: two gauges bonded parallel to the axis of the rod and diametrically opposed, and two others bonded perpendicular to the rod, mounted in a full Wheatstone bridge acting as an elongation sensor and avoiding bending effects. For both instrumentations, the sensors were required not to affect the corrosion protection of the tie-rods. The two tie-rods at both ends of the TMDC-4 wharf have been monitored with 3 couples of vibrating wire sensors, instead of one, in order to study the evolution of the normal load and the bending moment along the tie-rod.

In addition, sensors measuring the water level in the embankment (piezometers) are implanted behind the

Figure 4. Instrumentation implanted in each wharf.

back-wharf wall and linked to a "Campbell Scientific CR10X" data logger; 3 piezometers on the Cheviré-4 at both ends and in the middle wharf and 2 on the TMDC-4 wharf at one end and in the middle. Finally, some tidal gauges (controlled by PANSN) measure the real tide level every 5 minutes. In the case of the TMDC-4, two tidal gauges are located in Donges (4 km upstream) and in Saint-Nazaire (2 km downstream), which allows to interpolate the water level in front of the wharf. For the Cheviré-4, a tidal gauge is located 1 km downstream the Cheviré bridge.

Figure 4 shows the distribution of the sensors along of each wharf. In a general way, the instrumented tie-rods are marked and named by an "R" letter and by their longitudinal abscissa position x in meters. By convention $x = 0$ denotes the upstream extremity of the wharf.

5 MEASUREMENTS ANALYSIS

The analysis is performed at the tie-rods level. The main steps are: (i) data collection provided by the data logger; (ii) analysis of the untreated data and their physical meaning; (iii) data processing in order to highlight relevant correlations.

The acquisition period is 30 minutes, ensuring to observe the tide effects on the landing. The untreated signals saved by the acquisition system provide the local physical measurements; these are frequencies in the case of the TMDC-4 and electric voltages in the case of the Cheviré-4. A classical pre-processing of the measurements must be made in order to deduce the normal load in the tie-rods. Uncertainties of measurements are estimated: they are of less than 20 kN

for the TMDC-4 wharf and 10 kN for the Cheviré-4 wharf. All the measures taken into account for the present analysis are for service period without loading by ships (interval October 2002 to July 2003 for TMDC-4 wharf, interval January 2004 to October 2005 for Cheviré-4 wharf).

Two types of variations characterize the loads in the tie-rods:

- *temporal*: medium-term variations, where we question the levels of loads during a month (period of the moon rotation) and short-term variations where we are interested in the amplitude of the loads during a tide with a period of approximately 12 hours;
- *spatial*: variations of the load along the wharf, in each spatially distributed tie-rod.

We concentrate in this study in the medium-term evolutions.

5.1 Medium-term evolutions and statistical analysis

The medium-term load variations, for the non-operational phase, in the tie-rods studied for the two wharves, show a small evolution (Yáñez-Godoy et al., 2008a). They come on the one hand from the embankment loading and the conditions of service life and on the other hand from the seasonal cycles of the tide.

The analysis of the spatial load variation shows an important scatter from a tie-rod to another. This spatial variation of load shows a very distinct behaviour of the in-service structure compared to the design

Figure 5. Medium-term loading evolutions in each wharf.

Figure 6. Statistical distribution and fitting with a polynomial chaos in each wharf.

hypothesis. Research on the reasons of this variability taught us to have a prompt survey during the phase of construction (Yáñez-Godoy et al., 2008a). It underlines the need to define well the way of laying down tie-rods in order to keep an in-service behaviour as close as possible to the assumed and computed one.

Figure 5 represents the monthly average measured load in the tie-rods along the TMDC-4 wharf, during the period from October 2002 to July 2003, and the Cheviré-4 wharf, during the period from August 2003 to October 2005. The drawn mean profiles are obtained from monthly averages.

We can get statistics from monthly average measured load in the tie-rods along every wharf. To represent the considered measurements, we decided to use histograms (see Fig. 6).

5.2 Structural health assessment of wharves

We present now how to qualify the current structural state of the wharves from the information acquired by monitoring and its probabilistic analysis. We focus mainly on the tie-rods during service loading (non-operational phase). Two studies using in-service measurements are performed in the following sections:

- Verification of design load
- Verification of corrosion level

5.3 Verification of design load

This study lies on the loads obtained in design notes. They are considered implicitly as reasonable by the designer. The question is then to assess the probability to overrun this design value. This can be done by both methods, fitting predefined probability density function (pdf) to histograms or fitting with a polynomial chaos (PC) decomposition. In case of multimodal distribution (see Fig. 6), the first method implies identifying families of tie-rods by fitting several distributions. On the other hand, the second method systematizes the fitting from a data base and is selected in the following. This choice is also made to perform structural stochastic computations using spectral stochastic finite element method (Ghanem et al., 2003). We chose the estimate of maximum likelihood for the identification of PC decomposition (Desceliers et al., 2007). Then the problem is to identify the coefficients f_i of the one-dimensional polynomial chaos decomposition:

$$f(\theta) = f(\xi(\theta)) = \sum_{i=0}^p f_i H_i(\xi(\theta)) \quad (1)$$

where p is the order of the PC decomposition, $\xi(\theta)$ the Gaussian germ, i.e. a standardized normal variable and H_i the Hermite polynomial of degree i . By using the maximum likelihood method, coefficients f_i are solution of the optimization problem:

$$L(F) = \arg \max_F L(F) \quad (2)$$

where F is the vector of components f_i ($F = [f_0, \dots, f_p]$) with dimension $(p + 1)$, and L is the likelihood function:

$$L(F) = \prod_{j=1}^N p_f(f(\theta_j); F) \quad (3)$$

The likelihood function (3) takes values first very close to the numerical precision. Then the problem (2) is modified into:

$$-\log(L(F)) = \arg \min_F (-\log(L(F))) \quad (4)$$

The algorithm for solving the optimization problem (4) is detailed in (Schoefs, et al., 2007, Yáñez-Godoy, et al., 2008b). We make use of it to estimate coefficients f_i for every random variable. Distributions of every random variable are well represented by a first dimension 3rd degree PC (see Fig. 6).

This probability to overrun design value is called probability of failure from now on: the safety margin is then ' $M = F - F_d$ '. This service value is known

for Cheviré-4 wharf but unknown for TMDC-4 wharf. To progress in the analysis, we assume that the safety factor i.e. the ratio between the limit tensile strength F_c and the computed load in the design notes is the same for the two wharves. For Cheviré-4 wharf and for limit tensile strength F_c (1590 kN) and design value (691 kN) the safety factor is around 0.4.

We estimate from Figure 6:

- For TMDC-4 wharf: $P(F > 0.4 F_c) = 8.2e-3$
- For Cheviré-4 wharf: $P(F > 0.4 F_c) = 5.0e-4$

Moreover, we know that the service limit states correspond to a probability of occurrence on the life of the structure of about 0.5 (50%) to 0.01 (1%).

In both cases, the probability of failure for the non-operational phase is less than $1e-2$: it is convenient for service limit state. If the selected safety factor is 0.3 the probabilities of failure are respectively $1.3e-2$ and $1.2e-3$ for TMDC-4 and Cheviré-4 wharves.

5.4 Verification of corrosion level

This second study concerns the estimation of an acceptable corrosion level for tie-rods. In fact, assuming an acceptable level of failure probability allows addressing a new question: which acceptable corrosion level respects this safety target? We consider here for the service limit states, two levels of acceptable safety level: they refer to probabilities of failure of 10^{-1} and 10^{-2} . Cumulative density functions (*cdf*) can be obtained from Figure 6 and allow assessing the load in tie-rods corresponding to an acceptable safety level. These *cdf* and the corresponding experimental data are plotted for both wharves on Figure 7.

By knowing the load, the minimal residual steel area can be computed. The residual area for the three selected safety targets is summarized on Table 1:

This residual area divided by the initial area (56.7 and 44.2 [cm²] respectively for TMDC-4 and Cheviré-4 wharves) gives the percentage of loss of mater in terms of area (value between brackets in Table 1).

Higher is the target probability, less is the loss of steel area. The acceptable residual thickness is in the range [21%; 36%] depending on the target probability and the wharf. Note that Eurocode 3 (ENV 1993, Eurocode 3: Design of steel structures) allows the loss of 3 mm of thickness during 50 years of lifetime if no protection is provided. Here, it leads to residual

Table 1. Residual area allowed for tie-rods (cm²).

Probability of failure	TMDC-4 wharf	Cheviré-4 wharf
10^{-1}	13 (23%)	9 (21%)
10^{-2}	20 (36%)	10 (24%)

Figure 7. Cumulative density functions in each wharf.

area 49 cm^2 (86%) and 37.4 cm^2 (85%) respectively for TMDC-4 and Cheviré-4. Whatever the safety target, the acceptable residual area we obtain is lower than these values. It leads to conclude that the safety of tie-rods under service loading is satisfactory. This example is useful to reevaluate older structures since here tie-rods have an anticorrosion protection.

6 CONCLUSIONS

Risk analysis methodology led to a hierarchical scale of risks and highlighted tie-rods as fundamental components for two main reasons: the first being that their behaviour is very sensitive to building conditions and secondly they are hardly accessible after the building period. The profits of this analysis justified the important means of instrumentation to be foreseen since the design stage. Afterward, interpretation of the first measures has supplied to risk analysis the updating of the maintenance decision-making process.

Analysis of measured loads in tie-rods during service loading of the two pile-supported wharves showed a small evolution of medium-term load variation, though an important scatter of spatial load variation

has confirmed the sensibility to building conditions of tie-rods.

Structural health assessment (frequency of failure modes) of tie-rods has been performed to verify design load and corrosion level. The probabilistic analysis has been obtained from the information acquired by monitoring. A decomposition of measured loads in tie-rods on polynomial chaos is selected to represent more faithfully their probability distribution. Computed safety of tie-rods under service loading is satisfactory, risks are weak, and the analysis appears to be useful to reevaluate older structures. Future works will integrate loading of wind on container cranes and of ships and the use of mechanical models.

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