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► To cite this version:

Franck Schoefs, Humberto Yáñez-Godoy, Anthony Nouy. Identification of random material properties from monitoring of structures using stochastic chaos. 10th International Conference on Applications of Statistics and Probability in Civil Engineering, 2007, Tokyo, Japan. hal-01008274

HAL Id: hal-01008274

<https://hal.science/hal-01008274>

Submitted on 5 Oct 2020

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Identification of random material properties from monitoring of structures using stochastic chaos

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The modeling of in service behavior is of first importance when planning the maintenance of structures and when performing risk analysis. To this aim the monitoring of structures in view to assess the level of loading and the displacements offers the opportunity to compare the measured quantities to those expected. Two on-piles wharf have been monitored in the Nantes Saint-Nazaire harbors. The paper focuses on one of them. The stochastic modeling of tide loading is focuses on. A mechanical modeling is presented in view to identify mechanical parameters. An original method based both on polynomial chaos decomposition and maximum likelihood estimate is applied.

1 INTRODUCTION

The optimization of Inspection-Maintenance-Repair of structures in coastal area is still an actual challenge. In fact harbours include a set of mixed structures due to their building date and manufacturing concept with a great variability during steps of building. In this field, risk analysis is a growing topic. As assessment of the probability of failure from models (soil-structure interaction ...) is still a very complex field of research and as some components are not accessible for inspection, monitoring is the only way to understand the mechanism and suggest less complex but more suitable probabilistic models.

This is the case for anchoring rods in container wharf (see Figure 2). In the literature only few papers have been published on the field of wharf. Most of them suggest a monitoring of a single cross section assuming that the scatter with space is low (Rdatz et al. 1995, Dell Grosso et al. 2000, Gattermann et al. 2001, Marten et al. 2004). No statistical analysis is generally available. In Nantes Harbour, two on-pile wharfs have been instrumented in 25% of typical cross sections. The first one has been described and discussed in the literature (Yáñez-Godoy et al. 2006). The instrumentation of passive anchoring rods of the second one is first described in this

paper and the data are analyzed. Then the collected data are analyzed and a modelling of the stochastic process of tie-rod loading is suggested. The mechanical 3D and 2D finite models are briefly described. Finally an identification of basic variables of the mechanical model from data collected is suggested. As an alternative to the step by step inverse identification of basic variables based on the simplex algorithm assuming the PDF, a new method based on polynomial chaos identification is applied. It is shown to be robust.

This work is supported by both the European Community and FEDER funds within the MEDACHS Interreg IIIB Project (Marine Environment Damage to Atlantic Coast Historical and transport works or Structures: methods of diagnosis, repair and of maintenance) and by a CONACYT PhD-studentship (Mexico).

2 DESCRIPTION OF THE WHARF

2.1 Technological description

The studied structure is concerning the extension of the timber terminal of Cheviré, the station 4 (we are going to name it from now on Cheviré-4 wharf). The Cheviré-4 wharf is located downstream the

Cheviré bridge near Nantes city (west of France), in a fluvial ambiance, in the left strand of the river Loire. It is a wharf 180 m long and 34.50 m wide. The wharf is planned to receive ships maximum 225 m long and a 9.10 m draught.

Collaboration with the The Port Authority of Nantes Saint-Nazaire (PANSN) permitted this survey of the structure.

The building spread out over 1 year and 2 months, from October 2002 until December 2003. The wharf has been built from the upstream to the downstream direction. These periods include: preliminary works, the driving of the piles, the driving of the sheet-pile wall, concreting the back-wharf wall, and piles, installing the prefabricated elements of the platform, concreting the platform, implementing and compacting the backfill, lying down the rods following the advancement of the backfill, banking up, ending works and fittings.

The Cheviré-4 wharf is built on a network of 198 driven metallic piles filled up with concrete in the upper side, about 33 m long and with an outside diameter of 711, 762 or 863 mm. Capitals destined to center the load on the piles are placed on the head of each pile. A concrete deck 0.35 m high is put down on a network of reinforced concrete "T" type beams 1.35 m high, itself supported by the piles. The wharf is anchored by 37 passive sloped tie-rods, steel cylinders (75 mm diameter and 15 m long), behind every line of piles. These tie-rods are anchored in the back-wharf wall (2.20 m high) by means of a connecting rod, and at the other end in a reinforced concrete anchoring plate 2.6 m high and wide and 0.5 m thick. Behind the back-wharf wall a vertical sheet-pile wall 9 m high prevents the leakage of the small particles from the backfill; this curtain is linked to the back-wharf wall at its crest. The back-wharf wall is crossed by drainage channels at a height of 6.7 m – level indicated in marine cards spot height M.C.; the zero of the marines cards corresponds to the level of the lowest possible theoretical tide –

2.2 Design methods and main hypotheses

Only quasi-static behavior is considered for the design of these wharfs. Loading situations include: 1) vertical loading coming from the own weight of the structure, the cranes and the service loading; 2) horizontal loading coming from the embankment loading on the back-wharf wall, the variations of water level, the ship berthing, the ship mooring and the wind loading on the cranes.

In the case of horizontal loading, classically these types of wharfs are modeled by means of a two-dimensional similar structure to a porch. In this way, lateral elastic reactions of the different ground layers on the piles are sketched by a series of springs and the supports of the piles by toggle joints, perfect embeddings or elastic embeddings. Then, displace-

ments, deformations and efforts in the piles and in different parts of the platform are obtained. The above leads to the obtaining of global stiffness for each row of piles; immediately afterwards, these rigidities are modeled like elastic supports of an infinitely rigid beam which is analyzed for different horizontal loading situations, that allows determining for each charging situation the maximum reactions of every transverse row of the wharf.

The main hypotheses, which are assumed generally, come from expert criteria and studies of uncertainty accomplished during the preparation of the European semi-probabilistic code called Eurocode 7 (Magnan, 2006). Experts' opinion of designs of wharfs leads to different analysis: 1) the tie-rods are pre-stressed and are loaded by the platform depending of the platform deformation only; 2) immediately after construction, loading on the vertical reinforced concrete anchoring plate embedded inside the bank are sufficient to assume that the passive earth pressure is totally acting: limit state is reached. See more details in (Verdure, 2004). We focus here on loading where hazards and uncertainties are more important: horizontal loadings and especially the one acting from the bank to the river. In fact, this loading is the source of the most sensitive damages in structures, particularly the relative displacement between the platform and the embankment. According to the situation of analyzed loading, tie-rods and lateral capability of the piles are loaded principally. Due to the great stiffness of the platform, accomplished studies in (Verdure *et al.*, 2005) have shown a great variance reduction: hazards on pile behavior, assumed no correlated, are then slightly transferred. Similarly for earth pressure, the variance is reduced or even cancelled due to the high inertia of the back-wharf wall. On the other hand, a great hazard lies on the computation of the tie-rods behavior. That is why a monitoring of the tie-rods has been carried out during the construction of the wharf

3 INSTRUMENTATION

An original instrumentation strategy has been achieved: it aims for (1) following the global behavior of the wharf within the next 5 years following their building in view to setup models for the prediction of the evolutions in the time, (2) basing the maintenance policy on a better understanding of the in-service behavior, (3) finding the main variables that govern the behavior, and (4) performing reliability analysis during extreme events (storms) for in-service structures (Yáñez-Godoy *et al.*, 2006). A complete illustration of this strategy on four wharfs is available in (Schoefs *et al.*, 2004).

The objective being the understanding of the wharf behavior under horizontal loading – actions of the embankment, ship berthing and wind action on

the cranes – we chose to monitor the tie-rods, sensitive elements of the wharf that are not accessible after the building period. Additional information is then available after building like the displacements of the wharf, the tide level and the level of water in the embankment.

The wharf has been instrumented on twelve tie-rods (regularly distributed along the length of the wharf, see Figures 1 and 2) in order to follow the normal load in the rods cross-section. Electric strain gauges have been used, mounted in full bridge and bonded to the rods with an epoxy high temperature bond used for sensors manufacturing; these gauges are linked to a “Campbell Scientific CR10X” data logger. The wiring of strain gauges in a full bridge ensures a temperature self-compensation. The system also ensures the corrosion protection of the rods. In a general way, the instrumented 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.

In addition, sensors measuring the water level in the embankment (piezometers) are implanted behind the back-wharf wall and linked to the data logger; there are 3 piezometers, 1 at the ends and 1 in the middle wharf (see Figures 1 and 2).

Finally, a tidal gauge (controlled by PANSN) measures the real tide level every 5 minutes; this tidal gauge is located 1 km downstream the Cheviré bridge. The interest of these measurements is that the over-crests, due to the air pressure, the river rate of the flow and the wind, are taken into account.

4 DATA ANALYSIS AND HYPOTHESIS ON THE BEHAVIOR

4.1 Data analysis

The analysis is performed at the tie-rods level. We aim for characterizing a more global behavior, which concerns the set “soil-rod-anchoring plate”. The main steps are: (1) data collection provided by the monitoring device, (2) analysis of the untreated data and their physical meaning, and (3) data processing in order to highlight relevant correlations.

The acquisition period is 30 minutes, ensuring to follow the tide effects without involving a too important storage capacity (the present capacity permits to store 1 month of data). The untreated signals saved by the acquisition system provide the local physical measurements; these are electric voltages. A classical pre-processing of the measurements is made in order to deduce the normal load in the tie-rods (see Yáñez-Godoy, 2004).

Data collected from 2003 to 2005 are available. Data taken during the building period correspond to 2003. In this paper we analyze the 2 year interval January/2004-October/2005, for which loads in tie-rods have a very fair variation and integrate seasonal variability. During measures there was absence of exploitation and only embankment loading is the only loading situation on the wharf.

In order to give an overview of the distribution of loading in tie-rods along the wharf, we illustrate (Figure 3) a representation of several measures obtained at given dates. The mean values computed from data collected during a month are plotted in view to smooth effects of the lunar period. We can observe a great scatter in space and time that comes on the one hand from embankment loading and conditions of building and on the other hand from seasonal cycles of the tide (for more details see Yáñez-Godoy, 2004).

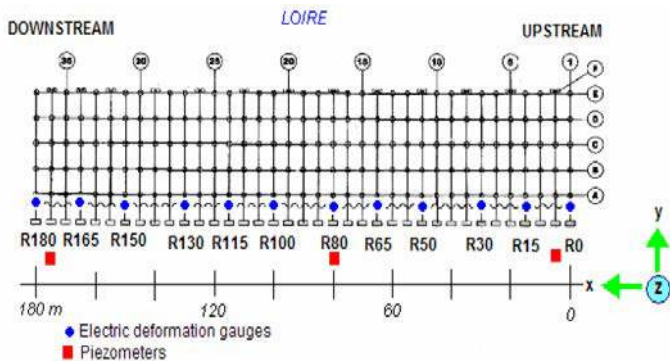


Figure 1. View of instrumentation in plane

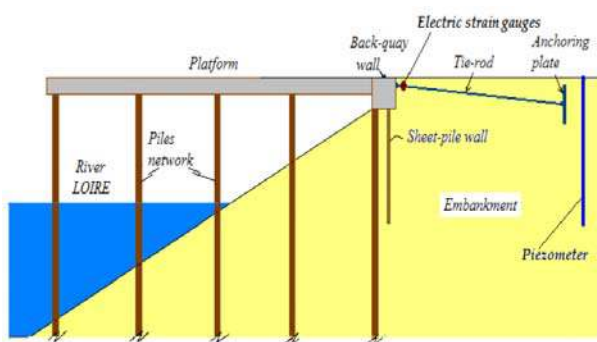


Figure 2. View of the instrumentation implanted on wharfs (cross-section)

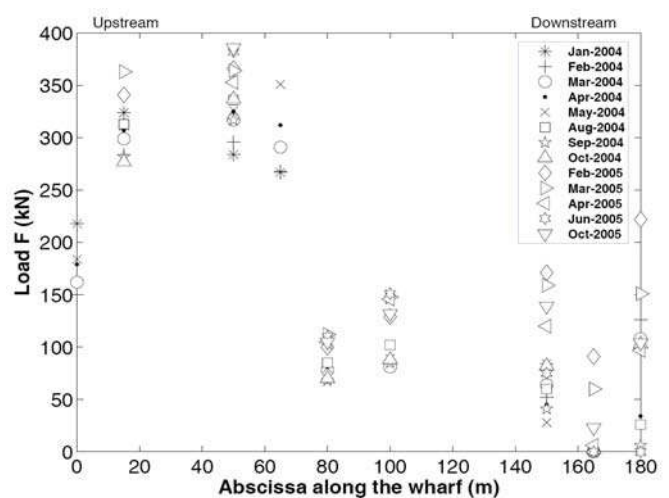


Figure 3. Distribution of the mean monthly loads measured in the tie-rods along the wharf

4.2 Correlation and hypothesis on the behavior

Tie-rods present sensitivity to tide level (Verdure, 2004 and Yáñez-Godoy, 2004) and it is directly linked to the stiffness of the set “soil-rod-anchoring plate”. Indeed, for each tide there is a modification of the soil around the tie-rod. From data we deduce the variation of measured loads in the rods, $\Delta F = F_2 - F_1$, corresponding to the water level variations of the Loire, $\Delta H = H_2 - H_1$, between two instants given t_1 and t_2 . The interval of selected time corresponds to the periodicity of the measurements (30 minutes). In France, we associate to the oscillation amplitude of semi-diurnal tide a coefficient named *tide coefficient* $CMAR$.

Previous studies have shown that the ratio $\Delta F / \Delta H$ has a great scatter for a given tie-rod for low $CMAR$ conditions ($CMAR < 80$) (Yáñez-Godoy, 2004). In fact this scatter is as large when analysing the variation of the loading in a given tie-rod with time than when studying the loading in several tie-rods at a given time. For these conditions, it cannot be considered as representative of the tie-rod. For high tide levels, the quasi-linear correlation between the load in the rods and the variation of the water level is shown to characterize tie-rods behavior. This relationship is shown in Figure 4 that plots this loading during a falling tide for 7 tie-rods ($CMAR = 100$). This paper aims to characterize the behavior of tie-rods for high $CMAR$: 6 values are selected from 95 to 100. Coefficients $CMAR$ higher than 100 occur rarely and few data are available.

Interest of studying high coefficient tide is for performing studies of structural reliability in case of extreme storm loading (Yáñez-Godoy *et al.*, 2006).

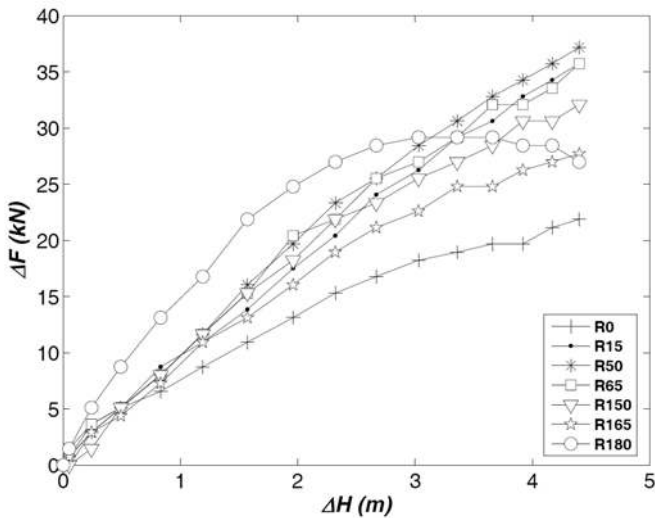


Figure 4. Variation of the measured normal load ΔF in the tie-rods in relation to water level variation of the river Loire ΔH for a falling tide ($CMAR = 100$)

5 STOCHASTIC AND MECHANICAL MODELLING

5.1 Stochastic modeling

Let us consider the stochastic process of loading variation during a tide of coefficient $CMAR$: ΔF_{CMAR} where $CMAR \in \{95, 96, 97, 98, 99, 100\}$. This is a stochastic process discrete in space and in time: $\Delta F(x_i, t_j, \theta_j | CMAR)$ where x_i is the position of the rod, t_j the time when $CMAR$ occurs and θ_j the event. The correlation of ΔF_{CMAR} with time is very fair and we assume a white-noise type process at the time level. Then:

$$\Delta F(x_i, t_j, \theta_j | CMAR) = \Delta F(x_i, \theta_j | CMAR) \quad (1)$$

It leads to assume that at each time t_j , a new event θ_j of the same variable $\Delta F(x_i)$ is obtained. Let us consider the structure of this stochastic process with space. We assume here that a single set of mechanical random variables governs this stochastic process.

In view to identify this set of random variables and to be consistent with this assumption, a post-processing of the samples is performed. In fact the scatter of the mean value of $\Delta F(x_i, \theta_j | CMAR)$ is significant (Figure 5). This bias is explained through the fair size of samples and the error of measurement which is around 10 [kN].

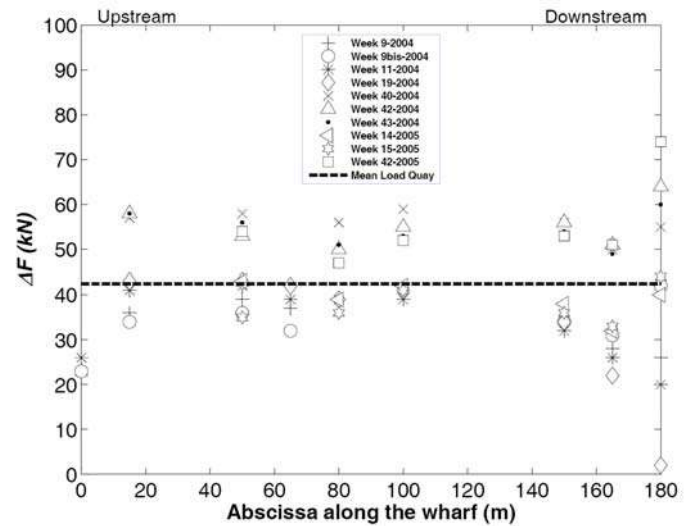


Figure 5. Variation of the measured loads in the tie-rods along the wharf, during falling tides with $CMAR = 100$

Let us consider $\mu_{\Delta F | CMAR}$, the spatial average of the expected value of $\Delta F(x_i, \theta_j | CMAR)$, defined by

$$\mu_{\Delta F|CMAR} = \frac{1}{n} \sum_{i=1}^n E(\Delta F(x_i, \theta_j|CMAR)), \quad (2)$$

where n is the number of tie-rods. By denoting $\Delta F^*(x_i, \theta_j|CMAR)$ the centered random variable associated to $\Delta F(x_i, \theta_j|CMAR)$, each variable $\Delta F(x_i, \theta_j|CMAR)$ can be written:

$$\Delta F(x_i, \theta_j|CMAR) = E(\Delta F(x_i, \theta_j|CMAR)) + \Delta F^*(x_i, \theta_j|CMAR) \quad (3)$$

We consider the following approximate expansion for $\Delta F(x_i, \theta_j|CMAR)$:

$$\Delta F(x_i, \theta_j|CMAR) \cong \mu_{\Delta F|CMAR} + \Delta F^*(x_i, \theta_j|CMAR) \quad (4)$$

This expansion allows filtering the fluctuations on the mean value: this bias is in fact mainly due to the low size of samples.

5.2 Mechanical modeling

A high linear correlation between the load in the rods and the variation of the water level is noticed as showed in Figure 4. This linearity is used to define a tangent modulus that represents overall stiffness of the set “soil-rod-anchoring plate” for high tide levels. The aim of mechanical modeling is to provide robust transfer functions that allows to identify $k(\theta)$ from the random variables defined in (6) for each coefficient $CMAR$. We have developed two mechanical models in order to represent spatial behavior along the wharf subjected to horizontal loading: the first one is based on a 3D finite-element model and the second one, a 2D model, which parameters are identified from the first one but is based on the beam theory. In aim of reducing computational costs, the second one is used in the following.

6 IDENTIFICATION OF TIE-RODS STIFFNESS

6.1 Steps of the flow-chart

In view to identify the variable $k(\theta)$ representing the tie-rods stiffness, the three following steps are considered after the transformation (4):

(i) estimation of a deterministic embankment loading, called tide loading $\Delta F_{TL, CMAR}$ in the following, during a tide of given coefficient $CMAR$, by knowing the loads in tie-rods and deterministic stiffness k_d ,

(ii) computation of each event of $k(\theta|CMAR)$ by knowing the tide loading and the modified distribution of ΔF_{CMAR} according to equation (4),

(iii) identification of this distribution by using stochastic chaos.

Note that step (i) is needed because of the lack of knowledge on the earth pressure loading (Verdure et al. 2003, Verdure 2004, Verdure et al. 2005). The deterministic value of k_d is taken at value 61.9 [MN/m]: it is a mean “reasonable” value because it corresponds to the stiffness of a tie rod perfectly embedded in the anchoring plate without soil. In fact presence of the soil tends to increase the stiffness when the possible elastic-displacement of the anchoring plate decreases this stiffness.

6.2 First Step: estimation of the tide loading

Following the flow-chart detailed in sub-section 6.1, the tide loading $\Delta F_{TL, CMAR}$ is computed by inverse analysis. The corresponding optimization problem is presented in (5).

$$\Delta F_{TL, CMAR} = \underset{\Delta F_{TL, CMAR}}{\operatorname{argmin}} \left(\sum_{i=1}^n (\mu_{CMAR, \max 10} - \Delta F^c(x_i, \Delta F_{TL, CMAR}))^2 \right) \quad (5)$$

where $\Delta F^c(x_i, \Delta F_{TL, CMAR})$ is the variation of loading in the tie-rod of abscissa x_i resulting from a computation with the deterministic model (see section 5.2) with a tide loading $\Delta F_{TL, CMAR}$ and a deterministic stiffness of tie-rods of 61.9 [MN/m]. Note that the mean variation of loading $\mu_{CMAR, \max 10}$ is computed from the 10 maximum values of available events: it allows to compute to use the same sample size whatever the coefficient $CMAR$. This problem is solved using a method of order 0 called simplex (Nelder et al. 1965).

6.3 Second step: building of the sample for k

For a given coefficient $CMAR$ and by knowing $\Delta F_{TL, CMAR}$ computed from (5) and the post-processed sample of $\Delta F(x_i, \theta_j|CMAR)$ deduced from (4), each event $k(\theta_j|CMAR)$ is solution of the optimization problem (6).

$$k(\theta_j|CMAR) = \underset{k}{\operatorname{argmin}} \left(\sum_{i=1}^n (\Delta F(x_i, \theta_j|CMAR) - \Delta F^c(x_i, k))^2 \right) \quad (6)$$

where $\Delta F^c(x_i, k)$ is the variation of loading in tie-rod of abscissa x_i resulting from a computation with the deterministic model and with stiffness k .

The set of events for $k(\theta|CMAR)$ is thus deduced from the solution of m inversed problem where m is the size of samples $\Delta F_{CMAR}(x_i, \theta_j|CMAR)$. This problem is solved using the same simplex algorithm as above.

By assuming that each coefficient $CMAR$ in the range [95; 100] has the same probability of occurrence, the distribution of variable $k(\theta)$ is composed of by all events $k(\theta_j|CMAR)$, whatever $CMAR$. This distribution is given on figure 6. The two first statistical moments μ_k and σ_k are respectively 32.24 [MN/m] and 13.07 [MN/m].

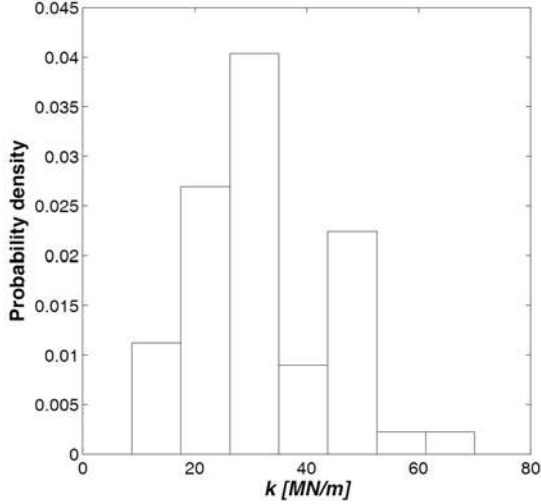


Figure 6. Distribution of k

7 MODELLING USING POLYNOMIAL CHAOS

7.1 Formulation of the problem

When distribution of variables don't follow a pre-defined probability density function and in view to systematize the identification from a data base and the stochastic computations, methods are now available (Desceliers et al. 2006, Ghanem et al. 2006, Sakamoto et al. 2002). We use here the estimate of maximum likelihood for the identification of polynomial chaos decomposition (Desceliers et al. 2006). Then the problem is to find the coefficients k_i of the one-dimension polynomial chaos decomposition (7).

$$k(\theta) = k(\xi(\theta)) = \sum_{i=0}^p k_i h_i(\xi(\theta)) \quad (7)$$

where p is the order of the polynomial chaos 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 k_i are solution of the optimization problem (8).

$$L(\kappa) = \arg \min_{\kappa} L(\kappa) \quad (8)$$

where κ is the vector of components k_i ($\kappa = [k_0, \dots, k_p]$) with dimension $(p+1)$, and L is the likelihood function (9).

$$L(\kappa) = \prod_{j=1}^N p_k(k(\theta_j); \kappa) \quad (9)$$

where N is the size of the sample of $k(\theta_j)$ (see 6.3) and $p_k(\cdot; \kappa)$ is the probability density function of the variable $k(\theta)$ defined in (7), depending on the set of polynomial chaos coefficients.

7.2 Algorithm for solution

First the likelihood function (9) takes very fair values very close to the numerical precision. Then the problem (8) is modified in (10).

$$-L \log(L(\kappa)) = \arg \min_{\kappa} (-L \log(L(\kappa))) \quad (10)$$

In view to systematize the algorithm it is suggested (Desceliers et al. 2006) to work in a standardized space by using properties of polynomial chaos and of the decomposition by using L_2 norm (11) (Ghanem et al. 1991).

$$\begin{cases} k_0 = \mu_k \\ \text{Var}(k(\xi(\theta))) = \sum_{i=1}^p k_i^2 = \sigma_k^2 \end{cases} \quad (11)$$

where μ_k and σ_k are respectively the statistical average and standard deviation of variable $k(\theta)$. They are computed from the experimental sample of $k(\theta)$ obtained in 6.3. The first condition reduces the number of unknown coefficients to p and the second one allows to search other coefficients on an hypersphere with radius σ_k . More over, by denoting k_i^* the quantity k_i / σ_k the conditions (11) become

$$\begin{cases} k_0 = \mu_k \\ \sum_{i=1}^p (k_i^*)^2 = 1 \end{cases} \quad (12)$$

These new conditions allow to search p coefficients $[k_1^*; \dots; k_i^*; \dots; k_p^*]$ on a hyper-sphere with radius 1. This last condition is interesting for the optimization of algorithms. Note that for $p=1$ the solution is the standardized normal probability density function.

A basic random search algorithm is used for solving (10) by knowing (12). It is based on Monte Carlo simulations.

7.3 Solution of the identification

Let us first consider a polynomial chaos of order 2. The solutions k_i^* and k_i are given in table 1.

Table 1. Coefficients for a polynomial chaos of order 2

k_i^*	[MN/m]	k_i	[MN/m]
		k_0	32.24
k_1^*	0.9891	k_1	12.93
k_2^*	0.1475	k_2	1.93

The mean and standard deviation of $k(\xi(\theta))$ are identical to those computed in 6.3 from the statistical distribution.

Figure (7) illustrates the variations of $-\text{Log}(L(\kappa))$ on the circle with radius 1. Note that coefficients can be either positive or negative due to the second condition of (12) and the fact that $\xi(\theta)$ is a standardized normal variable.

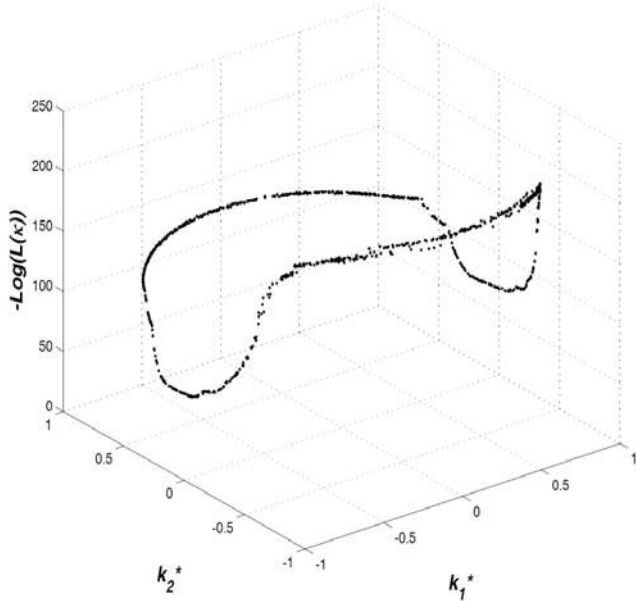


Figure 7. Variations of $-\text{Log}(L(\kappa))$ with the couple $(k_1^*; k_2^*)$.

By using the second property in (12), we can introduce an angular parameter φ (13).

$$\begin{cases} k_1^* = \cos(\varphi) \\ k_2^* = \sin(\varphi) \end{cases} \quad \text{with } \varphi \in [0, 2\pi] \quad (13)$$

The evolution of $-\text{Log}(L(\varphi))$ is presented on figure 8 where we can localize the minimum of the likelihood function.

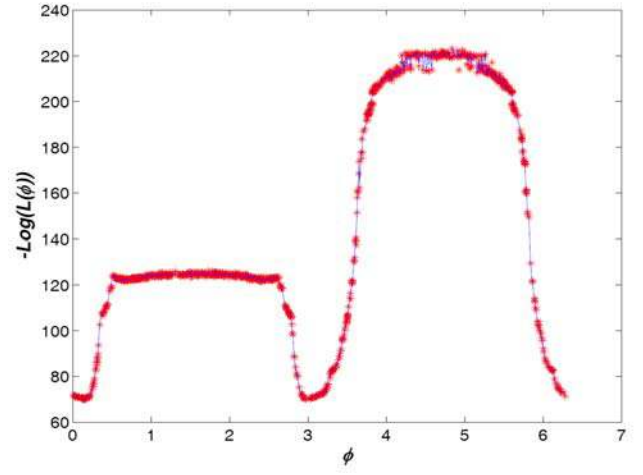


Figure 8. Variations of $-\text{Log}(L(\varphi))$.

The pdf of the obtained polynomial chaos decomposition is plotted on figure 9 and shows a convenient fitting of the statistical distribution of k .

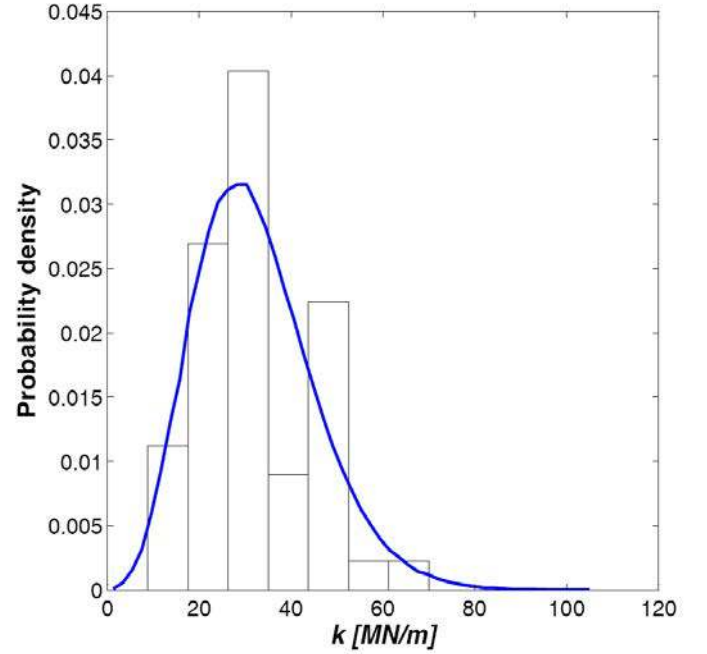


Figure 9. Statistical distribution of k and fitting with a polynomial chaos of order 2.

Let us now consider a polynomial chaos of order 3. The solutions k_i^* and k_i are given in table 2.

Table 2. Coefficients for a polynomial chaos of order 3

k_i^*	[MN/m]	k_i	[MN/m]
		k_0	32.24
k_1^*	0.9923	k_1	12.97
k_2^*	0.1163	k_2	1.52
k_3^*	0.0426	k_3	0.56

The mean and standard deviation of $k(\xi(\theta))$ are identical to those computed in 6.3 from the statistical distribution. Coefficients k_1 and k_2 are very close to those obtained from order 2 and coefficient k_3 is negligible. It leads to conclude that the polynomial chaos of order 2 is sufficient. A convergence test can be developed with the convergence of these coefficients or of the variance of the solution.

8 CONCLUSIONS

This paper first presents the complexity of wharf building and behavior. The strategy of monitoring which aims to characterize this behavior is then addressed. A mechanical modelling is addressed to underline the main variables that govern the scatter in loading on tie-rods.

It allows to identify the best distribution for these basic variables. An original identification is suggested: it is based both on maximum likelihood estimates and decomposition on polynomial chaos. This method avoids to assume a prior distribution type. A second order and third order polynomial chaos are considered for the illustration.

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