Analysis of lifespan monitoring data using Bayesian logic

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Abstract. In this contribution, we use a Bayesian approach to analyze the data from a 19-storey building block, which is part of the Punggol EC26 construction project undertaken by the Singapore Housing and Development Board in the early 2000s. The building was instrumented during construction with interferometric fiber optic average strain sensors, embedded in ten of the first story columns during construction. The philosophy driving the design of the monitoring system was to instrument a representative number of structural elements, while maintaining the cost at a reasonable level. The analysis of the data, along with prior experience, allowed the engineer to recognize at early stage an ongoing differential settlement of one base column. We show how the whole cognitive process followed by the engineer can be reproduced using Bayesian logic. Particularly, we discuss to what extent the prior knowledge and potential evidence from inspection, can alter the perception of the building response based solely on instrumental data.

1. Prologue

Singapore, April 11, 2001. The first sensor was installed in column C1 by me; the other nine sensors were fitted soon after by Sofotec.

In April 2001, Branko, the second author of this paper, was in Singapore, in charge of instructing Sofotec personnel (the local representative of the Swiss company Smartec [1]) on how to install interferometric fiber optic sensors on the rebar cages of the columns of a new 19-storey residential building. The owner of the building is Singapore's public housing authority, the Housing and Development Board (HDB). The HDB has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of HDB quality assurance program, it was decided to perform long-term structural monitoring on a new building project labeled Punggol East Contract 26. This pilot monitoring has two aims: to develop a monitoring strategy for column-supported structures such as buildings, and to collect data related to the behavior of this particular building providing information concerning its behavior and health conditions. The monitoring encompassed the whole lifespan of the building, from construction on. Now, in 2010, in Princeton, Branko remembers those times and tells Daniele, the third author of this paper, of what followed the installation. Daniele listens, sipping coffee and recording Branko's tale:

Manno, Smartec Headquarters, May 24, 2001. I'm told that the first storey slab was poured and monitoring started. All ten sensors survived pouring of concrete and work properly.

Manno, August, 2001. After the seventh storey was built, unusual behavior of column C9 is observed: the strain in this column seems to be smaller as an absolute value than the strain in the other columns. This unusual behavior was explained by HDB as the consequence of lower dead load in the zone where floors were empty. This under-loading or over-dimensioning of the column C9 was not critical but was kept under observation until the end of building construction. No other unusual behavior was noticed. I was delegated to check the data every six months and to analyze it once a year.

Manno, late May 2002. After one year, the construction of 19 floors was complete. The monitoring system works well and results are excellent: all the measurements are coherent and follow well a simplified numerical model (...). We decided to publish a paper with these initial results [2].

Manno, early June 2003. Two years after installation, the monitoring system works correctly. (...) A potentially unusual event occurred in the period September 2002 – May 2003. While the magnitude of most sensor strains increased by an absolute value, and some sensors more than for others, the strain change in column C3 was unusually small. The differences in strains among the columns are explained by partial occupancy of the building and by rheological effects (creep and shrinkage) that could differ between columns. The behavior of all the columns was still within expected limits and the unusually small strain change in column C3 was attributed to different temperature conditions at the time of the measurement and to load redistribution due to creep and shrinkage.

Manno, January, 2004. (...) Although it became clear that the behavior of column C3 is qualitatively different from the other columns, quantitatively this column fits the numerical model well. (...) we decided to do 48-hour continuous monitoring (...) to assess the influence of daily temperature variations combined with daily fluctuation of inhabitants.

Manno, August, 2004. The data from the 48-hour session indicated that the daily variations of strain cannot explain the unusual qualitative behavior of the column C3. Two options remained: the unusual behavior is a consequence either of the rheological effects or of the differential settlement of the column. Differential settlement was not excluded, but it was considered unlikely since the foundation slab seemed to be stiff enough to avoid this and an absolute strain increase, coherent with the other sensors, was seen during the last six months. The column behavior was still well within the error limits when compared with the numerical model, so the column behavior was not yet considered unusual. The column C1 experienced a "visible" increase in absolute strain, still within the error of the numerical modeling.

Manno, end of July, 2005. Another 48-hour session was performed and results were similar to those recorded the year before. At this point the unusual qualitative behavior of column C3, if any, can be considered as stabilized. It was decided to publish another paper [3].

Dubai, December 10, 2005. The November 2005 measurement showed a clear decrease in the absolute strain in column C3. I was intrigued by this result and I discussed it with Eng. Ng HDB; I asked if differential settlement in column foundations is possible for this type of building. After his affirmative answer, I had no doubt that the unusual behavior of column C3 was related to differential settlement in the column foundations. An approximate analysis showed that the differential settlement had an order of magnitude of one millimeter [4]*, and such a small differential settlement was not critical to building condition. We were all glad to know that the monitoring system could detect such a small deviation from normal structural behavior.*

The interview above shows that in four years of monitoring, Branko gradually changed his mind as to the possibility of a settlement at column C3; it also reveals that an engineer's perception of structural behavior is influenced not only by monitoring results, but also by verbal information he receives from other parties involved in the project. The goal of this work is to define a model which reproduces the engineering judgment formulated by Branko based on his personal experience and knowledge of the mechanical behavior of the building.

Analysis of the long-term data collected is particularly challenging for concrete structures since many sources of strain are involved, and it is virtually impossible to set up *a priori* an accurate numerical model predicting structural behavior to which the monitoring results can be compared. The complexity of this exercise is that the sources of information are of two completely different natures: (i) the instrumental data recorded by the monitoring system, and (ii) the information that columns of the building in can settle. While the first set of data is probably regarded by most engineers as quantitative, information (ii) is normally regarded as something qualitative, or part of the engineering judgment. We need a logic capable of blending the two information sets in a rational and quantitative manner, and we anticipate that Bayesian logic can be the answer. After describing more in detail the case study, below we first present the general paradigm of the method, and then we clarify the practical application to the specific case.

2. The building, the monitoring system

The Punggol EC26 project consists of six blocks with pile foundations; each block is a nineteen-storey building, with 6 Units supported on more than 50 columns at ground level. The block called 166A was selected for monitoring. A view of the building under construction is in figure 1(a) and the completed building in figure 1(b). The monitoring strategy was developed based on the different criteria presented in detail in the literature [4]. The main requirements were to perform long-term structural health monitoring of a representative number of critical structural members. Ten ground floor columns were selected as being the most critical elements in the building, whereas the number of sensors was adapted to the available budget. The identification of columns was based on numerical modeling. The column positions are shown in figure 1(c). The dominant load in each column is an axial compression force; therefore, it is supposed that the influence of bending on deformation can be neglected. Consequently, a single sensor per column, installed parallel to the column axis, but not necessarily at the load centre of the cross-section, was estimated as sufficient for monitoring at the local column level. The position of the sensor in the column is shown schematically in figure 2a. The length of the sensors was determined with respect to the available height of the column (3.5 m) and on-site conditions; hence, 2 m long sensors were used.

Several columns at the same level (storey) in a building of simple topology create a so-called scattered simple topology [4]. The analysis of a scattered topology uses several algorithms that are applied to assess the global structural behavior. Supposing the floor slab to have high stiffness, the columns supporting the slab are expected to deform by similar absolute values and the total strains in different columns are expected to be in mutual linear correlation. An example of detection of unequal foundation settlement is presented in figure 3b. The column with foundation subject to settlement will elongate while the neighboring columns will shorten. In this case the linear correlation between the elastic strains of the columns is lost.
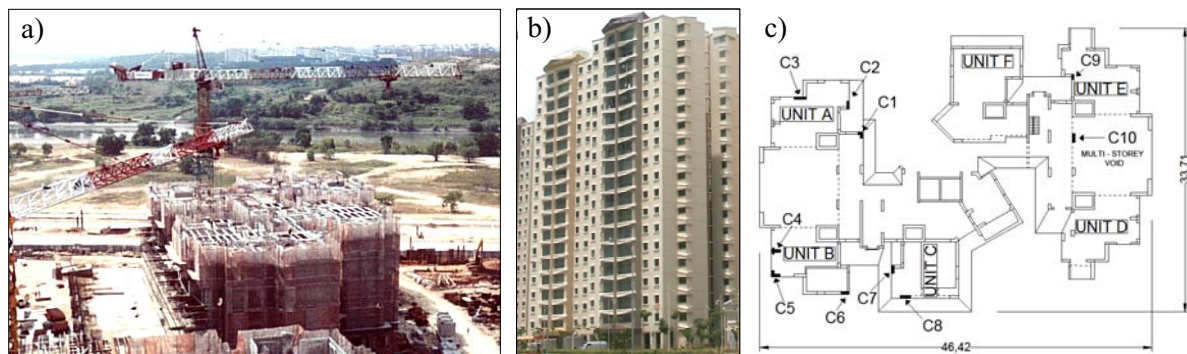

Figure 1: Block 166A during construction (a), and completed building (b); plan view indicating the location of columns equipped with sensors (c).
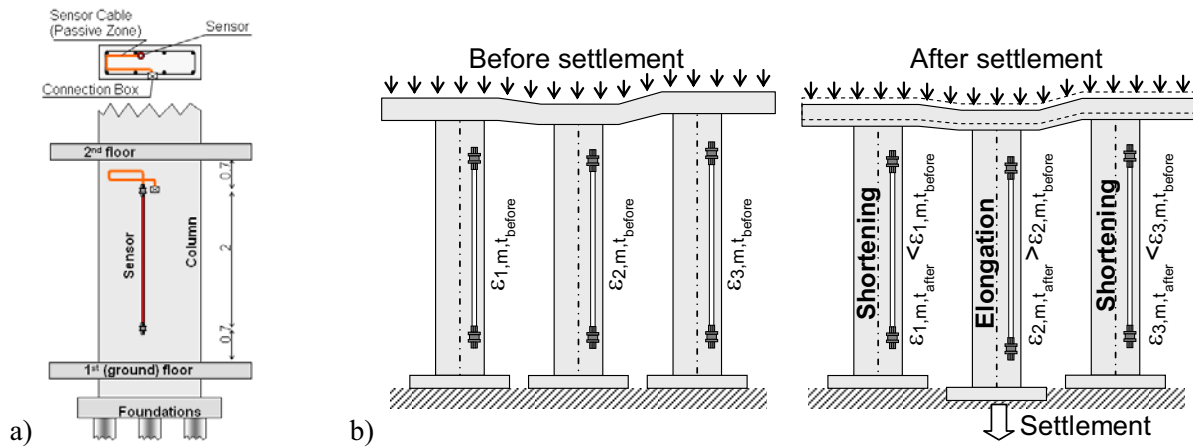
Figure 2: Position of the sensor in the column (a); detection of unequal foundations settlement (b).

In each column, the sensor was attached to a rebar before pouring concrete. Long-gauge fiber optic sensors of type SOFO [1] were selected. These sensors today show 100% survival rate (almost ten years after embedding in the concrete), high long-term stability and measurement error of 2 μm (equivalent to 1 $\mu\varepsilon$ for two meter long sensors). The long gauge length makes them insensitive to local material defects and suitable for monitoring inhomogeneous materials such as concrete [4].

3. What is Bayesian logic (and how it applies to structural monitoring)

The general paradigm of our approach is to try to recognize in real-time signs of a specific unusual behavior (in this case: settlement of a column), from a set of instrumental measurements **M**, using the principle of Bayesian statistical analysis. Bayesian theory of probability originates from Bayes' well known essay [5]; reference works on the subject are [6] and [7] while many modern specialized textbooks provide the reader with a critical review and applications of this theory to data analysis (see for instance [8] and [9]).

Assume the monitoring system makes use of a number Ns of strain sensors, labeled $(s_1, s_2, ..., s_{Ns})$, each providing values for each of k time values $(t_1, t_2, ..., t_k)$. $\overline{\varepsilon}_j(t)$ identifies the value obtained at time t from sensor s_j, and $\mathbf{M}_k$ indicates the set of values provided by all sensors to time t_k. In practice, we can divide the domain of the possible structural response into a mutually exclusive and exhaustive set of scenarios $(S_1, S_2, ..., S_{Nd})$, each defining a specific structural condition. The structural response ${}^n\varepsilon_j({}^n\mathbf{p}, t)$ for time t and sensor s_j in scenario S_n is controlled by a certain number of parameters (e.g.: stiffness, degradation), represented by vector ${}^n\mathbf{p}$. Assuming scenario S_n to be the real one and after appropriate selection of the scenario parameter ${}^n\mathbf{p}$, the measurements at sensor s_j and time t can be expressed as:

$$\overline{\varepsilon}_j(t) = {}^n\varepsilon_j({}^n\mathbf{p}, t) + {}^n e_j(t) \tag{1}$$

where $e_j(t)$ is an error that accounts for both instrumental noise and the inherent imprecision of the model assumed. Once measurements $\mathbf{M}_k$ become available from the monitoring system, Bayes' theorem allows calculation of the updated, or *posterior*, probability for each scenario S_n, from prior probability prob(S_n), scenario likelihood PDF$(\mathbf{M}_k|S_n)$ and evidence PDF$(\mathbf{M}_k)$, using the following expression:

$$\text{prob}(S_n|\mathbf{M}_k) = \frac{\text{PDF}(\mathbf{M}_k|S_n) \cdot \text{prob}(S_n)}{\text{PDF}(\mathbf{M}_k)} \tag{2}$$

where PDF denotes the *probability density function* of a random variable. Equation (3) reads: my estimated probability of having scenario n after acquiring the sensor data $\mathbf{M}_k$ is equal to the likelihood

of the data given the scenario, times my probability estimated a priori, normalized by the evidence of the data acquired. Prior probabilities assigned to each scenario reflect the initial judgment of the evaluator, independently of the outcome of monitoring. On the contrary, likelihood computation requires detailed analysis of the predicted structural response in each specific scenario. As long as errors are assumed to be uncorrelated for each time and sensor, the likelihood for the whole measure set $\mathbf{M}_k$ is obtained combining the likelihoods of all samples for all sensors and time intervals recorded:

$$\text{PDF}\left(\mathbf{M}_k \middle|{}^n\mathbf{p}, S_n\right) = \prod_{j=1,i=1}^{j=Ns,i=k} \text{PDF}\left(\overline{\varepsilon}_j\left(t_i\right) \middle|{}^n\mathbf{p}, S_n\right) \qquad (3)$$

The likelihood of scenario S_n is then calculated by marginalization of parameters ${}^n\mathbf{p}$, i.e. by integrating parameter likelihood on the whole domain $D^n\mathbf{p}$, using their prior distribution $\text{PDF}\left({}^n\mathbf{p}\middle|S_n\right)$ as weighting function:

$$\text{prob}\left(\mathbf{M}_k\middle|S_n\right) = \int_{D^n\mathbf{p}} \text{PDF}\left(\mathbf{M}_k\middle|{}^n\mathbf{p}, S_n\right) \cdot \text{PDF}\left({}^n\mathbf{p}\middle|S_n\right) \cdot d^n\mathbf{p} \qquad (4)$$

As the scenario set is complete and mutually exclusive, evidence of measures $\mathbf{M}_k$ is simply obtained by summing the scenarios:

$$\text{prob}\left(\mathbf{M}_k\right) = \sum_n \text{prob}\left(\mathbf{M}_k\middle|S_n\right) \cdot \text{prob}\left(S_n\right) \qquad (5)$$

In summary, given a fresh set of measurements $\mathbf{M}_k$, this procedure allows real-time update of the probability of each scenario using equations (2) to (5).

4. How Bayesian logic applies to our case

Now, the objective of this work is to let the reader clearly understand how the Bayesian updating scheme stated in the previous section applies to the evaluation problem introduced. For the sake of clarity we will keep this exercise as simple as possible, and we will assume that there are only two scenarios conceivable by Branko at any time of the monitoring history:

Scenario S_1: there is no settlement, all the columns behave essentially as per design;

Scenario S_2: column C3 is undergoing a settlement.

We recognize this drastic simplification does not reflect the variety and complexity of the cognitive mechanism which is behind Branko's perception, but again we want to stress that the real objective of the paper is to let the reader familiarize with the probabilistic logic, rather than getting lost in the details of a super-refined model

4.1. Modeling the mechanical behavior

Going back to equation 1, the strain recorded ε is seen as the sum of the prediction ε, based on a mechanical model, and a noise term e. The latter noise is here assumed to be a zero mean random variable which accounts for the fact that we, as engineers, are aware that for a number of reasons the prediction, although very refined, cannot always match exactly our instrumental data. These reasons include in our case: uncertainties in the temperature fluctuation; uncertainties in sensor temperature sensitivity; sensor noise; fluctuation of live load. The mechanical model defining ε_{tot} in general changes with the assumed response scenario and will be specified below: however there are some basic assumptions that hold for any of the two scenarios:

- there is no correlation between the elastic responses of different columns;
- the geometrical cross-section is deterministically known;
- the position of the sensor is likewise known;
- the load at each column is deterministically assumed, both for dead and live loads;
- mutual load redistribution among the ten columns investigated is not considered;

- the exact ambient air temperature is unknown, for the sake of the model it is assumed constant and equal to T=28°C (which reflects the Singapore climate), while any deviation is accounted for in the noise term.

Here we will not discuss the validity of these assumptions, but acknowledge that the engineer in charge of the evaluation assumed them to be true and, based on them, has reached his conclusions. Similarly, the mechanical model that is detailed here is what reflects the engineer's perception. This said, in the opinion of the authors the model seems appropriate to the case, and we insist on stressing that here the point is not to establish whether the model is appropriate or not, but rather whether it reflects or not the view and knowledge of the engineer at the time of evaluation.

4.2. No-settlement scenario

To go ahead with our exercise, we now define the mechanical models which reproduce the behavior of the structure in the two different scenarios assumed. We start with the no-settlement scenario, or Scenario 1: the total strain ε_{tot} expected at a sensor accounts for an elastic term ε_{el}, a creep term ε_{cr} and a shrinkage term ε_{sh}:

$$\varepsilon(t) = \varepsilon_{el}(t) + \varepsilon_{cr}(t) + \varepsilon_{sh}(t) \tag{6}$$

The elastic term is calculated based on the axial force N, which is assumed known for any specific column (and again any uncertainty in the load is thought incorporated in the noise term e), via the following equation:

$$\varepsilon_{el}(t) = \frac{N(t) \cdot k_e}{E_c A_{eq}} \tag{7}$$

where $E_c A_{eq}$ is the nominal axial stiffness of the column taking account of the contributions of concrete and steel and here assumed constant in time. Coefficient k_e, here referred to as eccentricity coefficient, is a random term, which accounts for the combined effect of the eccentricity of the sensor and a possible incidental load eccentricity. If the sensor were at the centroid of the section, then evidently coefficient k_e would be equal to one, independently of the load eccentricity. In reality the sensors are anchored to the stirrups: naming d_x and d_y the eccentricity of the sensor with respect to the two principal axes of the section and e_x and e_y the corresponding load eccentricity, we have:

$$k_e = \left(1 + \frac{e_x \cdot d_x}{i_x^2} + \frac{e_y \cdot d_y}{i_y^2}\right) \tag{8}$$

where i_x and i_y are the two radii of gyration of the section. The incidental load eccentricity is unknown, thus k_e should be regarded as a random variable with zero mean value, consistent with the design assumption of centered axial load for all the columns. Assuming the standard deviation of each eccentricity component equal to, say, 15% of the corresponding radius of gyration, and the two components uncorrelated, the standard deviation of k_e is calculated as:

$$\sigma_{ke} = 0.15\sqrt{\left(d_x/i_x\right)^2 + \left(d_y/i_y\right)^2} \tag{9}$$

To reproduce the effect of shrinkage we apply the model proposed by Eurocode 2 [10], so:

$$\varepsilon_{sh}(t) = -\varepsilon_{cd\infty} \cdot \frac{t - t_0}{t - t_0 + \beta_{ds}} \tag{10}$$

where $\varepsilon_{cd\infty}$ is the ultimate shrinkage and $\beta_{ds}=141$ day is a term, deterministic, accounting for the effective size of the elements h_0, here for simplicity assumed invariant with the columns.

A priori, the ultimate shrinkage (i.e. the concrete shrinkage at infinity time) is assumed normally distributed with mean value calculated according to Eurocode 2 and a coefficient of variation (CoV) of 40%. We clarify here that the CoV of a distribution is the ratio of the standard deviation to the mean. Similarly, we use the Eurocode 2 model for creep:

$$\varepsilon_{cr}\left(t\right) = \phi_\infty \cdot \sum_{k=1}^{i}\left(\beta_{t0,k} \cdot \frac{t-t_k}{t-t_k+\beta_H} \cdot \Delta\varepsilon_{el,k}\right) \tag{11}$$

where ϕ_∞ is the ultimate creep coefficient; $\Delta\varepsilon_{el,k}$ is the change in elastic strain within time interval t_{k-1} to t_k; $\beta_{t0,k}$ is a corrective term that takes account that each k-th load increment was applied at a time t_k posterior to concrete production time t_0; β_H is a term depending on effective dimension and relative ambient humidity, and estimated in 518 days in our case. We refer the reader unfamiliar with this notation to the text of Eurocode 2 for further details of the model. Here it is important to explain that in our case the parameters $\beta_{t0,k}$ and β_H are set deterministic, while all the randomness of the expression as written is the ultimate creep coefficient ϕ_∞. The prior distribution of the ultimate creep coefficient is assumed Gaussian, with mean value of 2.23, which again is the nominal value suggested by EC2, and 40% CoV. Again, for those readers unfamiliar with concrete design, we note that the large prior CoVs of shrinkage and creep parameters reflect the actual uncertainty typically involved in the prediction of these quantities at the design stage.

4.3. Settlement scenario

In the settlement scenario, or scenario S_2, the mechanical strain model is identical to that of scenario S_1 for all the columns except for column C3, where the total strain of equation (6) includes an additional term ε_{set} incorporating the effect of the settlement. Again, to reduce the number of variables involved and keep the example clear and simple, we can assume that within the time span considered in this investigation the column settlement changed linearly with time, thus:

$$\varepsilon_{set}\left(t\right) = q_{set} \cdot t \tag{11}$$

where q_{set} is the annual rate of elongation of column C3 due to settlement.

5. Analysis and results

To reproduce Branko's perception, we recognize that his initial view is based on the prior blind assumption that a settlement, although theoretically possible, is very unlikely: in numbers, this can be translated as a 1/1000 prior probability of scenario S_2, or 0.999 prior probability of scenario S_1. The perception changed abruptly in Dec 2005 when Branko talked to a HDB engineer, and understood that settlement was not unlikely. After this Branko estimated a settlement as very likely. To formally reproduce this point, we need to separate the initial perception consistent with this information from the knowledge acquired by instrumental monitoring. While the latter point is reproduced via the Bayesian updating process, the new information on the credibility of settlement is taken account for by changing to 2% the prior probability of settlement of column C3.

Table 1 summarizes the parameter distribution assumed *a priori*. The no-settlement scenario includes 12 parameters overall: the 10 eccentricity coefficients ${}^1k_{e,j}$, one per column, the ultimate shrinkage ${}^1\varepsilon_{cd\infty}$ and the ultimate creep coefficient ${}^1\phi_\infty$, the latter two assumed identical for all the elements. All the parameters are assumed Gaussian and uncorrelated.

Scenario S_2 is controlled by the same parameters, whereby the same prior distribution holds, plus the settlement rate q_{set} of column C3. In the mind of the engineer making the judgment, the initial perception is that, if any settlement is ongoing, the value of settlement rate is likely to be within a certain credible range. Consistent with this perception, we set the prior distribution of q_{set} uniform between 0 and 195 $\mu\varepsilon$ year^{-1}, corresponding to a mean annual rate equal to 30% of the maximum

elastic contraction of the column. Taking account of all the sources of uncertainty stated above, the measurement noise e is set Gaussian with a standard deviation considered as 50 με, i.e. roughly 10% of the ultimate strain expected at any column.

Using this prior information and applying recursively equations (2) to (5) we can calculate the posterior probability of each scenario, as well as the posterior distribution of the parameters involved. As apparent in equation (4), the Bayesian updating requires computation of an integral over the parameters domain, which is a very demanding task when the number of parameters is 12 or 13, as in our case. Many numerical techniques are available for this purpose, such as Monte Carlo, Monte Carlo Markov Chain methods and variational methods; an extensive review is provided in the book by MacKey [11]. In this application we made use of the Laplace asymptotic expansion, a deterministic method which approximates the posterior distribution of the parameters with an un-normalized multivariate Gaussian function [12].

The year-by-year results of the analysis are reported in the graphs of figure 3. In detail graphs (b) (c) and (d), show how the distribution of the ultimate shrinkage $\varepsilon_{cd\infty}$, creep coefficient ϕ_∞ and eccentricity coefficient $k_{e,3}$ of column C3 update with time (in the simulated engineering perception). Examination of (a) and (b) show that $\varepsilon_{cd\infty}$ and ϕ_∞ distributions basically do not depend on the scenario. Conversely, the estimate of $k_{e,3}$ changes with the scenario: it can be seen easily that, on the assumption that there is no settlement, the model tries to compensate for the measurement/model deviation assuming additional load eccentricity.

The last graph shows with a logarithmic scale the perceived probability of settlement under two different prior credibility levels: the initial engineering blind perception, and the knowledge-educated perception that other settlements have occurred in the past in similar construction projects, as learnt by Branko in Dec 2005. The bold line reproduces the trend of the settlement probability as perceived by Branko from the beginning of the monitoring period. Initially this probability is regarded as negligible, but as the data from the monitoring system are acquired, it increases gradually with time. In Aug 2004, settlement of C3 started to be considered a credible option, with a posterior chance of settlement prob(S_2)=0.8%; in Jul 2004 the same perceived probability was higher than 2%. Eventually on Dec 2005, after the Dubai discussion, prob(S_2) jumped to above 40% and approached deterministic certainty by the beginning of the seventh year of monitoring. These values are easily compared with the qualitative appreciation of settlement probability reported in the introduction.

Table 1. Prior distribution of random parameters

Scenario 1: no settlement

Variable	distribution	Mean value	Standard deviation
Eccentricity coefficient ^1k_e	Gaussian	0	as per Eq. (11)
Ultimate drying shrinkage $^1\varepsilon_{cd\infty}$	Gaussian	315 με	126 με
Ultimate creep coefficient $^1\phi_\infty$	Gaussian	2.23	0.89
Noise ^1e	Gaussian	0	50με

Scenario 2: settlement of column C3

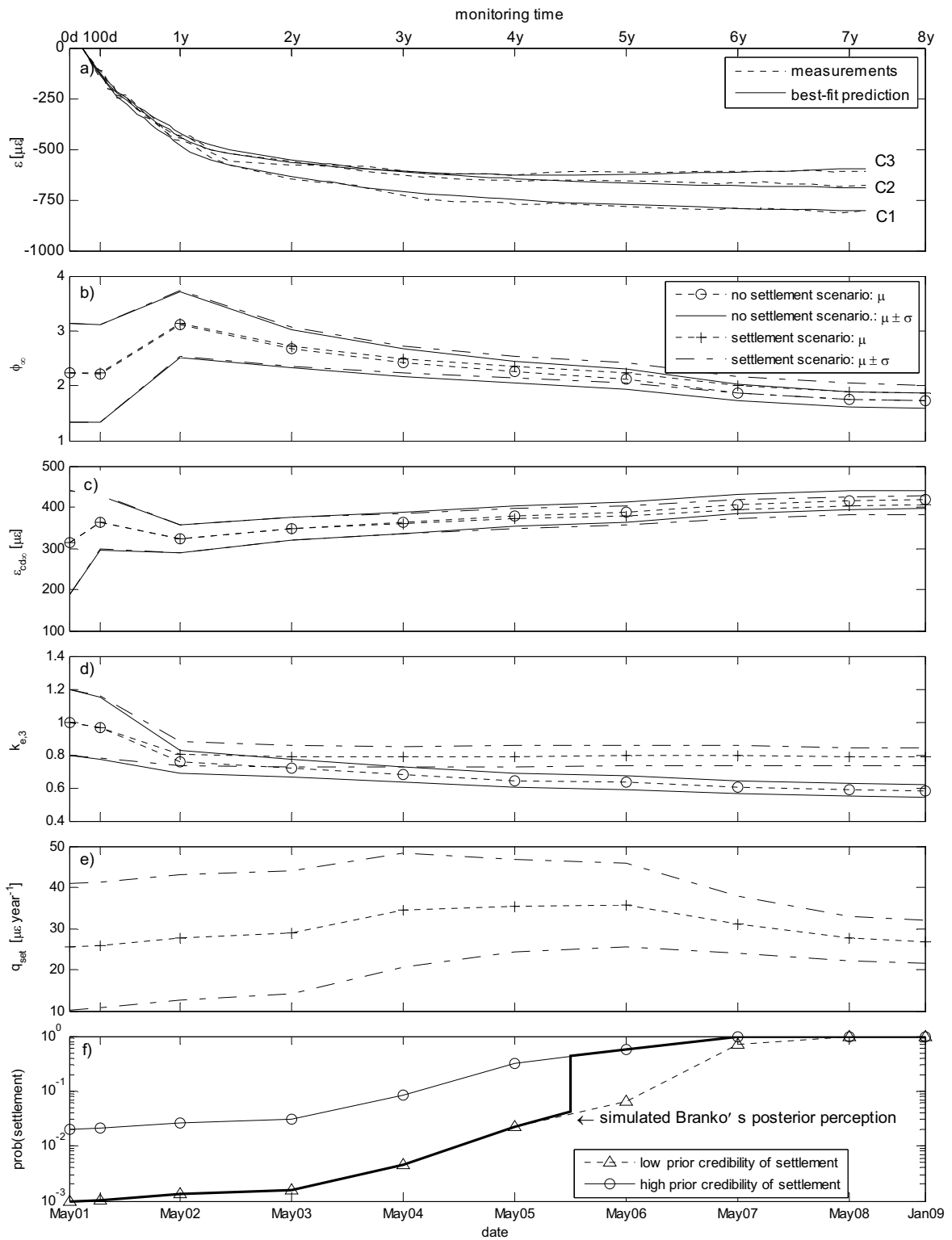| Variable	distribution	Mean value	Standard deviation
(Same variables and distributions as above, and in addition...)			
Settlement rate of column C3 q_{set}	Uniform [0, 195]	97 με year^{-1}	$97/\sqrt{12}$ =33 με year^{-1}

Figure 3: Recorded and simulated response of columns C1, C2 and C3 (a); posterior distribution of ultimate creep coefficient (b), ultimate shrinkage (c) and eccentricity coefficient of column C3 (d) in the two scenarios; posterior distribution of settlement rate (e); posterior probability of settlement under low and high prior credibility, and Branko's posterior perception (f).

6. Epilogue

Princeton, Dec 12, 2010. (...) Branko, in the end, what can we conclude from this story?
- The joint knowledge of monitoring response and past engineering experience let us recognize early even the small settlement occurring at Punggol E26 block.
- Bayesian logic helped not only to estimate the most likely value of settlement, creep and shrinkage, but also the degree of confidence of this information.
- Bayesian inference is a tool which allows quantitative handling of both mechanical behavior and engineering perception, be it experience or common sense.
- After all, any mechanical model aiming to reproduce the physical response of a structure is in fact a model of the reality as perceived by the engineer…
- … by the way where's Matteo, first author of this paper?
- In Trento packing his bags: he's off to Berkeley.
- That's great news. More coffee?

Acknowledgements

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