

Swelling effects in a reinforced concrete pier of Foz Dão bridge (Portugal). First approach for modeling and behavior interpretation

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Abstract.

The degradation of the Foz do Dão bridge, that served the IP3 road and is located over the Agueira dam reservoir, in Portugal, mainly due to the internal swelling reactions in concrete, resulting in visible cracking in its piers, led to the bridge replacement in August 2015. Since 2009, this bridge has been subject to several inspections, including underwater inspections, laboratory tests of cores, as well as periodic geometric levelling of the deck and ambient vibration tests. These actions were aimed to characterize its structural behaviour and to detect damage growth that might jeopardize safety.

The aim of this work is to characterize and interpret the structural behaviour of the highest pier. For this purpose, a three-dimensional numerical model, which considers the environmental conditions and the time-dependent behaviour of the concrete, was developed. The loads applied to the pier are the dead-weight of pier and the weight of the bridge deck, the pressure of the reservoir water, the effects of the thermal variations and of the swelling. The computing of the expansions considers the influence of the temperature and of the confining effect of the rebars and of the stress fields. The temperatures variations at the pier were computed using a thermal model. The model was calibrated considering data obtained by laboratory tests, on samples extracted from the bridge and by the deck levelling.

Keywords: Bridge, Internal Swelling Reactions, Pier, Viscoelastic Model.

1 Introduction

The bridge over the mouth of the River Dão, located over the Agueira dam reservoir, is 382 m long. The deck is of the girder type, composed of four longitudinal beams spaced 4 m apart and by crossbeams placed on the thirds of intermediate spans and also on the supports at the piers and abutments. This bridge, built in 1980, is degraded due to alkali-silica reaction, and, for that reason, it was replaced and closed to traffic in 2015 [1]. The new bridge was built in parallel as shown in Fig. 1.

The bridge has 8 reinforced concrete piers, composed by a shaft with a diamond cross-section and chamfered apices, with internal casting, with heights varying from 20 m to a maximum of 85 m (see Fig. 2).



Fig. 1. Bridge over the mouth of the Dão river. Old structure affected by the expansive reactions and, in parallel, the new box girder deck bridge.

Following an underwater inspection campaign, it was found that there were generalized anomalies, mainly in the submerged elements, associated with swelling reactions [1], namely vertical cracks in the pier shaft and random oriented cracks in the footing.

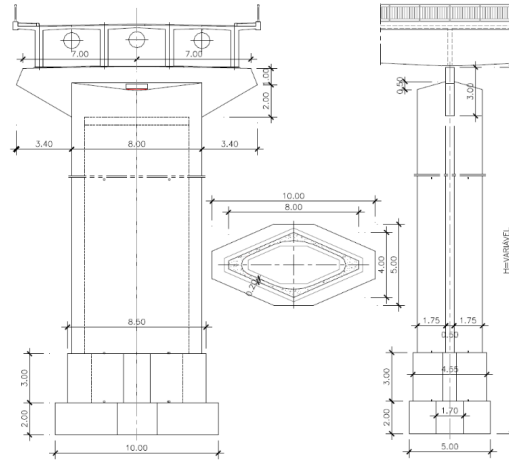


Fig. 2. Foz do Dão bridge piers dimensions [1].

From 2009 to 2021, this bridge has been subject to several inspections, including underwater inspections, laboratory tests of cores, as well as periodic ambient vibration tests [2] and geometric levelling of the deck for measuring the evolution of the vertical displacements of the deck over the piers [3]. The results of the surveys shown upward incremental displacements over time, consistent with the concrete swelling, and, also, with the decrease of stiffness identified by the ambient vibration tests. The last surveys pointed to clear deceleration of the displacement rates, in accordance with the stiffness stabilization determined by the ambient vibration tests. Laboratory tests performed in cores extracted from the piers in 2012, to access the concrete deterioration, also indicated that the remaining expansion potential of the concrete was low [4].

The main goal of this paper is to interpret the structural behaviour of the pier P5, the highest pier, by using numerical models, which are a very important tool in the management of structures affected by internal swelling reactions [5-7].

2 Numerical models

2.1 Finite element mesh

The finite element mesh used for modelling the structural and thermal behaviour of the pier and its rocky foundation is shown in Fig. 3. Due to the pier bi-symmetry, only one quarter of the pier was discretized. The mesh has a total of 50404 nodal points for 41646 volumetric 8-node hexahedral elements (38114 corresponding to the concrete pier and 3532 to the rock foundation) and 20482 2-node bar elements, to represent the rebars.

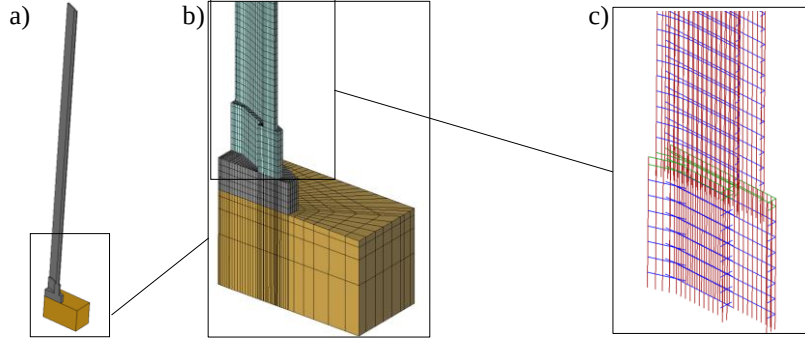


Fig. 3. Finite element mesh: a) pier and the rocky foundation (geometry); b) mesh detail of the pier bottom and of the rocky foundation; c) rebars mesh at the pier bottom.

2.2 Thermal model

The temperature distribution in the pier over time was computed by using a finite element code developed at LNEC [8] that solves the transient heat conduction equation, considering the air and water temperatures on the external pier surfaces.

The air and water average temperatures were represented by sinusoidal waves of annual period (1), where T_m is the average annual temperature, S_a is the semi-amplitude and ϕ is the number of days between the beginning of the year and the day of the highest temperature.

$$T(t) = T_m + S_a \cos \left(\frac{2\pi}{365} (t - \phi) \right) \quad (1)$$

The wave parameters were determined numerically by the least square method. For the air the adjusted wave curve is characterized by a mean annual temperature of 15.5 °C and a semi-amplitude of 6.9 °C. For the water reservoir, the temperature variation through depth was adjusted considering the monitoring values in 2 thermometers, located at different depths on the dam upstream face (Fig. 4).

No specific tests were performed for characterizing the thermal properties of the concrete, so the following values were considered, which correspond to average values for the concrete: thermal conductivity $k = 2.6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, specific heat capacity $c = 920 \text{ J}/(\text{kg} \cdot \text{K})$ and thermal expansion coefficient $\alpha_c = 1.0 \times 10^{-5} / ^\circ\text{C}$.

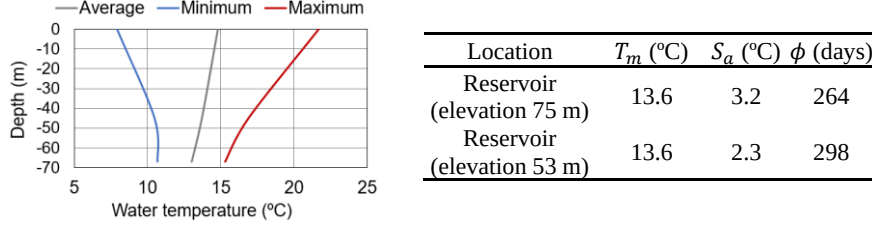


Fig. 4. Variation through depth of the water average annual temperature and amplitude (on the left) and parameters of the annual thermal wave curve (Eq. 1) at 2 different depths (on the right).

2.3 Swelling model

The concrete free swelling model assumes that the structural expansion evolution depends on the uncoupled effects of the temperature g_T , the internal humidity g_H and the stress state g_σ , according to the following equation:

$$\varepsilon_{exp}(H, T, \sigma, t) = \varepsilon_{exp,\infty} \xi_{exp}(t) g_H(H) g_T(T) g_\sigma(\sigma) \quad (2)$$

where $\varepsilon_{exp,\infty}$ is the long-term expansion (for a reference temperature T_{ref} and relative humidity of 100%) and ξ_{exp} is a function representing the time evolution of the expansive reaction, varying from 0 to 1. For ξ_{exp} an exponential sigmoid function is used, with a profile similar to the curves obtained in laboratory tests,

The adopted function for g_T (T is the temperature in Kelvin) is:

$$g_T(T) = e^{6000\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \quad (3)$$

The function g_σ , that considers the anisotropy of the expansion due to the stress state, is used independently in the three principal stress directions and is evaluated from an exponential curve, that was adjusted in LNEC to the experimental results obtained by Clayton [9] and Larive [10] (Fig. 5).

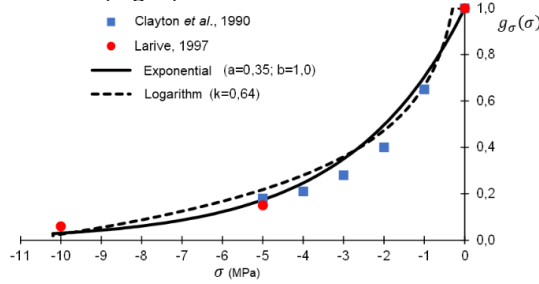


Fig. 5. Influence of the stress field on the swelling development

Relatively to the internal humidity effect, in this work it is admitted that there is always water to feed the reaction ($g_H = 1$). This simplification needs to be improved in future work, since the top zones of the pier, above the water level, can dry out during the dry season.

Fig. 6 shows the free swelling curve used in the numerical simulation until 2023, which has expansion long-term value of 2500×10^{-6} . The curve parameters were estimated considering information from the laboratory tests [4] and by using an iterative procedure to match the computed and the observed irreversible vertical displacements at the pier top.

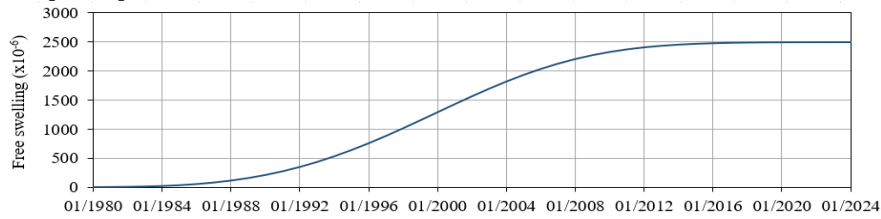


Fig. 6. Free swelling for the reference temperature of 14 °C.

2.4 Structural model

The structural modelling was performed by using a finite element code, that is being developed at LNEC [11-1414]. The concrete dead weight was applied instantaneously in an initial stage by means of vertical body forces. The water pressure was simulated by surface loads, applied on the external and internal faces of the pier, according to the reservoir level evolution (Fig. 7). The concrete temperatures and expansions were computed by using the thermal model and the expansive action model, respectively. The loads were applied considering a temporal discretization of two weeks.

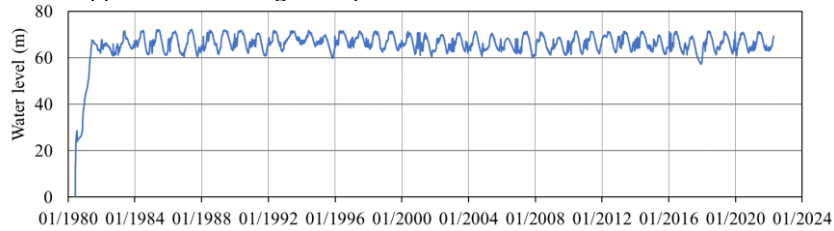


Fig. 7. Reservoir level from 1980 to 2022.

Two types of concrete were considered, one corresponding to the footing and the other to the pier concrete. The concrete deformability was simulated by a viscoelastic model, characterized by Poisson ratio of 0.2 and by the Bažant-Panula creep law [11], with the parameters shown in Table 1.

The behaviour of the rocky foundation and of the rebars (transversal and longitudinal) was considered linear elastic with modulus of deformability of 15 GPa and Poisson ratio of 0.2, for the rock mass, and 210 GPa and 0.2 for the rebars.

Table 1. Parameters of the Bažant-Panula creep law.

	E_0 [GPa]	Φ_1	m	β	n
Concrete footing	48	1,484	0,256	0,222	0,116
Pier	40	0,770	0,236	0,160	0,138

3 Results

The temperature fields for summer and winter are presented in Fig. 8: in summer, the higher temperatures occur in the emerged areas at the pier top (22.3°C), while in winter the opposite is true, with the lower temperatures occurring also at the pier top (8.6 °C).

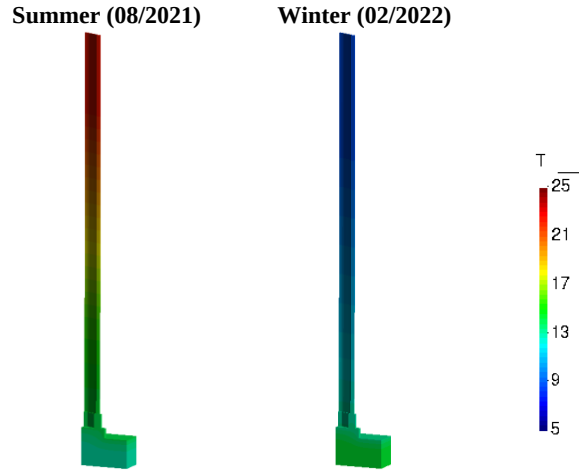


Fig. 8. Computed temperature fields in the pier in summer and winter.

Fig. 9 shows the evolution of the vertical displacements computed by the model, from 1980 to 2022, as well as the values from the geometric levelling measured at two different locations of the pier (upstream and downstream). The monitoring data is available only from the end of 2009 to the end of 2021. In this period, a good agreement between computed and observed values is noted. The computed response is also depicted in the second plot of Fig. 9, but the effects are separately represented, so the relative weight of each effect can be evaluated. The elastic response due to the permanent loads (dead-weight, deck weight and hydrostatic pressure) is close to 7 mm, about the same than the delayed response. The amplitude due to the thermal variations is higher, around 10 mm. After the nineties the swelling action starts dominating the vertical response of the pier, reaching values larger than 85 mm in 2023.

The stress fields and the structural expansions in the xx , yy and zz directions are presented in Fig. 10. The pier compressions in the xx direction are higher than in the yy direction, which leads to higher expansions in the yy direction. The vertical stresses increase from the top to the bottom of the pier shaft (due to the pier dead-weight), being lower at the basement and at the footing because of their wider sections. The higher vertical expansions occur in the footing, in the zones where tensile stresses occur.

The higher stresses in the rebars are computed in the zones where the swellings are higher, namely at the horizontal bars near the pier top (Fig. 11), where the tensile stresses reach values of about 530 MPa, larger than the steel strength (400 MPa), which leads to the yielding of the rebars. Unfortunately, no field measurements are available to confirm the yield of the rebars at this zone of the bridge.

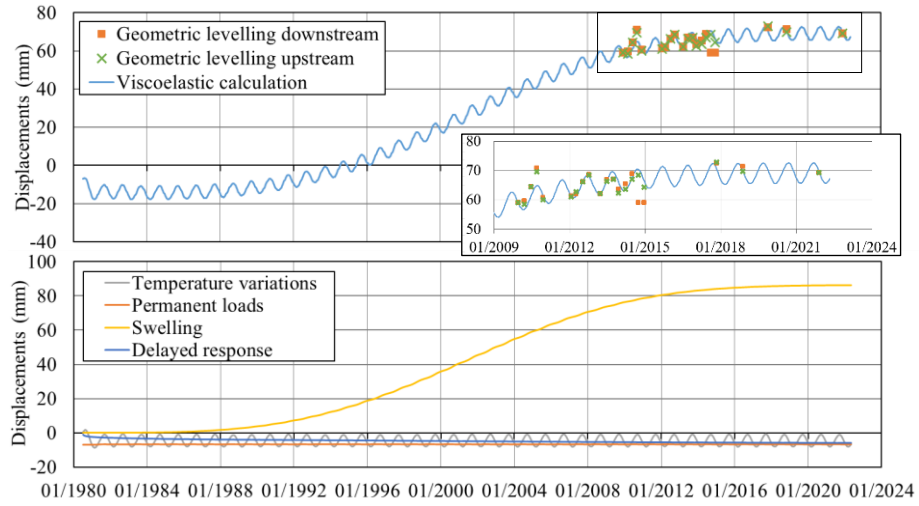


Fig. 9. Vertical displacements at the pier top, measured by geometric levelling and computed.

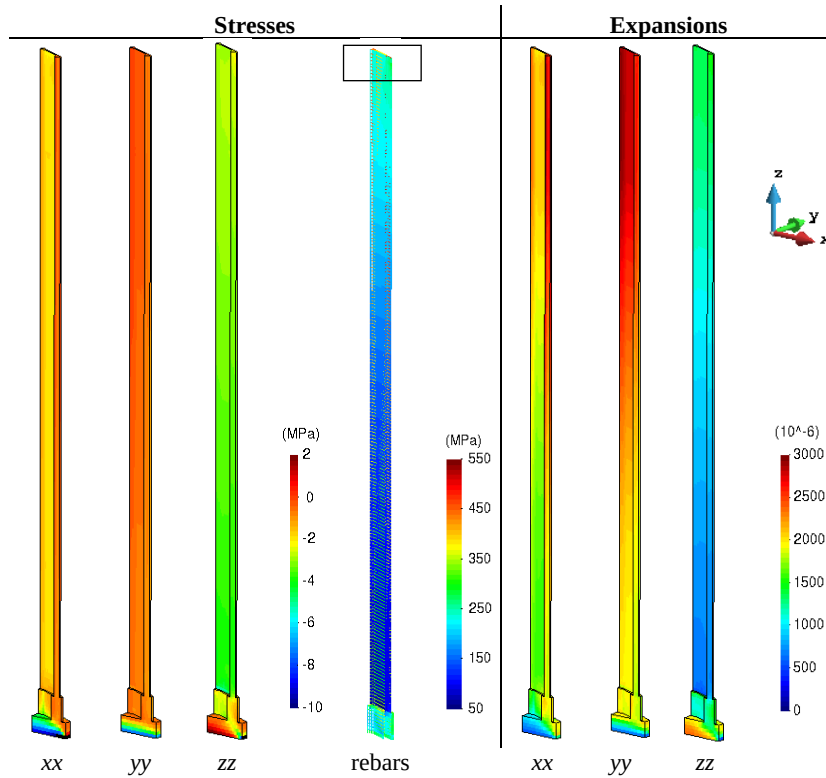


Fig. 10. Computed stresses and swellings for the three spatial directions.

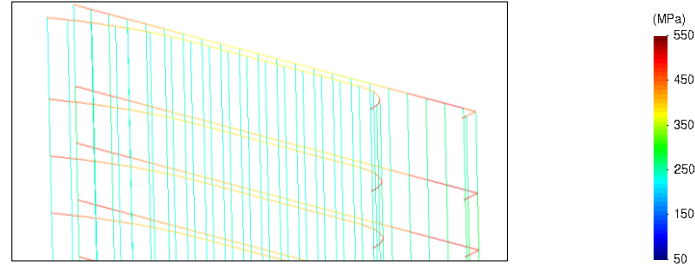


Fig. 11. Detail of the rebar stresses at the top of the pier.

4 Discussion and final remarks

In this paper the results obtained in a first approach for modeling and interpreting the swelling effects in a reinforced concrete pier of Foz Dão Bridge were presented. The vertical displacements measured by levelling and computed showed a good agreement, but the monitoring data is only available for the last 15 years. It was also shown that the computed structural expansions were highly dependent on the confinement effects due the stresses and the rebars.

Notice that the estimated long term expansion (2500×10^{-6}) has a high uncertainty, since, the available information of laboratory tests is scarce and the monitoring data is only available for the last 15 years. This will be addressed in subsequent work, by considering different scenarios of maximum expansion. Nevertheless, the last levelling surveys pointed out a clear deceleration expansion rates, in accordance with the stiffness stabilization determined by the ambient vibration tests and the results of laboratory tests, that indicated a low remaining expansion potential of the concrete.

The numerical modelling performed in this first approach relied in some assumptions, introduced along the paper, that induce uncertainty on the results in terms either of the computed displacement and stress fields. Since some of the simplifications can have a high influence in the computed results, in future work, the model will be improved in the following:

- i) develop a hygrometric model, so the effect of the concrete internal humidity will be taken into account in the swelling model;
- ii) model the non-linear behavior of the concrete, by using a visco-damage model, and of the reinforcement bars, by using a elasto-plastic model, so the yielding of the rebars can be considered in the analysis;
- iii) consider different scenarios of maximum expansion, to handle the uncertainty associated to the estimation of the long term expansion;
- iv) model the depreciation of the Young's modulus induced by the swelling, since the estimated expansion is of large magnitude.

These improvements will allow to quantify the influence of the aforementioned simplifications, to better interpret the actual condition of the pier and to estimate its residual structural capacity.

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