Application of hybrid HSCT-FE models to identify the swelling effect on a multiple arch dam

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Abstract

The safety control of large dams is based on the comparison between numerical model results and observation data. In the analysis of the observed behavior of dams it can be used statistical models for effects separation of the type HST or HSCT, numerical models of Finite Elements (FE), or, as proposed in this paper, hybrid models: HSCT-FE models. These hybrid models allow the separation of the main load effects, namely: elastic effect of hydrostatic pressure (H), seasonal effects due to environmental temperature variations (S), creep effect due to hydrostatic pressure (C), and other time effects (T), like the concrete swelling effect and the effect of creep due to the self-weight. These hybrid HSCT-FE models are being developed as an improvement of the traditional Hydrostatic-Seasonal-Time (HST) models because they are able to successfully isolate different components of the time effects. In these hybrid models, FEM results are used to calculate the self-weight creep response (using the computed FEM elastic response). The elastic and creep response to the hydrostatic pressure can be directly calculated by linear regression or can also be pre-defined using FEM results. The swelling effect is usually assumed as another time effect not related with the creep due to hydrostatic pressure nor self-weight.

The case study considered is Aguieira dam, an 89 m high multiple arch dam, with three double curvature arches and two central counterforts. This dam presents signs of swelling reactions, namely it was detected the typical cracking patterns, at both central counterforts bases, and the typical increase in the strain histories measured on the isolated strain gauges.

Keywords: *swelling reactions effect; FEM; HSCT models; HST models; large dams*

1. INTRODUCTION

The safety control of dams under operation is based on the comparison between observed data from monitoring systems and numerical data from mathematical models developed to simulate/predict the dam behaviour over time. Semi-statistical models for effects separation are usually adopted for the direct analysis of observed data, Hydrostatic-Seasonal-Time (HST) or Hydrostatic-Seasonal-Creep-other Time effects (HSCT) models. The Finite Element Models (FEM), based on the fundamental equations of structural mechanics are generally used for studies on simulation/prediction of dams' behaviour under operational conditions and studies for verification of dam safety conditions.

For the detection of abnormal behaviour derived from the pathological effects, e.g. concrete swelling effects, it is necessary to use robust models for effects separation, capable of distinguishing normal time effects, related to viscoelasticity, from other time effects, e.g., related to concrete swelling.

In this paper, a hybrid HSCT-FEM model is proposed, and it is applied to the case study of Aguieira dam (Figure 1.1).

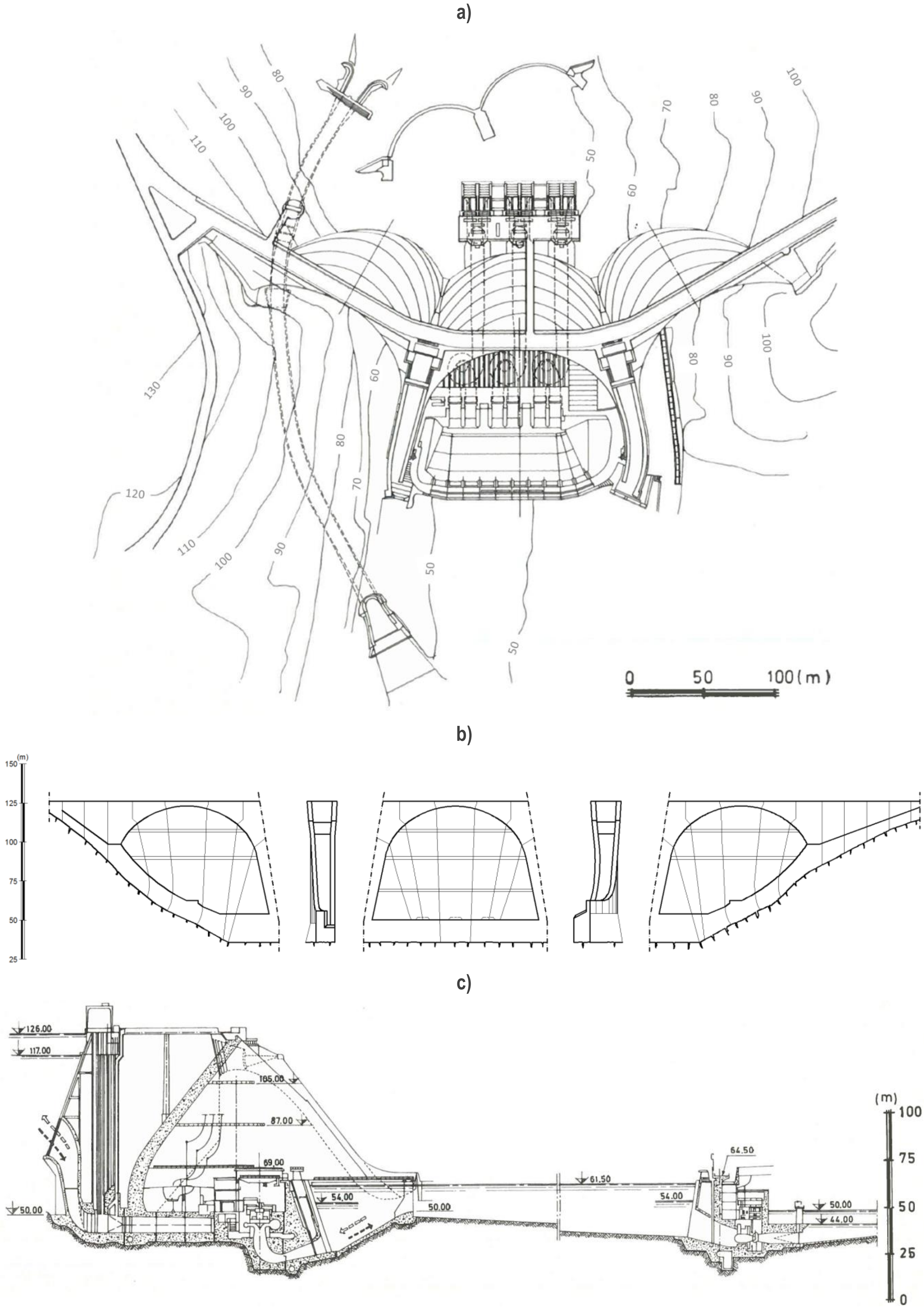

Figure 1.1: Aguieira dam. a) Downstream view; b) Plan view; c) Arches front developed view and counterforts front view; d) Cross section from the dam axis including the downstream Raiva dam

2. MODELS FOR EFFECTS SEPARATION OF THE TYPE HST, HSCT AND HSCT-FEM

The main purpose of the effects separation models is to isolate each load effect, enabling the detection of anomalous or pathological behaviour.

From the dam pathologies that can develop over time, the swelling is becoming more relevant, arousing the interest for its evolution and subsequent effects study. Many concrete dams have registered problems related to the swelling derived from the chemical reactions occurring between cement components and the aggregate, namely alkali-silica reactions (alkalis present in the cement and silica in the aggregate) [1-3]. The swelling reactions occur with relatively high humidity and temperatures, producing a gel that fills the concrete internal microstructure pores. This process eventually generates cracking, the consequent concrete damage, and a global volume increase (swelling). Many dams have problems created by the swelling reactions, the most serious cases in Portugal are: Alto Ceira, Fagilde, Santa Luzia and Pracana. The former Alto Ceira dam is an extreme example of the concrete swelling pathological effect consequences, which led to the dam decommissioning and precipitated the construction of Alto Ceira II dam, immediately downstream.

The proposed HSCT-FEM model, as the name suggests, allows the FEM and HSCT models integrated use. Additionally, the HSCT is able to separate the creep structural effect [4-6] from the other time effects. Consequently, the adopted regression model has the following composition.

$$u\left(h,T_{\mathrm{air}},t\right)=u_{\mathrm{e}}^{\mathrm{HP}}\left(h\right)+u_{\mathrm{e}}^{\mathrm{T}}\left(T_{\mathrm{air}}\right)+u_{\mathrm{C}}^{\mathrm{HP}}\left(h,t\right)+u_{\mathrm{C}}^{\mathrm{SW}}\left(t\right)+u_{\mathrm{swe}}\left(t\right)+k \quad (1)$$

Hence, the HSCT models are capable of making the time effect separation into one creep component related to the hydrostatic pressure (HP), one creep component associated with the self-weight (SW), and one other time effects component (for example, swelling, foundation movements, *etc.*). To single out the creep effect is important to distinguish the SW creep from the HP creep, for this purpose is useful to estimate the elastic response component for both loads. This procedure can be executed by the FEM.

The adjustment functions used to represent each separated effect correspondent to each term of the presented regression equation (Equation 1) is presented in Table 2.1.

Table 2.1: Adjustment functions used for each term of the regression equation

Term	Effect	Adjustment function
$u_{\mathrm{e}}^{\mathrm{HP}}\left(h\right)$	Hydrostatic pressure elastic effect	$a\left(e^{h/c_{\mathrm{f}}}-1\right),\quad 15\lesssim c_{\mathrm{f}}\lesssim 35$ (alternatively, the *a* value can be determined by the FEM)
$u_{\mathrm{e}}^{\mathrm{T}}\left(T_{\mathrm{air}}\right)$	Temperature effect	bT_{air} or $b_1\cos\left(\frac{2\pi\bar{t}}{365.25}\right)+b_2\sin\left(\frac{2\pi\bar{t}}{365.25}\right),\ \left(0<\bar{t}<365.25\text{ days}\right)$ [7]
$u_{\mathrm{C}}^{\mathrm{HP}}\left(h,t\right)$	Hydrostatic pressure creep effect	$\sum\phi(t)\,\Delta u_{\mathrm{e}}^{\mathrm{HP}}$
$u_{\mathrm{C}}^{\mathrm{SW}}\left(t\right)$	Self-weight creep effect	$\phi\left(t\right)u_{\mathrm{e}}^{\mathrm{SW}}$
$u_{\mathrm{swe}}\left(t\right)$	Swelling	$c\times\left(1-e^{-t^{n}/\beta}\right)$ where $\beta=t_{\mathrm{hs}}^{n}\times n/(n-1)$, $n=3.258$ and $t_{\mathrm{hs}}^{n}\simeq 8000\text{ days}$ (hs – half swelling)
k	Independent term	-

Table 2.1 displays the use of an exponential function to represent the HP elastic effect, alternatively, the FEM results can be used to better define the form of the exponential function that characterizes the elastic response to the HP variation (in Figure 3.4 left side is displayed the comparison between the results of the exponential function adjustment for the HP elastic effect and the results of the FEM for the same effect).

The HP creep effect is obtained by the water level variation discretization in even steps and the consequent application of the creep coefficients to the elastic displacement values calculated for each even water level step. The viscoelastic response is equal to the overlapping creep effect of each even step, in another words, is equal to the sum response of the monthly water level discretization. The creep effect estimation for the water level variation is given by the following equation.

$$u_{\mathrm{C}}^{\mathrm{HP}}\left(h,t\right)=a\times\left[\sum_{j=1}^{p}\phi\left(t,t_j^{'}\right)\left(e^{h_j/20}-e^{h_{j-1}/20}\right)-\sum_{j=1}^{p'}\phi\left(t_a,t_j^{'}\right)\left(e^{h_j/20}-e^{h_{j-1}/20}\right)\right] \quad (2)$$

Figure 2.1a presents a theoretical example of a reservoir water level evolution over time and its discretization for the abovementioned calculus. Figure 3.4 presents the case study results for the HP creep effect with a dark blue colour curve. There, it is noticeable the displacements gradual increase over time.

The temperature effect can be simulated with the air temperature values registered at the site (is usual to apply a phase shift of approximately 20 to 30 days, which is roughly the dam response time to an air temperature variation) or by harmonic functions with annual and/or half annual period [8]. The structural response to the temperature is presented in Figure 3.4 by the orange colour.

The self-weight (SW) creep effect is a viscoelastic dam response to the SW load. The SW is a constant action following gravity's direction, applied to the whole structure, developing a creep effect that can be estimated by the elastic displacements predicted by the FEM for the SW, based in the creep coefficients estimated by the creep function and taking into account the structure concrete mean age from the end of the construction period.

Figure 2.1b presents a theoretical example of evolution over time of the two SW displacements components, with the grey colour, the creep displacements component, u_C (u_e is the SW elastic response determined by the FEM). Figure 3.4 displays, for the case study, with the green colour, the displacements evolution over time derived from the SW creep.

The adjustment function associated with the displacements created by the swelling effect is presented in Table 2.1 and its development over time is presented in Figure 3.4 by the red colour line. The result is a sigmoid type curve, which slowly increases over time until half of its total displacement, where, at that point, changes from convex to concave (inflection point), moving then towards stabilization. The referred curve inflection, in what relates to swelling, is also named half-swelling point. For this study a half-swelling time of 8,000 days (approximately 20 years) was considered.

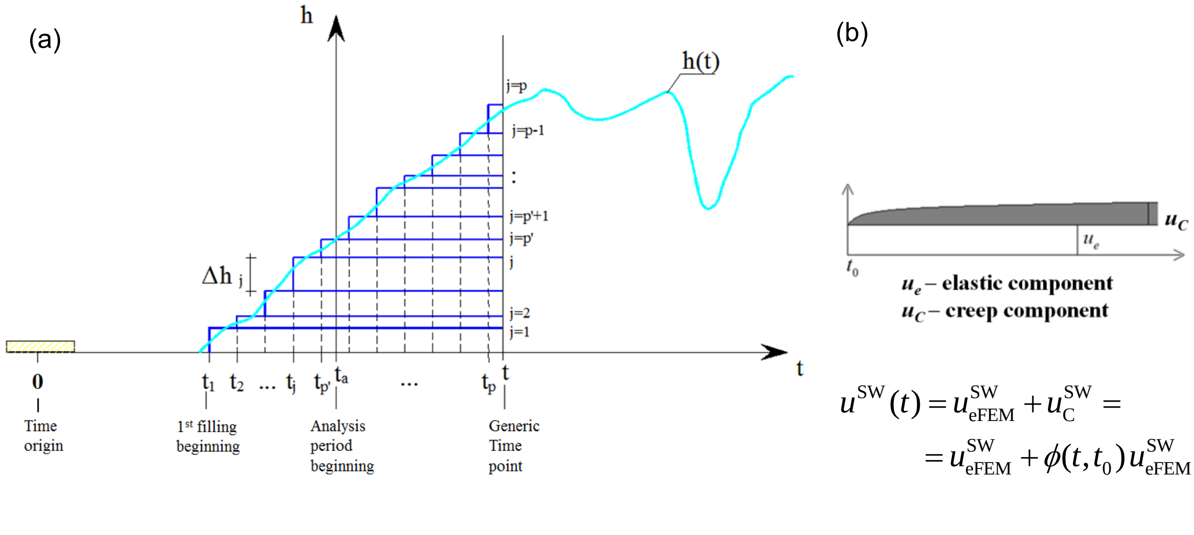

Figure 2.1: Creep behaviour over time. (a) Reservoir level discretizations in intervals (the reference epoch for time counting is approximately coincident with the mean construction period date). (b) Self-Weight (SW) elastic creep component

The independent term *k* is included in the model so it can take into account the initial observation (the first epoch of the analysed period), *id est*, *k* contains the variability of the dependent variable (displacements) not explained by the independent variables (effects).

With this formulation, with the observation data, with a FEM model and with the resort to the Least Squares Method (LSM), is obtained a curve adjusted to the observations (grey colour curve in Figure 3.4). It is important to point out that, before applying the LSM, the SW creep component is subtracted from the observed displacements values.

In order to obtain reliable results for the HSCT-FEM outputs is convenient to have observations in quantity, preferably obtained with assured quality and well distributed over time, where observed values are present at each year's seasons and at water levels representative of all the reservoir filling levels.

3. ANALYSIS OF AGUIEIRA DAM BEHAVIOR USING HYBRID HSCT-FEM MODELS

The present paper presents the measured displacements histories with the use of the plumb-line method, the geodetic method and the levelling method. The planimetrics results (plumb-line and geodetic methods) are associated with the horizontal displacements while the levelling is related to the vertical displacements.

Aguieira dam was used as the case study. Aguieira dam has a maximum height of about 90 m and is composed by 3 double curvature arches and two counterforts. This dam is nearly 40 years old, displaying small scale traces of swelling, observable through visual inspection in certain location and from the measurements at the isolated strain gauges. Aguieira dam geometry is presented in Figure 1.1 by its plan, front and cross section views.

For all observed dam points a HSCT-FEM model was considered with the following characteristics: (i) c_f value, associated with the HP elastic effect component (Table 2.1 – 1st row), equal to 25, with the *a* parameter being previously locked so it can be adjusted to the FEM calculated results; (ii) the temperature elastic effect is represented by an harmonic wave (Table 2.1 – 2nd row); (iii) the HP creep effect is simulated by the creep coefficients application to the elastic response, for the monthly water level history discretization in constant intervals, and considering a concrete material with a Bazant and Panula creep law in which: $E_0 = 41.5$ GPa, $\phi_1 = 1.6$, $\beta = 0.05$, $m = 0.33$ and $n = 0.22$, matching a concrete moderately damaged by swelling (Table 2.1 – 5th row, Equation 2 and Figure 2.1a); (iv) the SW creep effect is determined with the creep coefficients application to the elastic displacements estimated by the FEM for the SW action (Table 2.1 – 4th row and Figure 2.1b); (v) time effect related to swelling is given by the sigmoid shaped curve which is characterized by the expression present in Table 2.1 (5th row).

As mentioned, for the use of HSCT-FEM hybrid models are necessary results from a FEM model, specifically, in what is related to the developed model applied for the Aguieira dam case study, it's necessary results from the HP and SW elastic effects. The FEM model is also necessary for the results comparison between HSCT-FEM and FEM models. Figure 3.1 displays the adopted model.

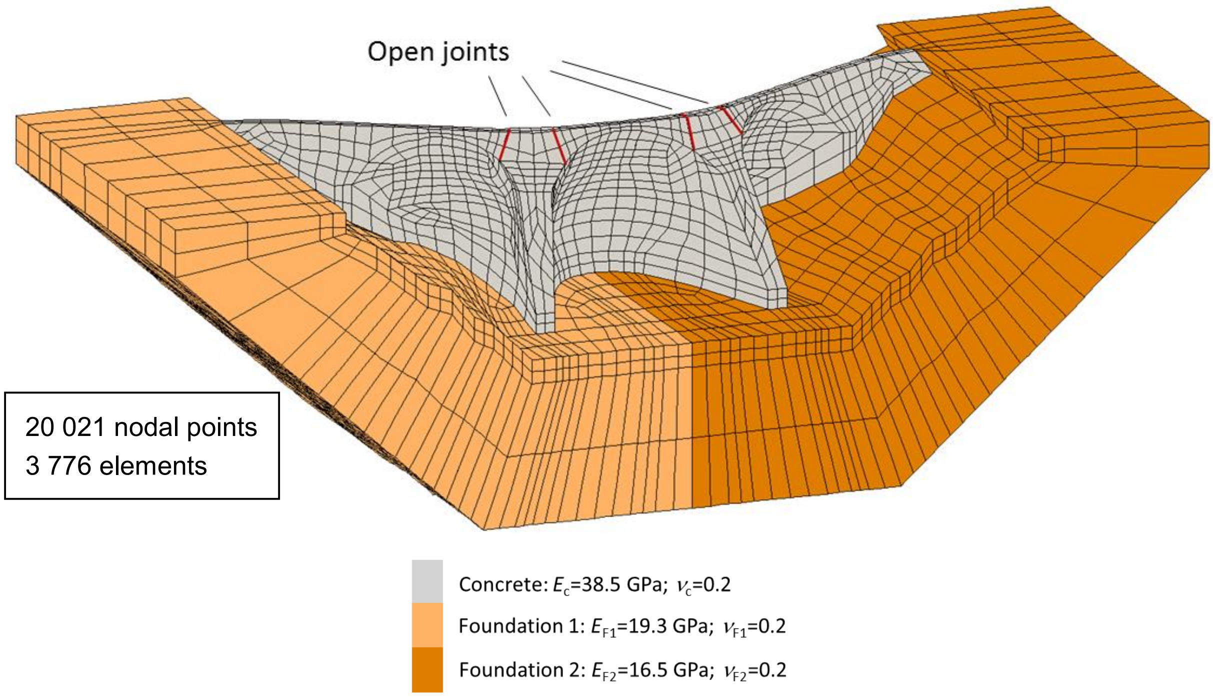

Figure 3.1: Aguieira dam FEM model.

The presented FEM model used isoparametric 20 nodes elements, with 27 Gauss points for the numerical integration. Since one of the main objectives is to make an accurate separation of effects in order to isolate the swelling effect from the observed results, to verify if this isolated effect resulting from the hybrid HSCT-FEM separation of effects is coherent, the results from it must also be coherent with the results from the FEM model. Therefore, to calculate the swelling effect from the FEM is necessary to estimate the swelling action for the accumulated period from the construction until the present date. This action, in order to have a valid FEM model, must be coherent with the observed from the isolated strain gauges scattered along the dam body. The program Expand2014 [8] was used to calculate the swelling load, considering, as input, the thermal and hygrometric field histories in dam body (calculated with PAT2.0 [9], from the temperature and humidity observed in dam faces), and the main parameters that govern the swelling reactions kinetic. The computed swelling values accumulated in the period 1984-2016, presented in Figure 3.2, show a good agreement with the accumulated swelling observed in the isolated strain gauges located in the dam body (Figure 3.3).

Since Expand2014 does not take into account the damage evolution over time and therefore the associated redistribution of stresses is not integrated, the swelling law can possibly be underestimated. Although, it is relevant to mention that, both, the expansive reaction and the dam global response are continuously under analysis. The observed global response include possible damage effects produced by the swelling reactions. Hence, the HSCT-FEM hybrid statistical model adjusts itself to the observations and the resulting displacements histories due to swelling should present a time evolution coherent with the strain histories directly measured on the isolated strain gauges, that should be also in a good agreement with the computed swelling values from Expand2014.

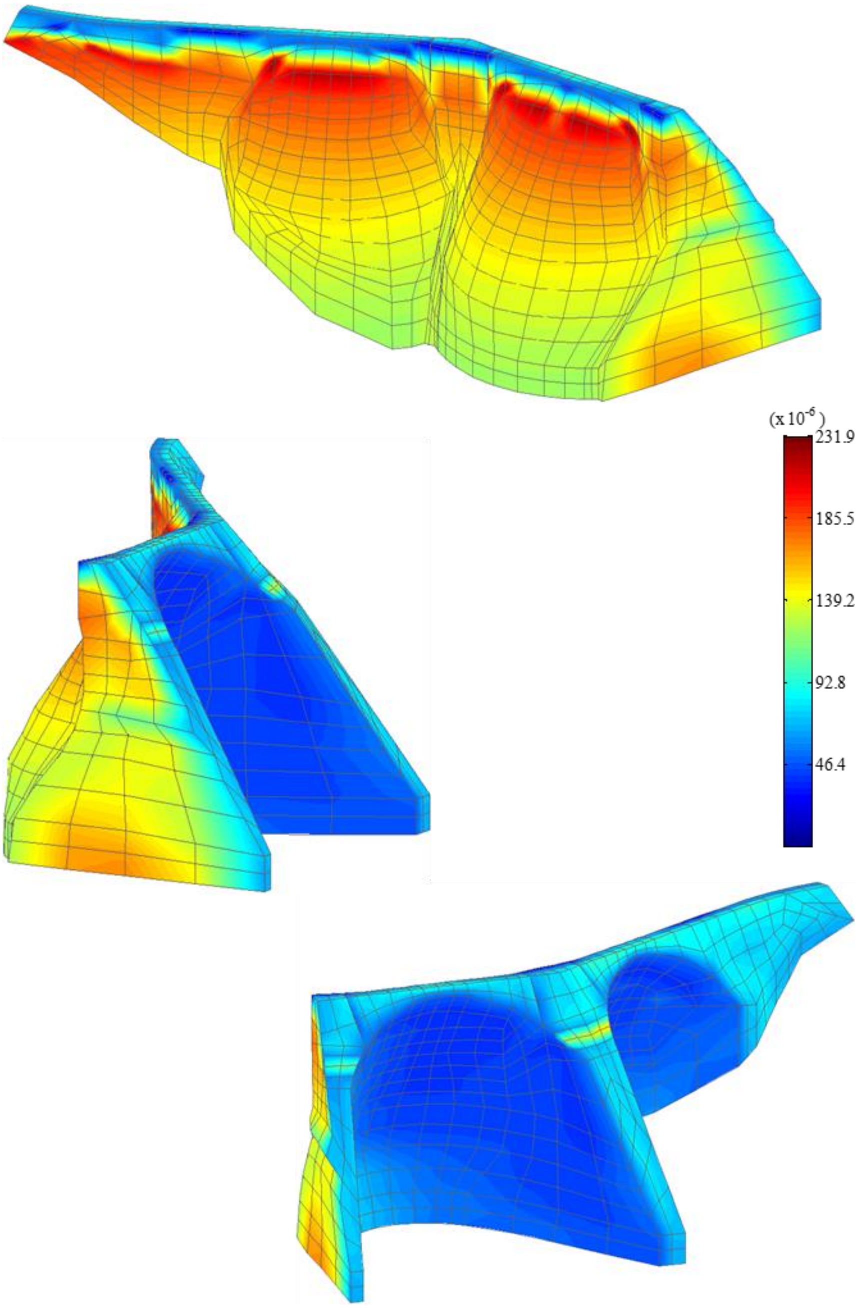

Figure 3.2: Accumulated swelling from 1984 to 2016. Results from Expand2014 [8]

As referred above, from the comparison between Figure 3.2 and Figure 3.3, it can be concluded that there is a coherency between the computed and observed swelling strains accumulated in the period 1984 to 2016. The computed values in the upstream face are mainly higher than in the downstream face, just like it is observed in the isolated strain gauges. Additionally, it can be emphasized that the highest values calculated with Expand2014 and the highest values observed with the isolated strain gauges are of about 230×10^{-6}.

Figure 3.4 presents the HSCT-FEM results for the radial displacements at the geodetic mark located at the centre of the central arch, at 122 m of elevation (near the crest). From its analysis is possible to verify the good adjustment HSCT-FEM obtained in the HP elastic effect and temperature effect diagrams (at the figure left side). In the first, as the water level increases, the downstream radial displacement increases, with an approximate maximum value around 21 mm (for the maximum reservoir water level); in the second, the maximum displacement in the winter is equal to 4 mm towards the downstream direction and is equal to -4 mm in the summer (towards the upstream direction). The temperature effect follows the referred harmonic behaviour.

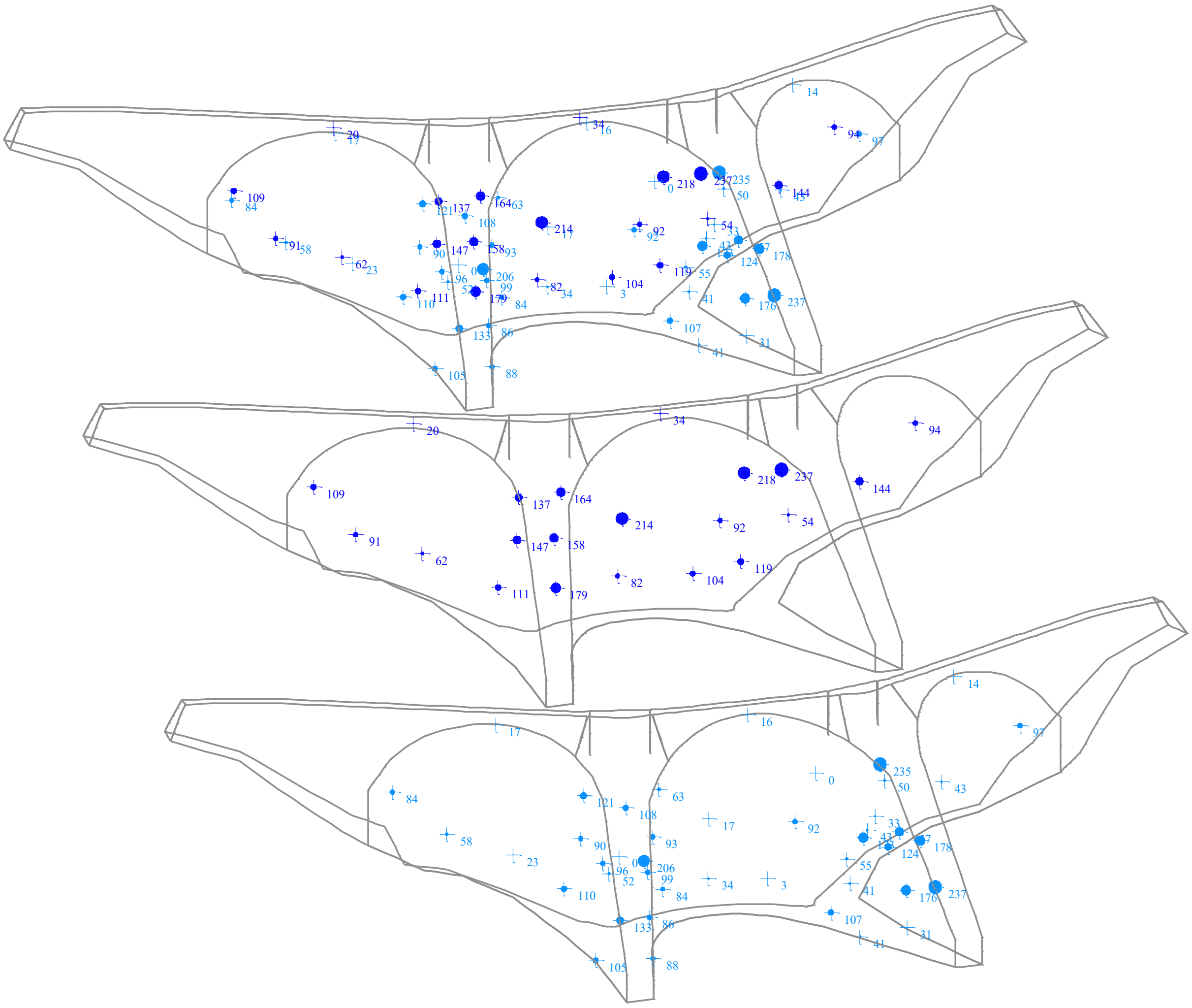

Figure 3.3: Observed values of accumulated swelling from 1984 to 2016. Results from the isolated strain gauges scattered across the dam body (values are all multiplied by 10^{-6})

In the effects separation graph (in Figure 3.4 right side) is observable over time, between 1980 and 2016, a good adjustment between the LSM displacements and the observed values.

The SW creep effect component displays a shape similar to what is presented in Figure 2.1b, *id est*, there is a small displacement increase towards downstream over time at this observation point location.

In the time effects graph, the HP elastic effect component follows the water level variation, over time.

The temperature effect component over time has a harmonic variation following approximately the annual air temperature variation, although there is a 20 day's phase shift between the temperature increase/decrease and the structural response in terms of the radial displacements towards upstream/downstream direction.

The HP creep effect component variation presents, as expected, an increase over time with a 30 mm maximum value towards the downstream direction. The swelling time effect involves upstream radial displacements equal to accumulated values of 4.5 mm between 1980 and 2016.

The HSCT-FEM effects separation results are compared with the FEM results in what accounts for the influence lines and the deformed shape. Therefore, Figure 3.5 compares the radial displacements observed by the geodetic method with the FEM results for the radial displacements (displacement fields) and the respective deformed shape for: the HP effect, the temperature effect (winter) and the swelling effect between 1980 and 2016.

Through Figure 3.5 results analysis is globally observable the agreement between HSCT-FEM and the FEM results. The HP elastic effect displays great similarity between the displacement fields obtained by the HSCT-FEM model and the FEM model. For example, at the central arch mid-span the obtained displacement value, resulting from the HSCT model, is around 21 mm, something very similar to what was obtained by the FEM. Similarly, the displacement fields, obtained by the HSCT-FEM and FEM, for the winter temperature effect are very close. At mid-span of the central arch top, the value obtained by the HSCT model, for the winter temperature effect, is approximately 4 mm, once again, coherent with the FEM results.

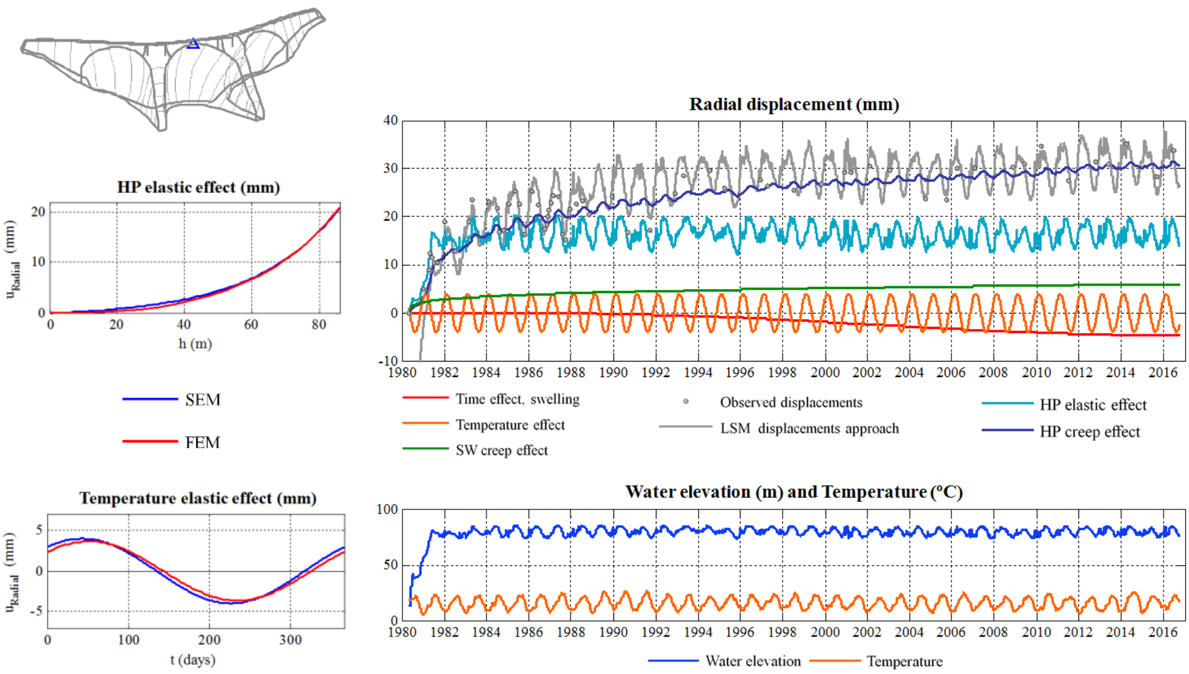

Figure 3.4: Separation of effects and comparison between HSCT/FEM. Radial displacement analysis at the central arch mid-span, at elevation 122 m, measured by the geodetic method. DamSafe3.0 program outputs

The radial displacements derived from the swelling effect accumulated between 1980 and 2016 (Figure 3.5c) reveal, equally, a good agreement between the HSCT-FEM estimated values and the ones determined by the FEM. The values obtained at the middle arch centre are around 6.5 mm.

Figure 3.6 presents the observation results measured by the geodetic method and plumb lines and the results from the FEM for the radial displacements derived from the swelling effect (accumulated effect from 1980-2016). The geodetic method results display areas with higher displacements, towards upstream; these areas are at the arches centres, with the side arches values being higher than the values at the middle arch. From the HSCT-FEM results analysis are observable maximum values of approximately 7 to 8 mm at the side arches and of 5 to 6 mm at the central arch.

At the counterforts plumb lines the maximum displacement values obtained are around 3.2 mm, which are possible to observe in Figure 3.6b and are coherent with the FEM results.

The vertical displacements, displayed in Figure 3.6c, developed by the swelling effect, measured by levelling, are in upward direction. The maximum value obtained is at the crest at the center of the central arch with a value near 9 mm, decreasing while approaching the counterforts. The HSCT model presents a 6.9 mm vertical displacement value for the left counterfort and a 6.4 mm value for the right counterfort, these values, once again, increase towards the center of the side arches. The HSCT model values, at the side arches center, are equal to 7.0 and 6.2 mm for the left and right arch, respectively. The displacement values decrease from the side arches to the embankments. Therefore, the minimum vertical displacements are found near the embankments and are of approximately 2 mm. Globally, the FEM vertical displacements due to the swelling, are also coherent with the results from the HSCT model.

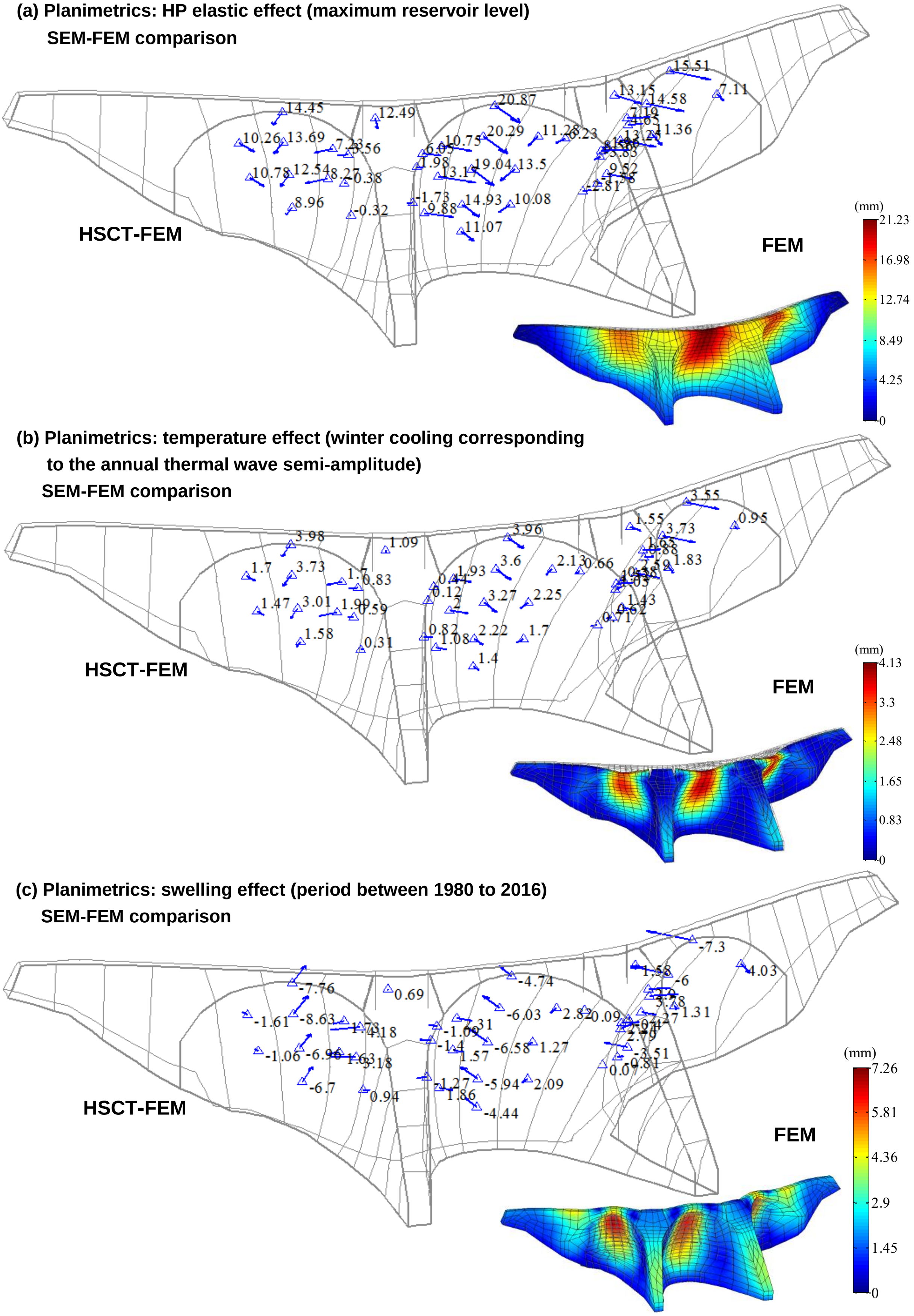

Figure 3.5: Geodetic method: radial displacements. Separation of effects and SEM/FEM comparison. Deformed shape obtained by DamSafe3.0

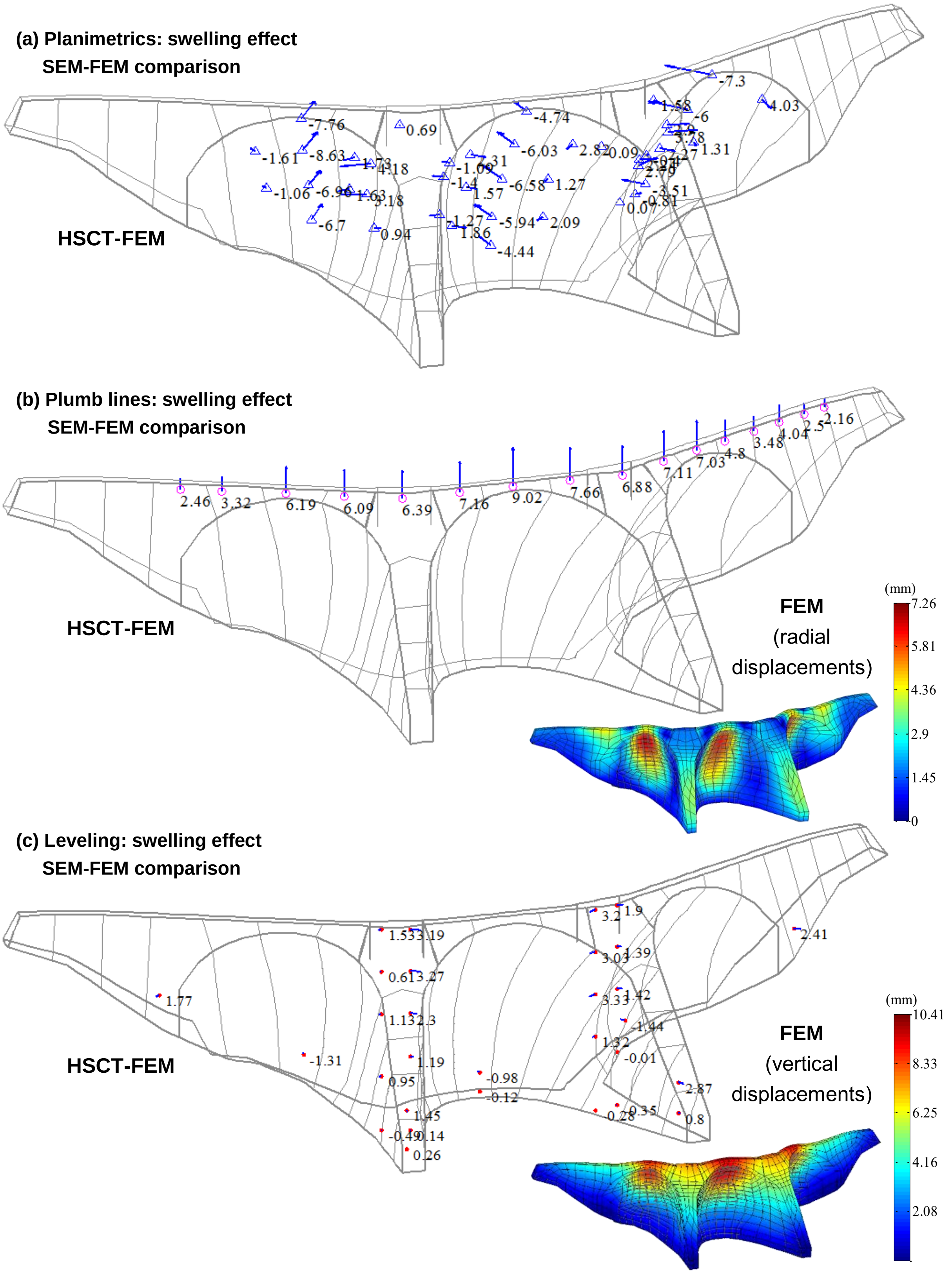

Figure 3.6: Radial and vertical displacements related to the swelling effect. SEM and FEM results comparison. (a) Planimetrics; (b) Plumb lines; and (c) Leveling

4. CONCLUSIONS

The used hybrid HSCT-FEM models for effects separation, based on a creep function for a concrete affected by swelling, *id est*, considering a creep doubling the one determined from the tested samples performed in 1980, with riddled intact concrete, achieves a great agreement between observed displacements (analysed through HSCT-FEM) and computed displacements (FEM). Particularly it should be emphasized, that, in what concerns the displacements due to swelling, it was obtained a great agreement between computed (FEM) and observed values (HSCT-FEM) for both horizontal and vertical displacements components. For the computation of the displacements due to swelling accumulated during the period 1980-2016 it was considered a swelling field in the dam body calculated by Expand2014 [8] (that uses, as input, the thermal and hygrometric fields in the dam body, estimated by FEM, using PAT2.0 program [9]) coherent with the values of the accumulated strains observed in the isolated strain gauges. The good agreement between computed and observed displacements due to the referred main effects is verified over a considerably long time span, of about 40 years. Considering this long period of analysis, the effects on contraction joints and on the rock foundation from the first filling have already subsided, furthermore, the good adjustment between observations and statistical model estimation is also present at the early stage of dam operation, right after the first filling. Finally, it can be concluded that the hybrid HSCT-FEM model used in the analysis of the observed Aguieira dam's displacement histories, is a model for separation of effects that is capable of identifying the temporal evolution of the displacement field due to swelling (considering the two horizontal and vertical components) which is consistent with the corresponding displacements calculated with the FEM, when creep effects due to self-weight and hydrostatic pressure are taken into account using a creep law adapted for damaged concrete with expansive gel in the microporous structure (twice the creep predicted for intact concrete, in this case).

5. REFERENCES

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