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RESEARCH ARTICLE

Hydraulic Models and Finite Elements for Monitoring of an Earth Dam, by Using GNSS Techniques

Gino Dardanelli[1*], Claudia Pipitone[1]

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Abstract

This work gives a comparison between different mathematical models for the evaluation of the movements of an earthen dam situated between Bivona and Alessandria della Rocca, in the province of Agrigento (AG), Italy. The models selected are of a hydraulic nature, already tested on concrete dams, and finite elements models which, on the contrary, exploit geotechnical parameters. The results obtained from the comparison of the displacement planimetric components and the relative time series of data over a period of two years appear to be fully satisfactory, in fact using both models of a hydraulic and geotechnical nature, we reach residues of just mm. To support this work, a monitoring procedure using GNSS techniques was taken into consideration. After that time series of the movements of some points at the top of the dam were attained in order to support the data obtained using the models, and to find the one that gives a better convergence.

Keywords

GNSS, earth dam monitoring, hydraulic models, FEM

[1]Department of Civil, Enviromental, Aerospace, Materials Engineering (DICAM)University of Palermo, Viale delle Scienze, building 8 - 90128 Palermo, Italy
[*]Corresponding author email: gino.dardanelli@unipa.it

1 Introduction

This work, which was carried out at the Polytechnic School of Palermo, attempts to investigate the extent of the displacement vector suffered by an earthen dam using models of a hydraulic and geotechnical nature, based on the different influences acting on it.

It's just a preliminary study, because in literature there aren't in specific models to describe the behaviour of earthen dam, so the aims of the work is to identify which variables have an influence on the displacements of this structure

Furthermore, at the end of the study, we wanted to point out that the GNSS techniques can provide static results comparable to other monitoring techniques, such as the use of total station and digital levels.

To support this process, the time series of data collected by GNSS (Global Navigation Satellite System) acquisition are analysed through the use of three receivers placed on the top of the dam at three different sections, respectively one in a central location, another one on the left bank and the last one on the right (Fig. 1), which acquire information relating to the displacement components continually within 24h. These data, taking advantage of the presence of permanent GNSS stations in the territory, are processed in a post-processing phase using the Professional version of NDA (Network Deformation Analysis) software. This software is also able to perform the corrections of tropospheric and ionospheric disturbance [9].

Fig. 1 Castello Dam

Data are analysed through a statistical analysis which aims to remove any outliers present and to assess long-term trends of movement. In succession, the definition of the displacements is taken into consideration, at first through an analysis of the existing models in literature involving essentially hydraulic variables. These models are different from each other with respect to the variables involved in their analysis, and they have been employed in existing works to analyse the behaviour of concrete dams. In this regarding way, their validation earth dams is innovative. The aim of this study is to understand whether such models can be used indifferently on structures that have different characteristics due to their composition and their structural response in terms of stress, assessing the comparison with the data series available. Based on these results, because of the fact there are no models in literature that describe the behaviour of earth dams they tried to make a comparison with modelling, which involve parameters that are related to the geotechnical characteristics of the dam, which are not negligible, for the purpose of the study. This modelling, carried out using commercial software, is based on a FEM (Finite Element Method), using the equations that govern the balance of continuous systems.

2 Background

Since the 1930s, researchers have turned their attention to the interpretation of time series using in-depth studies. Satisfactory results were found in Kolmogorov (1933) [20] and Wiener (1966) [27] in their respective academies. A few decades later, one of the first studies on time series was undertaken, adopting geodetic applications to the control problems of the structures. This is the case exposed in the impressive work developed by Sansò (1984) [23]. Other references available for the study of time series are those of Agnew (1992) [1], Langbein and Johnson (1997) [16], Zhang et al. (1997) [29], Mao et al. (1999) [17], Takacs and Bruyninx (2001) [26], Kenyeres et al. (2002) [18], and Bruyninx et al. (2003) [6], Williams (2003) [28], Bruyninx and Kenyeres (2004) [5], which may be referred to for further details, without claiming to be exhaustive.

Time series are often used as a support and comparison to other monitoring techniques with the aim of looking for new solutions for the interpretation of the behaviour of the studied structures. It is sufficient to consider various modelling based on different parameters and characteristics which attempt to obtain good results for modelling the actual behaviour of the dam. For example, a survey based on the FEM analysis was carried out to support a monitoring activity using conventional geodetic means, as well as GPS stations and an earth dam, where the instrumentation consisted of geotechnical equipment, accelerometers and GPS receivers [25]. The authors of the latter work made a comparison between mathematical modelling, involving the parameters related to the filling of the reservoir, and monitoring results, with reference to the central cross section of the dam. The results obtained by the two methods of investigation appear to be mutually comparable. With reference to the determination of models capable of providing support for the monitoring activities of concrete dams, De Sortis and Paoliani developed a new method of investigation. This involves two different approaches to the interpretation of its behaviour: a statistical approach which would allow the introduction of the auxiliary variables; and an approach providing for the use of techniques of a structural type, through finite element modelling, adopted to estimate the physical parameters involved in order to determine the relationship between the load agents and the movements on the top of the dam [12].

A modelling of this type will be resumed for an experimental study as a tool for carrying out a comparison between traditional and innovative techniques (GNSS) in order to evaluate the displacements of concrete dams. However, while in Europe and in other non-European countries, monitoring techniques that exploit satellite technology are widely used to control the structure's developmental movements over time, in Italy these techniques are not extensively used, if not only for experimental studies. This is because the current law states that displacement measures should be conducted using the total station for the planimetric component, and the digital level for the altitude component. An example of monitoring using GPS was conducted on a concrete dam by Barzaghi et al. [2, 3]. However, it has also been carrying out studies for several years aimed at establishing the time series of data of permanent stations in Sicily belonging to the network UNIPA NRTK GNSS [9], [10], [11]. Recently, there have been studies of stations located on sites interesting to monitor using satellite technology, such as the Castello dam, subject matter of this work [8]. In support of these investigations, a mean of intervention could be by defining models which correctly interpret the deformation behaviour of the structure.

An example of modelling found in existing works is the one which well interprets the behaviour of the Long Valley dam through numeric surveys [13]. A violent earthquake struck the dam in 1980, and the results from a continual monitoring activity over time were compared with those from non-linear dynamic analysis using the finite difference method, hypothesising a perfectly plastic elastic bond for the material which compose the dam. The results showed full compatibility between the data actually measured and those calculated with the model.

The models, which in some cases may present a previsional nature, can be a valuable aid in determining displacements, by supporting the monitoring activities required for the work. In particular, another study conducted on the Genna Abis dam showed the comparison between different monitoring techniques and existing models found in existing specialist literature. The results are those obtained from the comparison of the time series displacements of the dam acquired using pendulums, the time series of the GNSS data and the displacements obtained using different modelling types. The models investigated use both formulations in their physical parameters, which are directly measurable (deterministic), and auxiliary variables (predictors); the analysis of hybrid models took account of the mathematical formulation given in Barzaghi et al. (2012) [3].

3 Overview of derivation

With regards to an approach from a computational point of view for the processing of the time series of data, the analysis was performed using the Professional version of the software NDA, which makes ionospheric and tropospheric corrections. Specifically, the modelling of the tropospheric delay was carried out using the Saastamoinen (1972) [22] and Niell (1996) [21] mapping functions model, while the modelling of ionospheric error was obtained using the Klobuchar model (1996) [19] using the parameters supplied by the daily Center for Orbit Determination in Europe (CODE) of the Astronomical Observatory of the University of Bern.

Niell also kept the basic form of the Herring model (1992) [14] mapping function adding a height correction term assuming that the elevation is a function of only geographical parameters. In addition, the ocean loading correction in NDA Professional was based on Schwiderski's (1980) [24] model, and for the zenith troposphere estimation (affecting the baseline coordinates estimation) enable on both reference and rover stations (recommended for baseline over 15 km). For that reason in 1984, he improved his preliminary model in order to remove the causes of the shortcomings of earlier tides models. The data obtained from the processing with NDA [8], in order to better evaluate the behavior of the three stations in the dam was appropriated to carry out a transformation of reference systems, from a global to a local solution which is appropriate in the metric deformations analysis. The local coordinates are, therefore, obtained by an orthogonal coordinate system, defined as a point source to an area of interest; the coordinates of the other points are given through the positions North, East, and Up referring to that origin. Therefore, in a local coordinate system, having as its origin a generic point P_0, which in our case is made to coincide with station BIV3, the X axis has the direction of the development of the top of the dam, the Y axis will be orthogonal to this direction and the Z axis will be such as to complete the right hand triad. The coordinates of the other points will be provided using the matrices of roto-translation axis, shown in Eq. (1), as described in literature [15], [4].

$$\begin{bmatrix} E \\ N \\ U \end{bmatrix}_P = \begin{bmatrix} -\sin\lambda_0 & \cos\lambda_0 & 0 \\ -\sin\varphi_0\cos\lambda_0 & -\sin\varphi_0\sin\lambda_0 & \cos\varphi_0 \\ \cos\varphi_0\cos\lambda_0 & \cos\varphi_0\sin\lambda_0 & \sin\varphi_0 \end{bmatrix} \begin{bmatrix} X_P - X_0 \\ Y_P - Y_0 \\ Z_P - Z_0 \end{bmatrix} \tag{1}$$

In which: φ_0 is the latitude of the point P_0; λ_0 the longitude of the point P_0; X_0 represents the coordinates along X of P_0, in a Cartesian geocentric reference system; Y_0 represents the coordinates along Y of P_0, in a Cartesian geocentric reference system; Z_0 represents the coordinates along Z of P_0, in a Cartesian geocentric reference system; E is the coordinate along X in the local reference system; N is the coordinate along Y in the local reference system; U is the coordinate along the axis orthogonal to the axis N, and in the local reference system; X_P is the coordinate along X of a point P, in a Cartesian geocentric reference system; Y_P is the coordinate along Y of a point P, in a Cartesian geocentric reference system; Z_P is the coordinate along Z of a point P, in a Cartesian geocentric reference system.

Once obtained the values of the displacement components in the three directions (E, N, U), as a function of time, reported in MJD (Modified Julian Days), it was necessary to perform a statistical study, first of all removing outliers of the time series and subsequently showing a tendency to long-term displacements. This was necessary in order to assess the differences between the models analysed and the time series of data, synthesized through the use of moving averages calculated for the data of each station.

For the calculation of the moving average, it was decided to use a SMA (Simple Moving Average), which corresponds to an arithmetic average. The number of samples to be used, referring to the study of the moving average, was calibrated in an appropriate manner, performing various analyses relating to time intervals of 7, 14, 28 and 56 days. The results showed that the most reliable data to evaluate the trend of the series displacements of the three stations in the dam are those relating to the calculation of the average movement over a period of 56 days. Furthermore, it is important to point out that the study of the moving average allows the evaluation of the trend of the displacements which acquire a scattered evolution and, therefore, not directly measurable through a simple or polynomial regression analysis.

3.1 Hydraulic models

The models in this case will be analysed are classified according to physical parameters directly measurable on-site, or on auxiliary variables which are involved in the process, in order to reach a solution to the problem. The models which involve only physical parameters, such as air temperature, the share of the reservoir or the height of rainfall, which, alternatively, can be estimated through the use of probabilistic calculations, are defined deterministic. Obviously directly measured data are preferred to estimated values, in fact in the latter case there would be an increase of uncertainty in the estimate of the data. A model of the deterministic type valid for evaluating the displacements (S) of points placed at the culmination of a dam is the following.

$$S = a \cdot t + b \cdot T_{mwater} + c \cdot H + d \tag{2}$$

Where T_{mwater} is the temperature of water averaged on measurements recorded between the current date and 14 days before, H is the height of the reservoir, in meters above sea level. The other terms *a, b, c, d* represent the parameters of the model, that is, the constants which have to be calibrated in a timely manner, in order to obtain plausible results.

Another example of a deterministic model [7], already experimented in existing works on the time series, is based on the observations of the behaviour of some arch dams, whose mathematical formulation is the following:

$$S = a \cdot H^3 + b \cdot T_p + c \tag{3}$$

Where H is the portion of the reservoir and with T_p the air temperature in correspondence of the dam. Also in this case the constants *a, b, c* represent the parameters of the model, which needs to be calibrated in a timely way.

There are also some models based purely on the use of auxiliary variables, which have no direct connections to the physical variables put into play. For example, there are models, such as PoliMi (be discussed below), which are formulated on the basis of the observation of oscillatory behaviour, both annual and possibly biannual, typical of the points placed on the top of concrete dams. The PoliMi model based on what has already been said, uses time as an auxiliary variable and has the following mathematical formulation:

$$\begin{aligned} S &= a \cdot t + b + A\cos\left(\frac{2\pi t}{T}\right) + Bsen\left(\frac{2\pi t}{T}\right) \\ &+ C\cos\left(\frac{4\pi t}{T}\right) + Dsen\left(\frac{4\pi t}{T}\right) \end{aligned} \tag{4}$$

Where the variable t represents time expressed in days, T is the oscillation period, equivalent to 365 days and S represents the displacement in the top of the dam, finally, a, b, A, B, C, D represents the parameters of the model.

Finally, there is another type of models, called hybrids, which exploit the advantages of the two categories of models previously discussed. In fact they exploit directly measurable physical parameters and auxiliary variables as well. They often appear to be more compatible with real data and that because they correlate variables of a different nature. An example of a hybrid model [12], was also employed to supervise the Castello dam. This model involves sinusoidal functions over an annual period T which express the periodic component, the auxiliary variable time in days and functions involving the share-dam H of the dam.

Analytically, the formulation of the model is the following:

$$S = a \cdot t + b + c\ sen\left(\frac{2\pi t}{T}\right) + d\ \cos\left(\frac{2\pi t}{T}\right) + e \cdot H + f \cdot H^2 \tag{5}$$

Where the variable t represents time expressed in days, T is the oscillation period, equal to 365 days H represents the share of the reservoir and S represents the displacement in the top of the dam, in a direction parallel or perpendicular to the crest, in *a*, *b*, *c*, *d*, *e*, *f* represent the constants of the model.

All of the physical parameters which are involved in the equations models (as water level, air and water temperature) referred to the data recorded in situ were available from the studies of the dam supervisor. However, nowadays it would be possible to acquire data by using other innovative techniques, as for example the use of remote sensing.

3.2 Geotechnical model

Despite the acceptable solutions obtained from the comparison between the models of a hydraulic nature and the series data obtained experimentally for the Castello dam, the last phase of this work attempts to find a model valid for earth dams, given that in existing literature there are no models dedicated to this type exclusively of artefacts. For this reason, this research was addressed to a Finite Element Modelling which using the equations of the continuous, would allow any limitations arising from the mathematical point of view and from the solution of differential equations. Finally, the results of this model will be compared to the hydraulic model which is, amongst the ones mentioned above, closer to reality.

The finite element method, as is known, exploits knowledge of a group of equations which includes equilibrium equations,shown in (6). These establish the equilibrium relations between: the forces acting on the structure and the tensions arising from them. The constitutive equations in (8) establish the relationship between stress and strain and finally the congruence equations in (10) establish the relationship between deformations and displacements.

$$\underline{L}^T \underline{\sigma} + \underline{p} = 0 \tag{6}$$

In this expression σ represents the vector that includes the six components of stress, while the vector $\underline{p}$ encloses the components of the forces acting on the continuous; $\underline{L}^T$ represents the transpose of the matrix within which the partial derivatives are present in the three components of the continuous space:

$$\underline{L}^T = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \tag{7}$$

$$\underline{\dot{\sigma}} = \underline{M}\,\underline{\dot{\varepsilon}} \tag{8}$$

$\dot{\sigma}$ represents the vector of infinitesimal increments of tension, $\dot{\varepsilon}$ that increases infinitesimal deformation, while $\underline{M}$ is the stiffness matrix, shown in Eq. (9):

$$\underline{M} = \frac{E'}{(1-2\nu')(1+\nu')} \begin{bmatrix} 1-\nu' & \nu' & \nu' & 0 & 0 & 0 \\ \nu' & 1-\nu' & \nu' & 0 & 0 & 0 \\ \nu' & \nu' & 1-\nu' & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2}-\nu' & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2}-\nu' & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}-\nu' \end{bmatrix} \tag{9}$$

Where E is Young's modulus, and v is the Poisson's module. The quote (′) indicates that the referenced values effective.

$$\underline{\varepsilon} = \underline{L}\underline{u} \tag{10}$$

In which $\dot{\varepsilon}$ represents the vector of the deformations and $\underline{u}$ the displacement vector.

Combining these groups of equations leads to a single differential equation of second order, in which the only unknown quantities are the displacements of the structure. This can only be resolved by numerical integration with the help of appropriate software. Using such software, the solution is found through the discretization of the domain structure by using a grid called mesh, which divides the work, properly schematized, in a triangular or rectangular finite element mesh. The variables contained within the differential equations are calculated at the intersections of the grid, called nodes, and sometimes in the middle of the finite elements.

In particular, the movements to the nodes which make up the mesh of the finite elements of the structure are compared to the value of the nodal components of the elements which constitute the mesh $\underline{v}$ through a nodal matrix $\underline{N}$ that from the inside are collected to the interpellant functions, noted also as form functions.

$$\underline{u} = \underline{N}\underline{v} \tag{11}$$

Taking into account the shape of the equations in Eq. (10), replacing the displacement vector with a vector obtained by Eq. (11); the result is obtained the shape of the vector of the deformations:

$$\underline{\varepsilon} = \underline{L}\underline{N}\underline{v} = \underline{B}\underline{v} \tag{12}$$

In which $\underline{B}$ represents the matrix which contains the derivatives of the interpolating functions. At this point, the equation of the continuous, which can be rewritten in a similar form, taking into account the stress state unknown $\underline{\sigma}^i$ and the previously known $\underline{\sigma}^{i-1}$ and his infinitesimal increase $\dot{\underline{\sigma}}$, will be written as a function of the nodal displacements that we want to determine in discrete form, through the following expression:

$$\begin{aligned} &\delta\underline{v}^T \int \underline{B}^T \Delta\underline{\sigma}\, dV = \delta\underline{v}^T \int \underline{N}^T \underline{p}^i\, dV \\ &+\delta\underline{v}^T \int \underline{N}^T \underline{t}^T dS - \delta\underline{v}^T \int \underline{B}^T \underline{\sigma}^{i-1} dV \end{aligned} \tag{13}$$

At the end of this process, the solution of the equation (not of the linear type), will be determined through an iterative procedure which allows the fulfilment of the conditions of equilibrium of the continuous for all the points. The equations described above are taken from the manual of the software we used to solve the problem, in which there are variables of a geotechnical nature, to consider mechanical property as well as soil stiffness and hydraulic. In fact it is important to consider, for example, the changes of the level of the water which influences the behaviour of the dam. The software used is Plaxis and the main geotechnical parameters which are involved in the process for the Mohr-Coulomb model are: the effective Young's modulus E' and the effective Poisson's ratio v', the friction angle ϕ' and the cohesion c'. Each parameters which is related to the different soils of the structure, can be obtained from basic test on soil samples and our case from the studies of the dam managers. This software simulates the real behaviour of the structure, imposing plane strain conditions, starting from simplified geometric patterning of the cross sections of the dam, which are most representative of the problem.

4 Numerical analysis

The time series of the movements in the two planimetric upstream-downstream and crowning components refers to the new local reference system, which has its origin in the stationary site BIV3. The acquisition of data began on 04/08/11 (corresponding to MJD 55659) and ended on 05/13/13 (corresponding to MJD 56425). In the graphs below, there are gaps which show, in that period, a lack of acquisition or processing of data in post processing. On a time period between 2011 and 2013, the situation with reference to the three stations, in both planimetric directions, shows that the displacements are contained in a range between ± 10 mm, with a dispersion of data compared to the average value, almost the same for all the three stations. Existing outliers, in a minimum percentage, with reference to the tolerance provided for each station were removed. Here below are the graphs relating to the series analysed for each station, cleansed of any errors.

After that it will follow a comparison between the time series and the existing models in literature, as discussed in the previous paragraph. In particular, for the implementation of the FEM model, it was considered the composition of the dam and its cross section. The earth dam, in fact, consists of coarse-grained homogeneous material (alluvium of the valley), and it has a bituminous surface in the internal side, the vertical cross section of maximum height has a trapezoidal shape, with width at the head of 9.00 m and width at the base of 214.00 m approximately.

5 Comparison of models

Regarding the up-down direction conclusions for each station can be drawn, separating time intervals for each year (2011: MJD 55659 to 55926; 2012: MJD 55927 to 56199; 2013: MJD 56308 to 56425), from the comparison between the time series and the models. In particular for station BIV1 the De Sortis-Paoliani model and the Carosio model, are in no way applicable to represent the evolutionary behaviour of the movements of the site, as evidenced by the obvious differences between the two representations and the trend of the moving average of the series (Fig. 2, a).

The remaining models, on the contrary, show a very good convergence of results in the different periods analysed, with deviations below 2 mm for both models in the different periods considered. In particular, in the first time window, the results obtained using the deterministic model are better, with lower deviations than those of the PoliMi model, while in the second period analysed, the comparison shows that the results of the PoliMi model are better than the deterministic model, in fact the trend of movements compared is convergent too. As regards the last period, neither of the two models is able to provide results that are compatible with those obtained from the series. However, compared to the models discussed above, it is clear that the residues have considerably lower values. With reference to station BIV2 (Fig. 2, b), without doubt the situation appears better than that of station BIV1. The deviations of all the models have residues below 3–4 mm, in fact compared to the moving average, feature values are always rather low and the models which fail to properly represent the behaviour of the structure (Carosio and De Sortis-Paoliani). Once again,

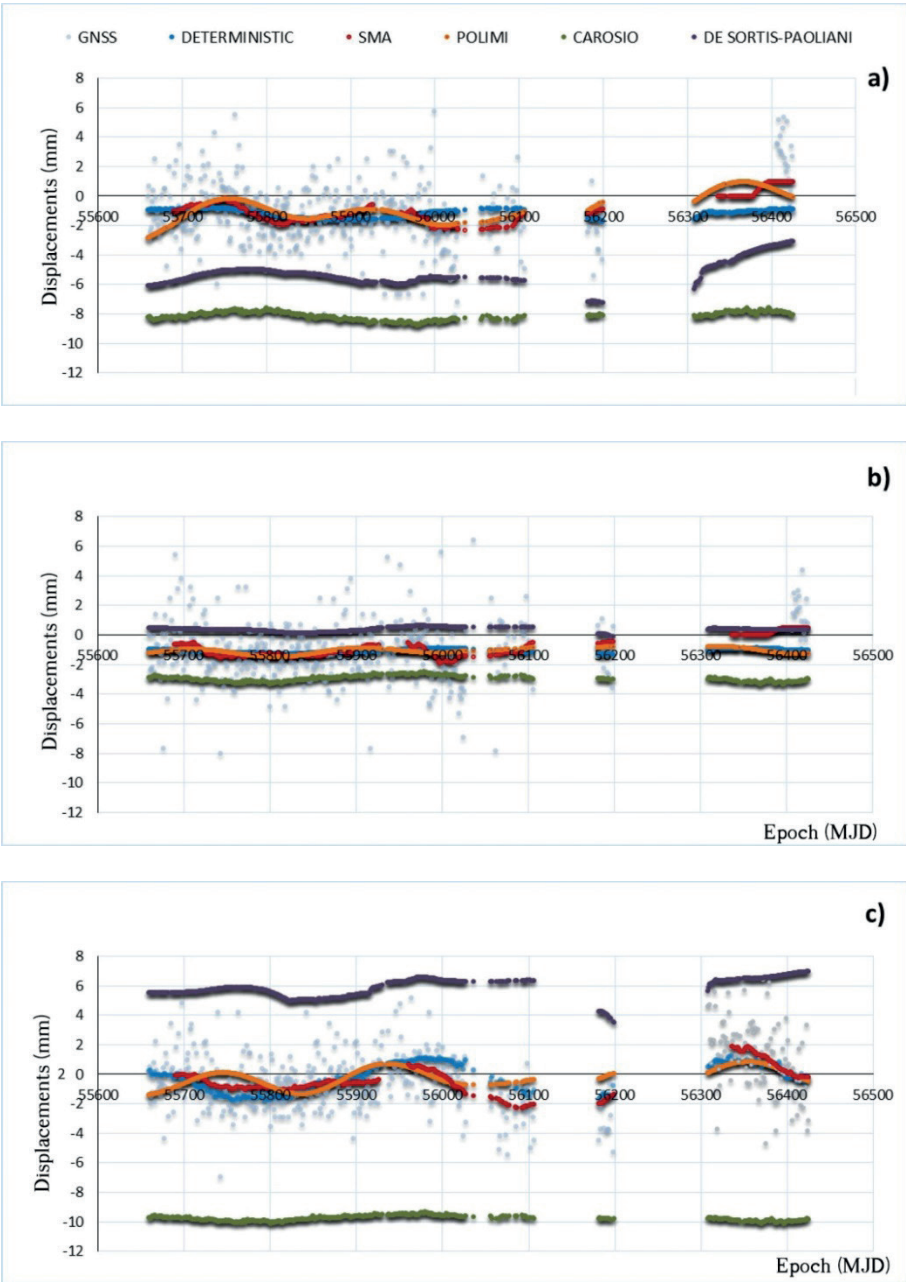

Fig. 2 Comparison of upstream section with various models; a) BIV 1, b) BIV2, c) BIV3 top to down

it is evident that the deterministic model and the PoliMi model obtained the best convergence of the results. In fact, if we consider the different time periods separately, it is clear that in the first period as in this case can be obtained an excellent overlap of data of the deterministic model and the moving average, and in certain points it is possible to obtain the same values, with zero deviations. In the second period it is possible to obtain a good convergence of the average with both models (deterministic and PoliMi), while, in the later period, again, neither of the two models is able to approximate the performance of the calculated moving average. However, it is worth noting that the De Sortis-Paoliani model, which had not provided results compatible with those of the average in the first two time windows in the latter period, succeeds in approximating the development of the average, with deviations below 0.5 mm (Table 1).

Taking into consideration station BIV3 (Fig. 2, c), in the same way as is evident from station BIV1, it is possible to observe that neither the Carosio model, nor the De Sortis-Paoliani model provide results compatible with those of the moving average of the series, that present rather high deviations; while the remaining two models have a good convergence of results.

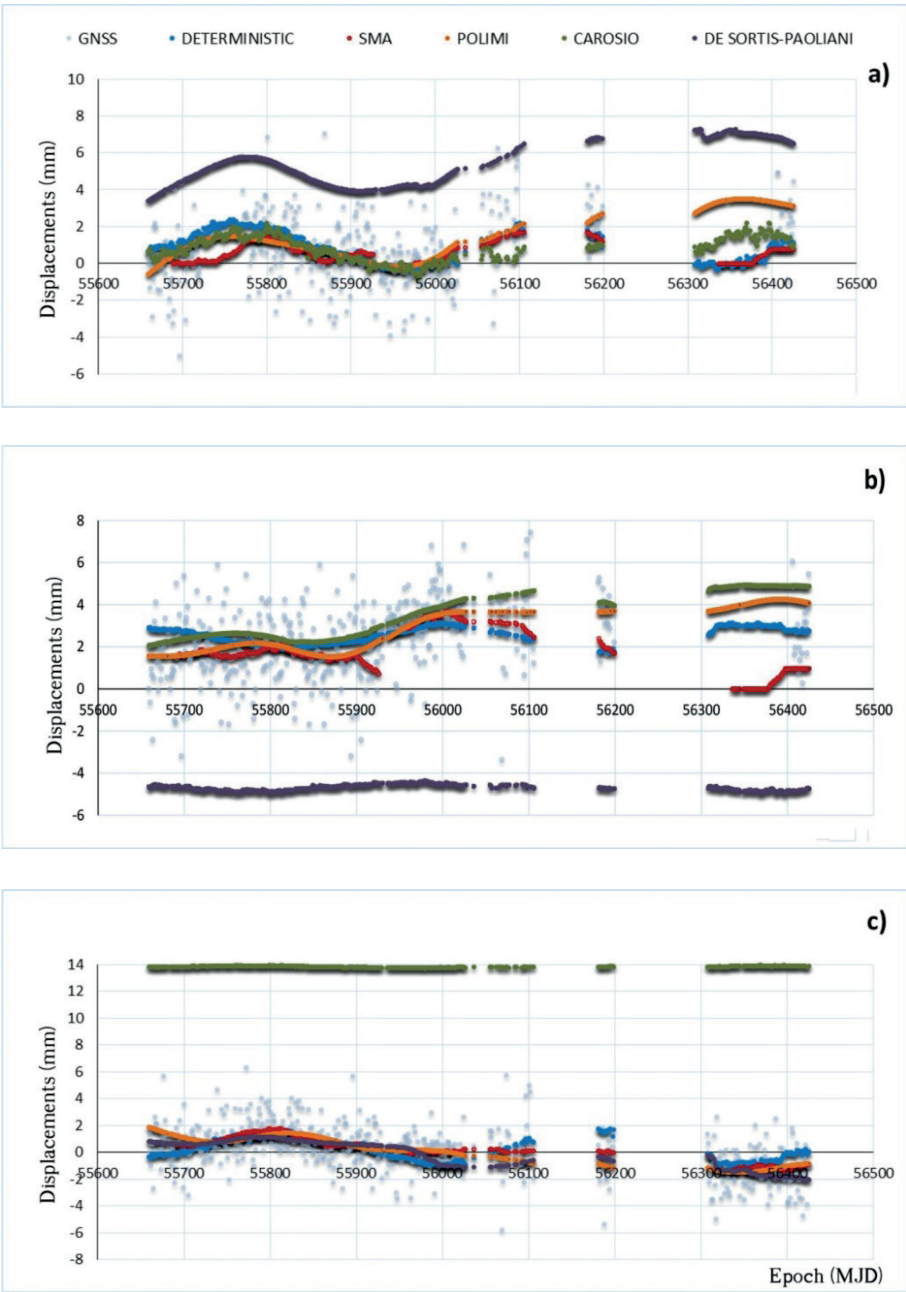

Fig. 3 Comparison of crowning section with various models a) BIV 1, b) BIV2, c) BIV3 top to down

Table 1 Deterministic model values, up down section

Deterministic model			
Range (MJD)	Up-down residues (mm)		
55659-55926	BIV1	BIV2	BIV3
Max	1.0	0.6	1.0
Min	0.0	0.0	0.0
Mean	0.3	0.2	0.5
Sdev	0.2	0.1	0.3
55927-56199	BIV1	BIV2	BIV3
Max	1.6	1.0	2.3
Min	0.1	0.0	0.0
Mean	0.8	0.5	1.0
Sdev	0.4	0.3	0.5
56308-56425	BIV1	BIV2	BIV3
Max	1.9	1.5	1.1
Min	1.0	0.9	0.0
Mean	1.4	1.2	0.4
Sdev	0.4	0.3	0.3

Once again with reference to the first period, the deterministic model provides full compatibility, as regards both to the performance of the movements, and the residues obtained from the comparison with the moving average (Fig. 2, c). The PoliMi model, however, presents a very low discard, as the other stations do. In the second period, although initially the results obtained with the PoliMi model seemed better, the best performance results is the deterministic model. Finally, in the last period, for the first time the results obtained with both models are compatible with those of the moving average, with deviations which do not exceed the threshold of mm. Overall with reference to the planimetric up-down direction component, it can be said that the best results compatible with those of the time series, are obtained using the deterministic model and the PoliMi model. Between the two models on site, the results of the deterministic model offer better convergence which lends itself well to the approximation of the movement of the structure analysed. Below we report on graph the comparison between the deterministic model and the moving average, divided by time intervals for the other planimetric displacement component (Fig. 3).

As for station BIV1, with the exception of the De Sortis-Paoliani model, the remaining models have good results compatible with the moving average calculated. In the first period, in particular in the initial phase, all of the three models have a discard slightly higher than a mm, while from about MJD 55800 to the end of the first period, there is a full convergence of results of the models, with considerably reduced residues. In the second period, it is possible to observe that the PoliMi model provides a better adaptation to the series while the representation of the displacements obtained with the Carosio model differs from the average performance, although the values of the residues are restrained. Finally, in the last period, the only model able to represent the trend of the series is the deterministic one, the residues in fact are sub-millimetre (Fig. 3, a). In the first period the station BIV2 is different from the station previously analysed, and the Carosio model which cannot grasp the movements of the structure, while the remaining have restrained discard the best adjustment to the series is provided by the PoliMi model. In the second period, amongst the three models, it is once again the deterministic model which is able to optimally approximate the data series, presenting sub-millimetre residues. In the last period, however, one of the models are able to approximate the data series, although the deterministic model presents fewer offsets than all of them (Fig. 3, b).

Finally, with regard to station BIV3, it is also evident in this case that the *Carosio* model fails to fit the series data because it maintains high discard, always above 10 mm, while all the remaining models have a compatible trend with that obtained with the moving average, and generally have a discard below 2 mm. In particular, in the first period, initially there is a better adaptation to the average values with the *De Sortis-Paoliani* model, but soon after the deterministic model provides perfectly consistent results with those of the moving average. In the second period, the values of the average are not fully compatible with the data obtained from the three models. However, despite the differences are greater than the previous case, they are still restrained. Finally, in the third period, the three models provide results that can overlap with those of the moving average. The best convergence seems to be the one obtained using the *PoliMi* model (Fig. 3, c). As observed, with reference to this displacement component, it is possible to say that compared to the previous case, of the four models analysed at least three for each station are able to recognise the movements of the dam, providing very low residues, sometimes even sub millimetres. As in the previous case, the *PoliMi* model and deterministic model are the best. The latter, in particular, provides values that are fully compatible with the values of the moving average in most of the cases analysed. Below, table 2 expresses the values of the wastes of the latter model referring to the moving average for each period, which highlights what has been said. Based on these results obtained, we investigate another geotechnical model using FEM analysis and compare it to the deterministic model in order to evaluate its reliability. Of all the hydraulic models this model provides the best approximations with the series values. *Plaxis,* the software used allows us to achieve results in terms of displacements by imposing the conditions of plane strain, with reference to the representative sections of the dam. The parameters involved are the characteristics of stiffness and mechanical strength of the dam body, expressed through the definition of *Young* and *Poisson's* modulus, the value of the cohesion intercept, the angle of shear, and the dilatancy angle. The values obtained from processing have a monthly frequency, evaluated for each station, and are compared to the point data extrapolated from the deterministic model. In particular, regarding the planimetric component of the displacement, the software provides the displacement of the points of the dam in one direction, orthogonal to the top of the dam, while the displacements obtained with the model for each station are calculated with reference to the two planimetric components (upstream-downstream and crowning). For this reason the value extrapolated from the model will be equal to the resultant of the two components. The results are below in Figure 4.

Table 2 Deterministic model values, crowing section

	Deterministic model		
Range (MJD)	**Crowing residues (mm)**		
55659-55926	BIV1	BIV2	BIV3
Max	2.1	1.8	0.8
Min	0.0	0.0	0.0
Mean	0.9	0.7	0.2
Sdev	0.6	0.4	0.2
	Deterministic model		
Range (MJD)	**Crowing residues (mm)**		
55927-56199	BIV1	BIV2	BIV3
Max	0.9	0.6	1.8
Min	0.0	0.0	0.0
Mean	0.2	0.4	0.8
Sdev	0.2	0.1	0.4
56308-56425	BIV1	BIV2	BIV3
Max	0.6	3.1	1.3
Min	0.0	1.7	0.0
Mean	0.2	2.5	0.6
Sdev	0.1	0.6	0.4

A comparison was carried out between data obtained from the model and the data of the displacement altitude component from GNSS to assess whether the furthermore geotechnical model is able to recognise the deformation of the structure,

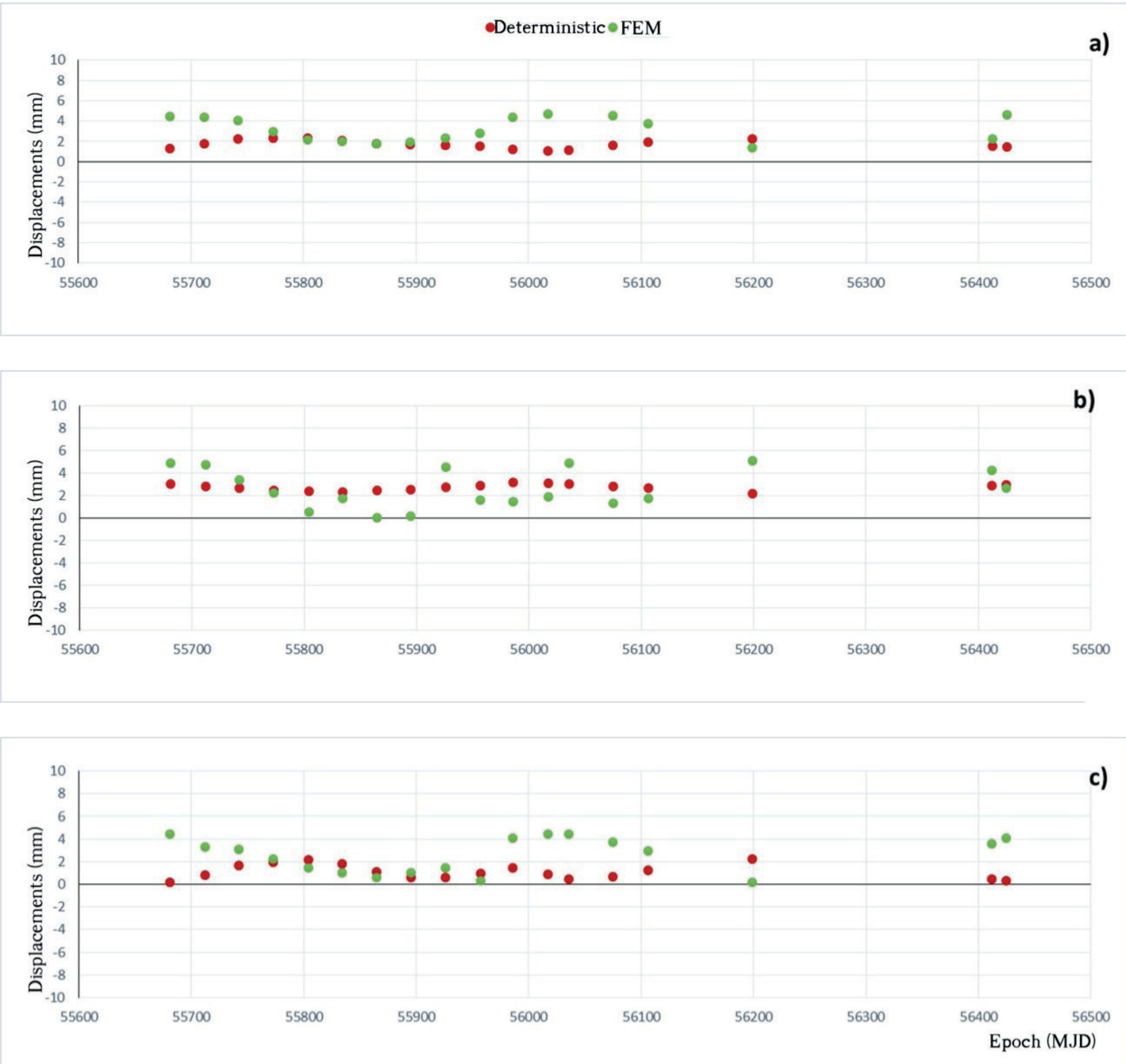

Fig. 4 Comparison of planimetric displacements; a) BIV 1, b) BIV2, c) BIV3 top to down

also with regard to the elevation component not investigated with models of hydraulic nature. Reported with reference to the planimetric component, the geotechnical model is able to approximate the results obtained using the deterministic model. The deviations between them are millimetric and in no case is the threshold of 5 mm exceeded. In particular, with regard to station BIV1, some of the data obtained with the geotechnical model have an almost superimposable trend with the data obtained using the deterministic model (Fig. 4, a). The same result can be observed with station BIV3, although the differences are slightly superior to the previous (Fig. 4, c). For station BIV2, however, it should be noted that the data of the hydraulic model follow a regular pattern in contrast with those obtained with the geotechnical model, although the differences between the two prove to be restricted, always below 3 mm (Fig. 4, b). In any case as for the displacement altimeter component, the geotechnical model cannot describe the deformation behaviour of the structure. This emerges from the remarkable differences between the two representations. Deduce that it is necessary to conduct a more detailed study to understand the causes of this failure.

These applications, based on the acquisition of data using GNSS techniques are still experimental, since the Italian law did not recognize the legal validity of the monitoring by these technique. At present there is not a regulatory intervention about this subject. The relevant legislation is still the levelling, as prescribed by the Law of the 18th May 1989, no. 183. This standard requires that each dam managing body should conduct periodic topographic operations on the structure, in order to evaluate the displacements or deformations which could be

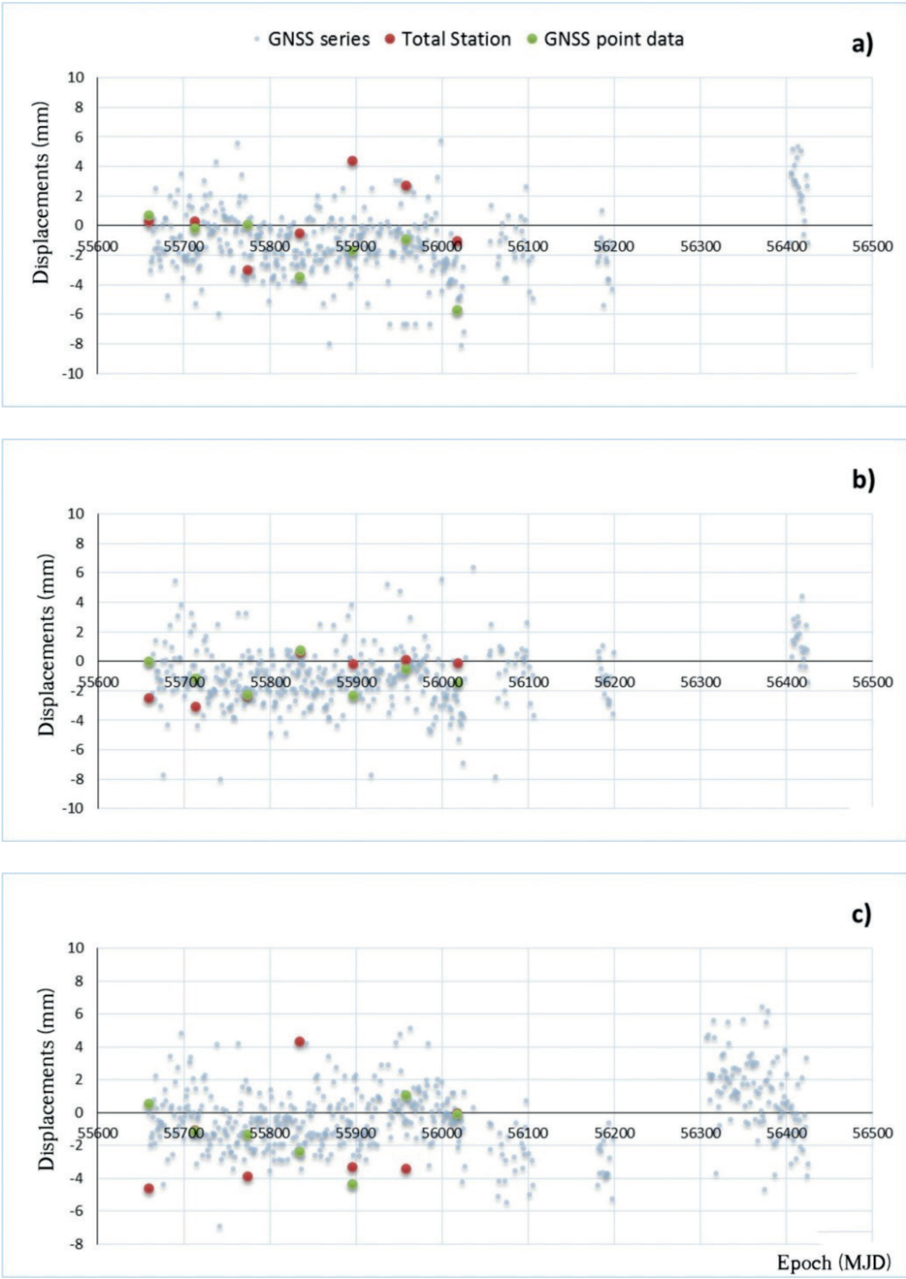

Fig. 5 Comparison of upstream sections beetween Total Station and GNSS data; a) BIV 1, b) BIV2, c) BIV3 top to down

in place as a result of hydrodynamic forces. For this reason it appropriate to compare the time series data collected by GNSS techniques with those obtained using traditional geodetic instruments (total station and digital level) of the managing body of the dam; you can see the results below.

As it clear from the graphs (Figs. 5, 6), the measurements obtained using the total station are punctual, measured on a quarterly basis, in contrast to the time series which, using continuous monitoring over time, allows to understand aspects of the structure on the basis of its behaviour, variable in time. What can be observed from the comparison is that the differences between the data relating to the two control techniques do not exceed the threshold of 6 mm for stations BIV1 and BIV3 (Figs. 5–6, a, c), while for station BIV2 the residues are restricted to about 8 mm (Figs. 5–6, b). As regards the altimeter component (up direction), in the same way a comparison between the data recorded using spirit levelling and the values of the time series was made (Fig. 7). As expected, the values of the vertical component of movement compared to the planimetric are more dispersed. In particular, the GNSS data are included in a range of 20 mm, while the data of the spirit levelling have variations ± 2 mm. Data recorded continuously from the receivers are included in the time period that goes from MJD 55659 to 56199. From that date, data were no longer recorded until the last date of monitoring. This explains the gap present in the graph. In any case, the differences related to the two major techniques highlight differences in the order of 5–6 mm.

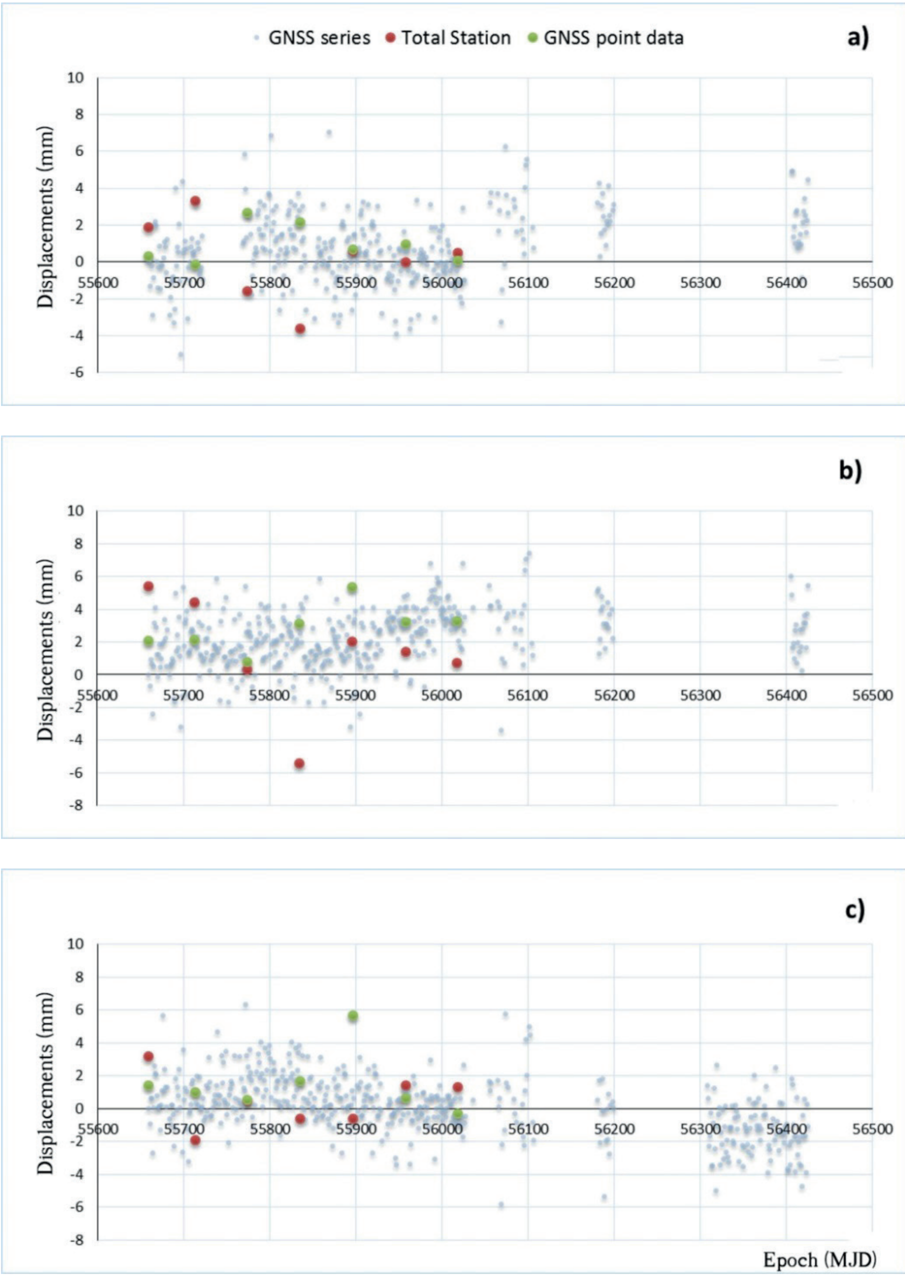

Fig. 6 Comparison of crowning sections beetween Total Station and GNSS data; a) BIV 1, b) BIV2, c) BIV3 top to down

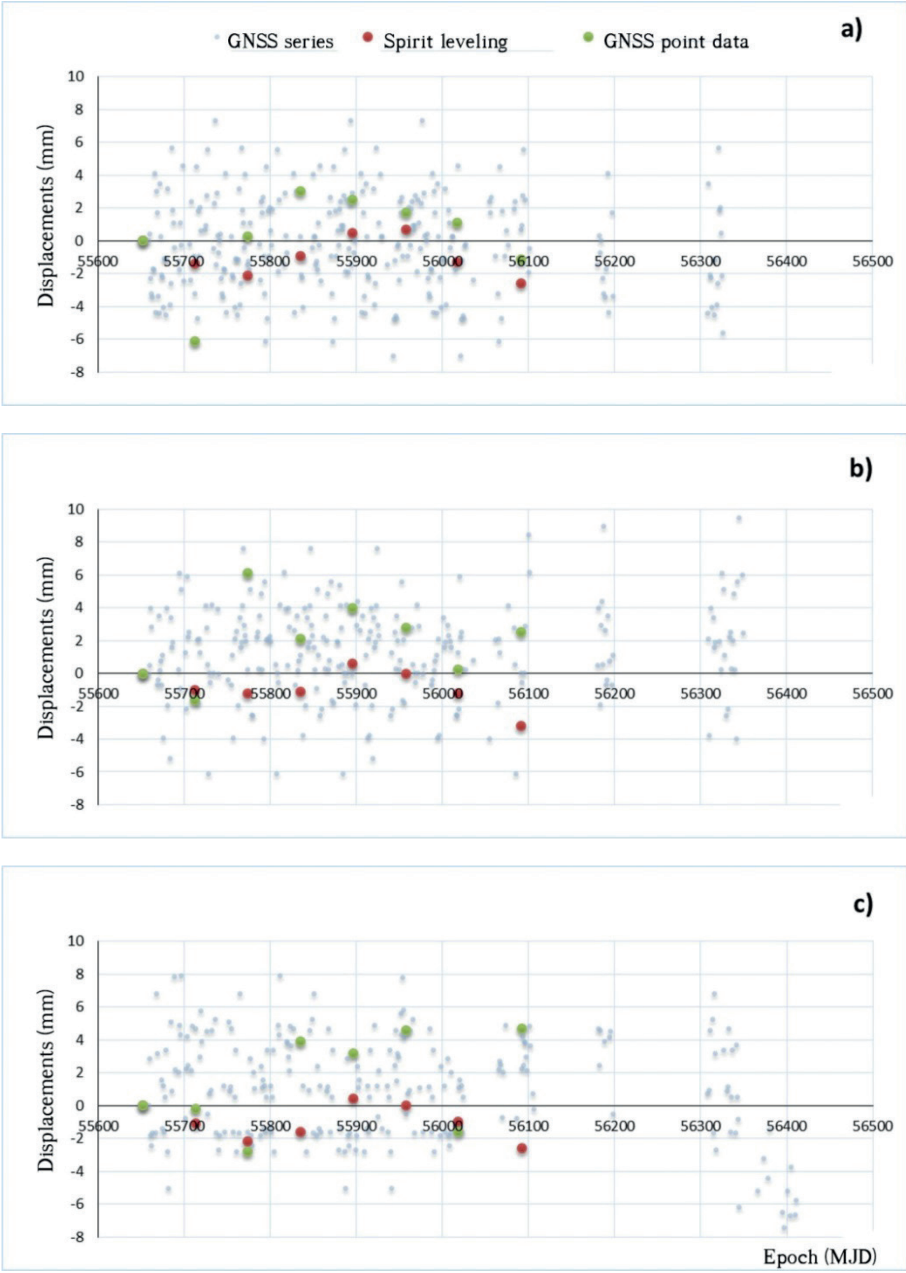

Fig. 7 Comparison beetween spirit leveling and GNSS data; a) BIV 1, b) BIV2, c) BIV3 top to down

6 Conclusions

From the preliminary results about the comparison between the time series, relating to the movements in the two planimetric components (upstream-downstream and crowning), and the models of a hydraulic nature existing in specialist literature, there are encouraging results which show a difference between measured and observed data of a few millimetres in both directions. The best results are those obtained with the predictive PoliMi model, but even more with deterministic modelling. Moreover, with reference to the model of a geotechnical nature, it appears surprising how similar the data obtained for the planimetric component are to the performance obtained with the deterministic model, with residues in the order of few millimetres. However, these results do not correspond to the comparison between the displacement altitude component obtained using modelling and time series. This is an indication that more research is needed to identify any other significant parameters involved in the deformation process of the work, which has not been taken into account. It is certainly necessary to conduct more research, with an attempt to make a more adequate interpretation of the behaviour of loose materials which constitute the dam. This may be possible by making further comparisons with the data obtained using suitable geotechnical instrumentation, such as through settlement gauges, carrying out back analysis aimed at evaluating the evolutionary performance of the characteristics of strength and stiffness of the lands which make up this work.

However, from the comparison between the series obtained by the GNSS techniques and the data obtained with the traditional techniques of displacements measurement, it is necessary to highlight the potentials of satellite survey for the supervision of works of such complexity. The results obtained in post processing in the permanent stations of the experimental network of the University of Palermo are comparable to those of the levelling campaign, based on dataset of two years time. It would be also important to repeat this experiment in other sites in Italy. In fact similar results to those reported could lead to the possibility of a proposal for an amendment of the law currently in force in the field of structural monitoring of the health of dams. Nevertheless, the GPS technologies are now ripe to be used in the regulatory-legal system, whatever the methodological approach employed.

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