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# Numerical Modelling of Sant'Anna Flood Control Reservoir (Panaro River, North Italy): A Tool for Predicting the Behavior of Flood Control Structures During Flood Events

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**Abstract.** In the last years, several flooding phenomena have occurred, mainly due to climate change. A flood control reservoir is one of the most widely used structural means of managing flood events. The main purpose of these reservoirs is to temporarily store the flood water and release it slowly at a safe rate after flooding so as not to cause damage downstream. These reservoirs consist of a system of levees and a flood wall built longitudinally and transversally to the river, respectively. A monitoring system (piezometers and hydrometers) is generally installed to control the response of both structures to flood events. The definition of a numerical model of the levees and the flood wall can be a powerful tool to simulate the behavior of the structures under flood events, through which any anomalies can be identified by comparing the analysis with the in-situ measurements. This approach makes it possible to identify any criticality of the structures and to define all the mitigation actions necessary to preserve their integrity, preventing tragic collapses. In this context, this note presents the numerical model of levees and flood dam that define the Sant'Anna flood control reservoir (Panaro river, north Italy). The geotechnical models were built according to both laboratory and in situ tests and calibrated using the monitoring results of some flood events that happened between 1997 and 2020. The note, therefore, presents some preliminary analyses.

**Keywords:** Monitoring · numerical model · flood events · risk mitigation

## 1 The Case History: The Sant'Anna Flood Control Reservoir (Panaro River, North Italy)

The Sant'Anna flood control reservoir was built to ensure the hydraulic safety of that area of Padana Plain close to the city of Modena and lessen the intensity of flood occurrences in the valley section of the Panaro river.

The Sant'Anna flood reservoir covers a total area of 3 km$^2$, with a storage area oriented in a SW-NE direction delimited by main and secondary levees and it is divided into two distinct basins: a larger in-stream basin straddling the watercourse (78% of the entire basin) and a subsidiary one on the orographic right.

The flood dam consists of a fully overflowing concrete gravity barrier (Fig. 1). The outflow is provided not only by the spillway sill, but also by nine rectangular spans all guarded by flat gates. Downstream of the main structure is the dissipation basin equipped with four rows of staggered ties. The downstream plate on which the structure is built is headed on three longitudinal diaphragms with a length of 19.50 m, of which the two below the retaining structure are also transversally connected.

Five geotechnical investigation campaigns (1998, 2006, 2008, 2016 and 2020) were carried out to identify and characterize the ground and the material involved in hydraulic processes induced by the temporarily store of the flood water and its release. Many in situ investigations (boreholes, CPT and SPT tests, permeability tests), classification analysis (grain-size distribution, Atterberg limits, natural water contents) and mechanical laboratory tests on undisturbed and reconstructed samples (shear direct, triaxial, oedometric and resonant column tests) were carried out. The analysis of the experimental results on the basis of physical and hydro-mechanical characteristics allowed the identification of 6 soil macro-categories whose characteristic parameters have been used in the numerical modeling as described below (Table 1).

In 2016 a monitoring system consisting of piezometers and hydrometers along the levees and at the flood dam, was installed. Nine sections along the main and secondary banks (Fig. 2a) were equipped with Casagrande piezometers, 2 along the central vertical axes of the banks and two more at the toe of the countryside face (Fig. 2b); 4 piezometers were installed along the river shaft and, at the barrage 10 piezometers and 2 hydrometers, one upstream and one downstream, were positioned (Fig. 2c).

Several studies have been conducted to assess the hydraulic efficiency of this flood control reservoir (e.g. [1, 2]), but few analyses have been performed to establish its geotechnical behavior.

Assessing the geotechnical performance and stability of these structures under the action of flood events allows the early detection of possible damage. The integration of numerical models and field-monitoring data helps to implement this process of geotechnical evaluation of the structures [3]. In this context, this paper presents the numerical model of levees and flood dam that define the Sant'Anna flood control reservoir (Panaro River, Modena, Northern Italy).

## 2 Geotechnical and Numerical Model Levees and Flood Dam

Numerical models of the levees and flood dam of the Sant'Anna flood control reservoir were built by gathering all available data from historical documents on the flood control reservoir project, survey of land (performed in 2016), and geotechnical investigation campaigns.

Nine 2D geotechnical models of the levee sections with piezometers were reconstructed (Fig. 2a). The dimension of each model is about 100 m in length and 30 m in height. The domain was discretized, adopting a 15-node triangular mesh, into about 8000 elements to ensure excellent reconstruction of flow phenomena. Static and hydraulic boundaries conditions were defined as follows: model base fixed in the vertical direction

**Fig. 1.** Flood dam of the Sant'Anna flood control reservoir [4].

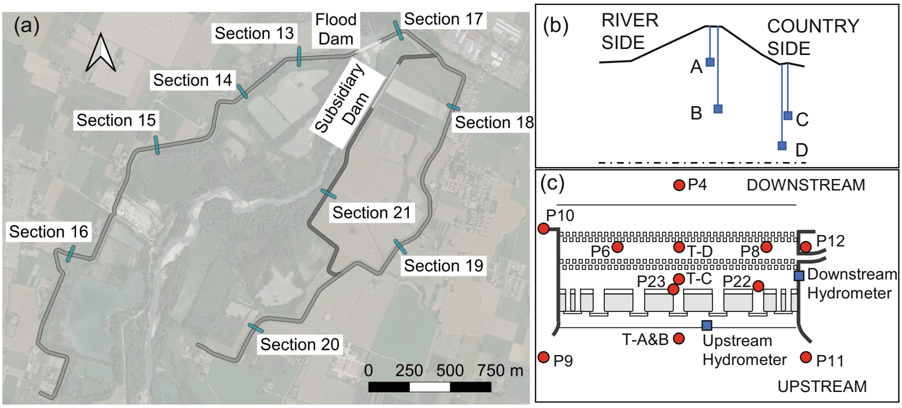


**Fig. 2.** (a) Levees and flood dam layout; (b) Levee section with piezometers location; (c) Location of piezometers (dot) and hydrometers (square) at the flood dam.

and impermeable; lateral sides fixed in horizontal direction and free flow. A Mohr-Coulomb elastoplastic constitutive model was adopted for all soils and the plastic diaphragm. An example of one levee model (section n. 14 – see Fig. 2a) is shown in Fig. 3.

The 2D numerical model of flood dam is shown in Fig. 4. The whole model measures 135 m in length and 50 m in height. It was discretized in 15323 elements adopting a 15-node triangular mesh. The retaining structure and the downstream plate were modelled as a no-porous elastic material. To adequately account for the presence of the holes equipped with gates to regulate the river flow, the unit weight assigned to the dam was appropriately calculated. The three diaphragms under the plate were modelled as no-porous elastic beam elements, whereas foundation soils were modelled as Mohr-Coulomb elastoplastic model. Interfaces elements were also implemented between the soil and the structures: diaphragms and plate. The properties of the interface elements were assigned by applying a reduction factor (R) to the parameters of the soils in contact with the structures. For the diaphragms-soil interfaces, an adhesive-attritive behavior was adopted with a reduction factor R = 0.7. A simple attritive model characterized by the same friction angle of the soil foundation (R = 1) was assumed for the plate-soil interface. The hydraulic and static boundary conditions of the flood dam model were adopted similarly to the levee models.

Soil geotechnical parameters adopted in the analyses for both models are shown in Table 1. Table 2 reports the structural parameters of the flood dam.

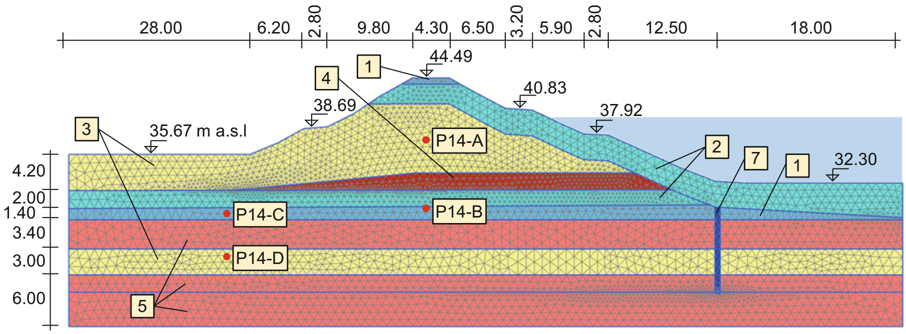


**Fig. 3.** Numerical model of a levee (section 14)

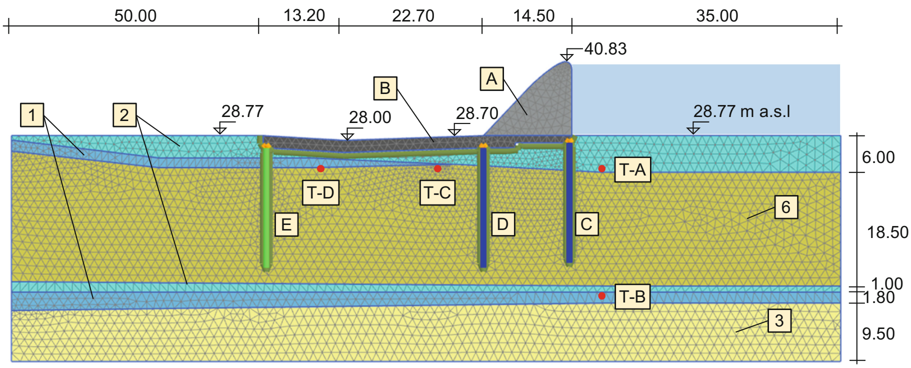


**Fig. 4.** Numerical model of the flood dam

## 3 Preliminary Analysis and Results

The previous described models were used to carry out numerical simulations using the commercial finite element, plane strain software PLAXIS 2D® [5]. Coupled hydromechanical analyses were performed on each levee and flood dam models to simulate their response during reservoir and discharge operations adopted to manage flood events. Flood events occurring between 1997 and 2020 were considered for the calibration of the models. This note reports only the preliminary analyses performed on the structures under the action of the historical flood event occurred in December 2020. The reservoir

**Table 1.** Soil geotechnical parameters

| | Gravel and Sand | Sand with clayey silt | Sandy silt | Clay | Clay and silt | Sandy Silt and Clay | Cement bentonite |
|---|---|---|---|---|---|---|---|
| ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| $\gamma_n$: kN/m$^3$ | 20 | 18.6 | 19.6 | 17.5 | 19.0 | 19.0 | 19.0 |
| $\varphi'$: ° | 34 | 32 | 28 | 18 | 27 | 24 | 27 |
| $c'$: kPa | 1 | 3 | 14 | 14 | 29 | 18 | 29 |
| K: m/s | $2.8 \cdot 10^{-4}$ | $1.2 \cdot 10^{-6}$ | $1.0 \cdot 10^{-8}$ | $1.9 \cdot 10^{-8}$ | $1.5 \cdot 10^{-8}$ | $1.4 \cdot 10^{-8}$ | $1.0 \cdot 10^{-12}$ |
| $\upsilon$: - | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| E: kPa | 42190 | 25550 | 11920 | 5525 | 11680 | 2920 | 11680 |

**Table 2.** Structural parameters of flood dam

| | Dam | Plate | Diaphragma | Diaphragma | Diaphragma |
|---|---|---|---|---|---|
| ID | A | B | C | D | E |
| $\gamma_n$: kN/m$^3$ | 22 | 24 | – | – | – |
| w: kN/m/m | – | – | 19.2 | 19.2 | 24 |
| d: m | – | – | 0.8 | 0.8 | 1.0 |
| $\upsilon$: - | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| E: kPa | $30 \cdot 10^6$ | $30 \cdot 10^6$ | – | – | – |
| EA: kN/m | – | – | $24 \cdot 10^6$ | $24 \cdot 10^6$ | $30 \cdot 10^6$ |
| EI: kN/m$^2$/m | – | – | $1.3 \cdot 10^6$ | $1.3 \cdot 10^6$ | $2.5 \cdot 10^6$ |

storage and outflow discharge curves in terms of upstream water level recorded during the flood event are shown in Fig. 5. The average velocity of reservoir storage was estimated at 0.37 m/h, while the average velocity of flow discharge is 0.18 m/h.

The analyses of the levees were performed in three steps: an initial phase, a reservoir storage phase, and an outflow discharge phase. The initial phase was carried out to assess the initial stress state condition of the model. During this phase, the water level of the model was set based on the piezometer values recorded before the flood event.

The last two steps of the analysis were conducted by means of flow simulations imposing the progressive raising or lowering of the reservoir level based on reservoir storage and outflow discharge curves. Slope stability analyses were also conducted.

The numerical results of the increase in pore-pressure were compared with those measured by the installed piezometers (Table 3). Figure 6 shows the comparison of measures of the piezometers during the reservoir storage and the flow discharge with the corresponding value obtained by the numerical model.

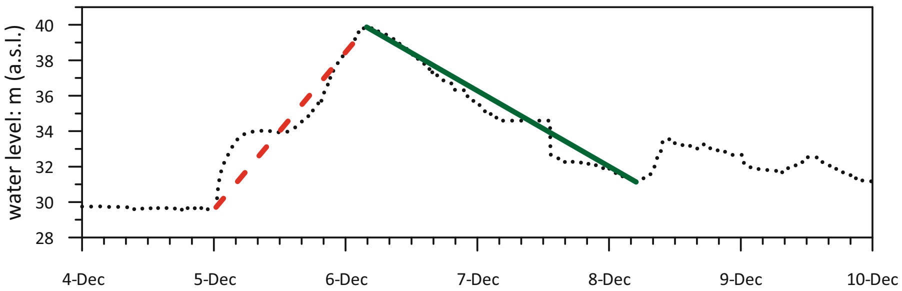


**Fig. 5.** Recorded reservoir storage and outflow discharge curves (dot line), average velocity of reservoir storage (dashed red line), and average velocity of flow discharge (solid green line)

**Table 3.** Comparison of the increment of pore pressure model and piezometer measurements

| Piezometer (Fig. 3) | End of reservoir storage phase | | End of flow discharge phase | |
|---|---|---|---|---|
| | P14 – B | P14 – C | P14 – B | P14 – C |
| Numerical Model: m | 1.70 | 0.85 | −0.41 | −0.96 |
| Real measurement: m | 0.55 | 0.59 | 0.82 | 0.74 |

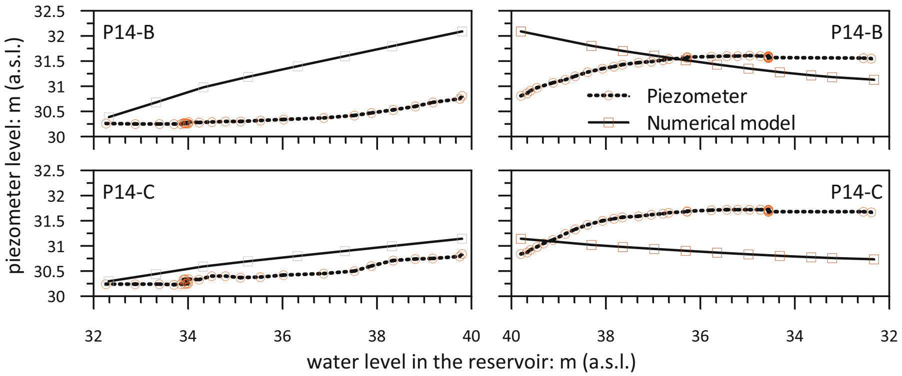


**Fig. 6.** Comparison of the measured piezometer levels with the corresponding numerical results

The differences observed between the numerical simulation and actual field measurements are due to the way the reservoir phase was simulated. This phase was modeled through steady state analysis, increasing the water level in the reservoir step by step. This choice made it possible to define an upper bound condition that can only be reached if the flooding phase takes place at a very low speed. The slope stability analyses showed Safety Factors higher than 1.5 for all phases analysis.

As shown in Table 3 and Fig. 6, the comparison between pore pressure computed in the model and the measured pressure does not consider either piezometer P14 - A or P14 - D. The first because it is located above the groundwater level, the latter because its measurement is governed by the regime of the deeper aquifer, a hydraulic condition that has not been implemented in the model. A coupled transient flow analysis was conducted on the flood dam applying a progressive increment of the reservoir level till to the maximum value reached during the reservoir storage phase. The numerical values of the increase in pore pressure at the end of reservoir storage were compared with those measured at the point where piezometers are installed (Table 4). Also in this case, the deepest piezometer (T-B – see Fig. 4) was neglected in the comparison, its measurement being governed by the deepest aquifer.

**Table 4.** Comparison of model pore pressure model increase and piezometer measurements below the flood dam at the end of reservoir storage

| Piezometer (Figs. 2(c) and 4) | T-A | T-C | T-D |
|---|---|---|---|
| Numerical Model: m | 11.01 | 3.24 | 2.98 |
| Real measurement: m | 9.08 | 6.00 | 5.94 |

This first analysis showed some differences between numerical results and measurements. The piezometer T-A provides a value that is out of agreement with the actual level in the reservoir, which is better captured by the numerical model. In terms of hydraulic head loss under the plate, the numerical results show higher reductions than real measurements. Better correlations between measurements could be obtained by inspecting the condition of the installed instruments and refining the hydraulic conditions of the model by carrying out a parametric analysis to take into account the local variability of hydraulic parameters.

Furthermore, to assess the stability of the structure against uplift phenomena induced by the pore pressures, transient flow analyses were performed considering different holding durations of the maximum water level in the reservoir. Finally, a steady state flow analysis was carried out to evaluate the maximum possible pore pressure regime under the structure. Figure 7 shows the pore pressure distribution under the structure at different time of maximum reservoir level stationing: at the end of the reservoir storage, 24 h, 75 h, 7 days and 15 days after reaching the maximum storage level and under steady state condition. Based on these results, an uplift stability analysis of the retaining structure was conducted according to NTC18 [6]. By applying partial coefficients and neglecting the stabilization contribution provided by the friction of the diaphragms, the destabilizing force (resultant hydraulic under-pressure) remains lower than the stabilizing force (total weight of the structure) as required by the code.

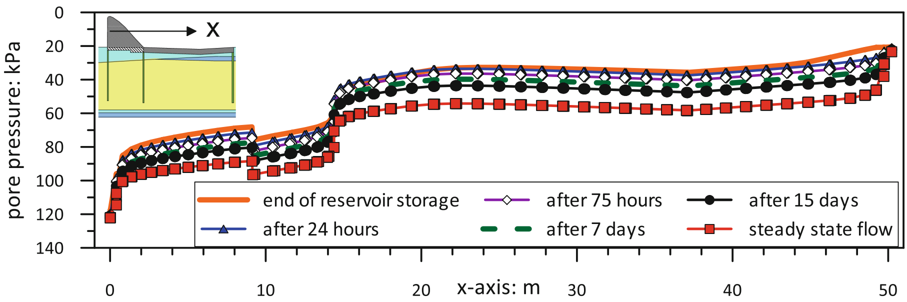


**Fig. 7.** Distribution of the pore pressure under the flood dam.

## 4 Final Remarks

Numerical models of levees and flood dam defining the Sant'Anna flood control reservoir (Panaro river, north Italy) have been presented. These models have been used to perform transient and steady state flow analyses, slope stability and uplift assessments of the structures. The preliminary results reported in this note have referred to the response of the structures to the flood event recorded in December 2020. Although the 2D model is not able to account for 3D spatial variability of hydraulic conditions, leading to differences in the comparison between numerical results and data recorded by monitoring devices, a satisfactory response of models in representing the actual response of the structures can be observed. Optimizing the numerical analysis requires both a verification of the installed equipment and an in-depth parametric study to accurately characterize the hydraulic parameters. A 3D model would be more accurate in simulating the spatial variability of hydraulic parameters, but would require a complete reconstruction of the landscape, which cannot be achieved with existing data. Despite the observed differences, these preliminary results highlight that the models can be adopted as potential digital twins, i.e. a combination of the reality and digital models capable of capturing real time behavior of the structures, assessing their current state and predicting their response, detecting any problem in advance and thus preventing dramatic damage. The advantage of these digital twins is that their characteristics can be updated based on additional information that becomes available over time and data from of monitoring system.

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