Rehabilitation and upgrade of Giudea Dam

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ABSTRACT: The Dam and the Impound of Giudea, for the water supply of Pistoia Municipality, were completed and accepted at the end of 1973. They were interested in 1990 by some local slides, which obliged to empty the reservoir. As the occurred phenomena were attributed to the degradation of the clayey materials, the dam rehabilitation design outlines include the substitution of the collapsed soil with other of better characteristics, the disposal of a protected waterproof geomembrane on the upstream face and the dam crest raising, in order to fit the Italian Dam Code in force. Meantime the bottom outlet and the draw-off pipes will be located in a new tunnel on the right bank. In the impound, the left bank of the reservoir will be reinforced in the weathered zones with a gravelly embankment. The seismic hazard and the safety assessments of the dam have been finalized according to the state of art.

1 INTRODUCTION

The Giudea Impound, located in Gello site in the Pistoia Municipality, was conceived in the ’60s for the water supply of the town.

The plant, finally accepted at the end of 1973, operated regularly until 1990, when the occurrence of some slides obliged to empty the reservoir. After a preliminary study phase, the Municipal Administration appointed the design of the rehabilitation measures of the impound and the contextual upgrade of the works, according to the Italian Dam Code in force.

In 1993 a cofferdam was built upstream of the embankment, in order to make some preliminary arrangements at the foot of the dam, so allowing a provisional partial impound of about 65000 m^3 (see Fig.2) . The Final Design for the complete rehabilitation of the reservoir was approved by the National Regulatory Agency at the end of 1996.

In 2007 the seismic safety assessments of the dam and the appurtenant works in the upgraded lay-out have been developed.

Meanwhile a new quarry area of gravelly and silty-sandy materials for the remodelling of the embankment and the reinforcement of the left bank of the reservoir has been investigated and characterized under the geotechnical profile. It is located in the Primavera Lakes zone, adjacent to Ombrone Pistoiese River, about one kilometre South of the city, where the co-ordinated construction of an important Expansion Impound for flood control is planned.

2 GENERAL ELEMENTS ABOUT THE WORKS AND THE FIRST PHASE OF OPERATION

The Giudea Impound is an “outside the river-bed” basin, located at the foot of the Apennines North-West of Pistoia, at the head of a valley determined by Rio dei Fontanacci Stream; it is used to modulate and store the winter and spring flows of a near stream.

The reservoir, which originally had an useful capacity of about 660000 m^3, is placed in a formation of shaley clays inglobing sandstones and strongly weathered and fractured grey limestones.

The availability of semi-pervious materials in the immediate surroundings and the relative deformability of the foundation grounds oriented the original design towards an homogeneous embankment dam about 32 m high, realized with compacted shaley clays and protected upstream with a rip-rap layer and downstream with a filtering foot blanket. The embankment was built between 1965 and 1970 and regularly accepted in 1975. The crest, 6 m large and 295 m long, was at 150.06 m a.s.l. elevation, with normal water level at 147.76 m a.s.l. . The net freeboard resulted 1.8 m. Being the impound "outside the river-bed", the spillway was conceived for relatively modest discharges: having an overflowing sill 10.8 m long on the right bank, with a 0.5 m water head it was able to evacuate a 6.8 m^3/s discharge.

The bottom outlet and the draw-off consisted of two side by side steel pipes, respectively 450 mm and 400 mm ϕ, which passed, in a special concrete embedding, under the dam abutment.

In 1990 autumn, without any evident premonitory signal, at first on the upstream shell of the dam (Fig.1), then on the left bank of the reservoir, several some meters thick rotational slides interested the slope.

Some deformations appeared indeed on the upstream face, with the formation of several fractures and a general lowering of the profile from the upstream edge of the crest until about 137 m a.s.l., that is for the superior 13 m, and with a more or less remarkable raising at the inferior elevations; movements on the face occurred also later.

After some provisional stabilization works at the foot, the phenomenon practically stopped.

Since the preliminary studies, the reason of the failures seemed to be connected with the weathering of the embankment material, argillites and their alteration blanket, in contact with the water of reservoir.

A wide experimental investigation, with the intervention also of Prof. P. Colombo, confirmed that the slides happened in a phase of draw-down and that for such a condition the slope of the upstream face was inadequate to the actual reduced shear strength of the shell fill.

Figure 1. Giudea Impound - In evidence upstream shell slides (2007)

3 REHABILITATION WORKS DESIGN

The concept design involves the substitution of the displaced fill with material of better characteristics and the transfer of the dam watertightness function from the body of the embankment (original design) to an impervious geomembrane on the upstream face. In that way all the dam body, including both the new "rehabilitated zone" and the old embankment, still consisting of clayey material, is preserved from the contact with the water.

The reinforcement of the left bank of the reservoir, in the loosened zones, with a gravelly embankment adequately profiled (Fig. 2), is considered as well.

With the new design outlines, in addition to upgrade the works according to the in force

Italian Dams Code , it is possible to increase the useful capacity of the reservoir up to about 802000 m^3. Furthermore, with an important modification of the original lay-out, the bottom outlet and the draw-off pipes will be located in a dedicated new tunnel, with horseshoe section of 2.40 m, which will cross the right side, without interfering with the dam, and will convey the water to the contiguous Tazzera Stream valley. As it is shown in the typical cross section (Fig. 3), the new crest elevation is 153.40 m a.s.l., with a raising of 3.34 m, and the net freeboard now results 3.45 m; the maximum height of the dam above the downstream foot is 33.40 m.

The lay-out of the dam reproduces the upstream concave shape of the original embankment: the new axis is displaced 6.60 m downstream and the overall crest is 395 m long.

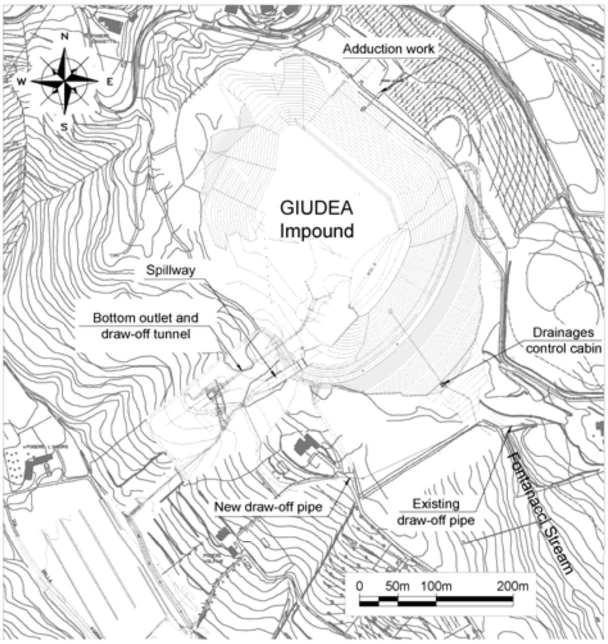

Figure 2. Giudea Impound – General lay-out

The new embankment has a zoned section. On the upstream face an impervious PVC geomembrane, 1.5 mm thick, is interposed between two polypropylene continuous filament 350 g/m^2 geotextile sheets and ends in the waterproof "plug" located at the foot of the face. The watertight “package” lays on a 50 cm thick draining layer constituted by alluvial gravel of small size and is protected by a layer of selected gravelly material, 90 cm thick, and by a limestone rip-rap, 60 cm thick, formed by quarry elements.

In the typical cross section, which inglobes the pre-existing embankment, adequately profiled, four main zones can be identified:

- the upstream impervious toe plug;
- the upstream shell in gravelly alluvia;
- the upper central zone in gravelly silt;
- the downstream shell constituted by gravelly alluvia.

The wide impervious "plug" at the upstream foot connects the geomembrane and the foundation watertight clay formation. It will be formed with silts coming from Primavera Lakes adequately selected and compacted, partly added with 8% bentonite powder. Between the geomembrane and the existing embankment, preliminarily modelled with arrangement excavations, a new upstream shell about 8 m thick is realized in alluvial material of good mechanical characteristics selected from the gravels of the named Lakes.

The upper central zone is of alluvial origin and represents a semi-pervious barrier against the hypothetical remarkable filtrations in case of any breakage of the geomembrane; the material comes from the cultivation of the surface silty layer (70%) of Primavera Lakes mixed with the gravels below (30%). The downstream shell is formed with clean alluvia; the covering thickness of the old shell is between 4 and 9 m. The face is protected by a 40 cm thick layer of grassy vegetable soil. The shell itself rests on a draining blanket which, joining the remaining part of the original oblique drain, keeps low the level of the saturation curve and removes any water filtration of different origin. In the upstream shell, both the draining layer upon which the geomembrane is located and the blanket at the interface with the existing embankment, discharge into a drains collector. It conveys through the existing steel pipes ϕ 450 and ϕ 400 mm of the original bottom outlet and draw-off, which have been verified with an endoscopic investigation and supplied with discharge limiters; the seepage waters flow to a new measure and control cabin, equipped with a gauge station, immediately downstream of the dam. In the same cabin also the waters in case coming from the downstream oblique drain and draining blanket, already belonging to the old embankment, are collected.

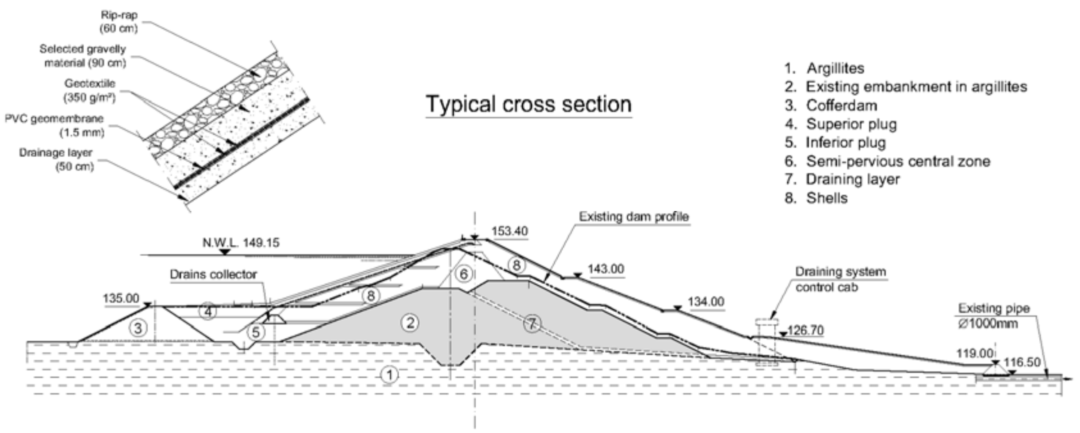

Figure 3. Giudea Dam – Cross section

4 GEOLOGICAL AND GEOTECHNICAL OUTLINES

4.1 *Geology of the area*

The foundation and the reservoir of Giudea Dam fall within a typical hilly landscape shaped in the argillites and siltstones of the Sillano Formation, a geological unit referred to the Upper Cretaceous-Lower Eocene. The unit tectonically overlies the Marmoreto Marls Formation (Upper Oligocene-Lower Miocene), constituted by prevailing layered brown calcilutites and light coloured silty marls, which outcrops on the NW bank of the reservoir almost above the maximum water level. Lithologically the Sillano Formation is predominantly composed of weak highly tectonized shaley clayey materials showing a complex structural pattern of numerous shears and faults, which determine a chaotic structure of blocks and fragments of limestones, sandstones and marls, with dimensions ranging from decimetres to several meters, included in a mainly clayey matrix. The formation occupies almost all the reservoir area and its very low permeability ensures appropriate watertight conditions for the reservoir banks.

The geomorphology of the area surrounding the Giudea Impound is marked by the presence of local slides and instability phenomena of the slopes, generally modest in scale, but widely involving the argillites. In these phenomena are included the mentioned small episodes, which have marginally involved, during the past operations of the basin, some local sectors of the reservoir banks, inducing limited mobilizations of the shallow weathered strata of the argillites.

4.2 *Geotechnical characterization of the dam foundation grounds*

The geotechnical characterization of Sillano argillites, which constitute the foundation of Giudea Dam, is the result of various geological and geotechnical campaigns, carried out starting from the earliest stages of the design work.

Indeed in the dam area a series of boreholes with undisturbed core sampling for physical-mechanical laboratory analysis, several trenches and exploratory shallow wells have been performed. The argillites show the structural features typical of the "complex structural formations" widely outcropping in the Apennines Chain. According to the classification originally proposed by ESU (1977) for those types of formations, Sillano argillites can be attributed to types B2 and B3, corresponding to clayey strongly tectonized rock masses with a chaotic structure, including irregular clasts and fragments of more competent rocks.

In detail, the boreholes carried out in the foundation grounds of Giudea Dam have identified the presence, beneath a superficial layer of eluvial clay about 3÷4 m thick, of weathered grey-brown argillites, gradually passing to the underlying dark-grey unweathered argillites, located around 10 to 12 m deep from ground level. A summary of the physical and mechanical properties derived from the geotechnical investigations for these lithotypes is shown in the following Table 1.

Table. 1 – Physical-mechanical characteristics of foundation argillites

Lithology	γ_d [KN/m^3]	W [%]	< 2μ [%]	PI [%]	c' [KN/m^2]	φ' [°]
Weathered argillites	17.5÷20	11÷30	34÷36	17÷18	1.4÷5	22÷29.5
Unweathered argillites	17.5÷20	12÷15	17÷18	17÷18	25.5÷59	22.5÷27

γ_d = dry unit weight; W= natural water content; < 2 μ = passing % ; PI = Plastic Index; c' = drained cohesion;

ϕ' = drained shear strength angle

4.3 *Geotechnical characteristics of the existing embankment and of the soils to be used for the rehabilitation*

The existing embankment, mainly formed by compacted clay materials derived from the excavations of the argillites in the dam section, was the subject of various geotechnical investigation and studies. In 2006-2007, also the alluvial deposits in the area of Primavera Lakes were investigated, in view of their use in some internal zones of the new Giudea Embankment and for the reinforcement of the left side of the reservoir. That area, covering approximately 6.5 hectares, is situated some kilometres SE of the dam site, at the confluence of Tazzera/Torbecchia and Ombrone Rivers. The materials consist of recent and terraced alluvial sediments constituted by a superficial layer, few meters thick, of sandy silts lying on gravelly-sandy deposits, partly affected by the natural ground water level. In detail, the materials composition corresponds to prevailing low gravelly silts with sands (silt 61-68%, sand 30-34%, gravel 0-7%) in the superficial part of the deposits, passing to underlying gravel and pebbles and sandy gravels (pebbles 24-69%, gravel 13-60%, sand 4-21%, fine fraction 1-20%).

The investigations carried out on the existing embankment and in the Primavera Lakes area have included numerous shallow wells and boreholes with sampling, at various depths, for laboratory analyses. The basic geotechnical parameters derived on the basis of investigations and tests conducted on these materials are summarized in Table 2.

Tab.2 - Geotechnical characteristics of the dam materials

Dam materials	γ_u [kN/m^3]	γ_{sat} [kN/m^3]	c' [kN/m^2]	φ' [°]
Existing embankment	20.0	20.5	10	20
Cofferdam	20.0	22.0	0.0	30
Plug at upstream foot	19÷20	20.5÷21.5	0.0÷1.0	20÷32
Semi-pervious central zone	20.0	21.5	0.0	25
Shells and reinforcement embankment	20.0	22.0	0.0	32

4.4 *Dynamic characterization of the foundation grounds and of the existing embankment materials*

The reconstruction of the seismic P and S waves speeds within the foundation grounds and the existing embankment of Giudea Dam is derived from the results of geophysical investigations.

In particular, a down-hole test was performed in a vertical hole, 30 m deep, drilled in the dam foundation argillites, at the foot of the downstream slope of the existing embankment. It has found average values of Vp equal to 920 m/s and over 2500 m/s, respectively for the weathered more superficial argillites and for the unweathered deeper ones. The corresponding average speeds Vs grow from 280 m/s to 520÷800 m/s. Vs_{30} parameter is equal to 506 m/s.

Furthermore some MASW tests, based on the measure of the propagation speed of the Rayleigh superficial seismic waves, were carried out from various positions through the body of the existing embankment, allowing the reconstruction of Vs profiles, in one and two dimensions. They were executed, respectively, from the dam crest road and from the downstream banks of the embankment, around levels 143 and 135 m a.s.l., and oriented according to the longitudinal direction of the dam. The results of the MASW tests in the existing embankment body show the presence, next to the crest of the embankment, of a low speed seismic zone, characterized by values of Vs between 120 and 150 m/sec, where a probable state of relaxation exists. Deeper the speeds tend to increase up to values of the order of 350 to 450 m/s, despite local decreases, probably due to lack of uniformity of the materials in the construction phase.

5 WORKS SEISMIC SAFETY ASSESSMENTS

Being Pistoia Municipality classified as second seismic category, in 1995 both the dam and the reinforcement embankment on left side were positively verified with the pseudostatic method, according to the Italian Dams Code, even in the rapid draw-down condition following a breakage in the waterproof lining.

In 2007 limit states seismic analyses have been developed, assuming the following return times:

- ultimate limit state (SLU), with important damages, but without uncontrolled release of water: 1000 years;
- collapse limit state (SLC) with irretrievable damages and uncontrolled release of water: >2500 years.

6 SEISMIC HAZARD EVALUATION

The study has taken into account the historical and instrumental seismicity of a big area containing the site and the maxima effects observed in the municipal territory, making reference to the parametric catalogue of the Italian earthquakes (WORKING GROUP CPTI, 2004). The biggest macroseismic intensity values observed in Pistoia City are included between VIII and IX MCS degrees, as consequence of local earthquakes.

For the seismic hazard evaluation CORNELL (1968) methodology has been adopted.

The source zones have been identified with reference to the ZS9 simplified model, proposed by the Working Group for the compilation of the seismic risks map of INGV.

A recurrence law has been associated to each source zone according to the Gutenberg-Richter algorithm, using the above mentioned parametric catalogue of the Italian earthquakes.

In the study the attenuation laws proposed by SABETTA *et al.* (1996), on the basis exclusively of Italian data, have been adopted.

Taking into consideration all the seismic zones, the peak values of the ground motion (PGA and PGV) and the spectral values of acceleration (PSA) have been calculated, as a function of the return time, for a position in the middle of the crest.

The reference vibratory motions have been finally defined by comparing the results of the hazard evaluation with the values supplied in 2006 by INGV in S1 project for Civil Protection and prudentially adopting their envelope. For the site 0.21 and 0.28 g peak acceleration values and the response spectra summarized in Fig.4 have been so adopted, respectively for 975 and 2475 years return times. It was then selected a set of six artificial accelerograms in accordance with the reference motions, obtained assuming a couple of magnitude and distance values respectively between 5.6 and 5.9 and between 10 and 15 km.

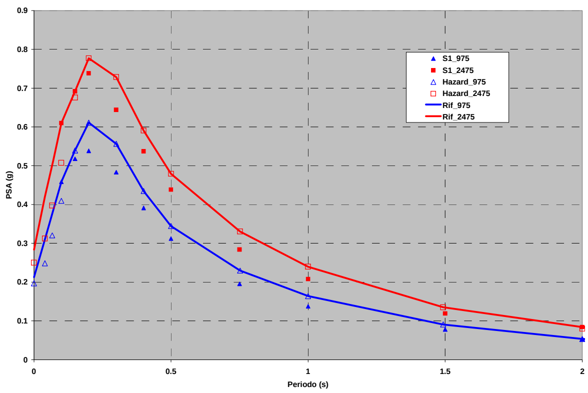

Figure 4. Response spectrum of reference vibratory motions (red: 2475 years, blue: 975 years)

7 DAM DYNAMIC ANALYSIS

For Giudea Dam the high degree of compaction specified for the construction of the granular shells, in addition to the nature of the abutments formation and of the materials of the existing embankment, excludes the occurrence of liquefaction phenomena or the reduction of strength under cyclic loads. It was then developed a dynamic analysis, considering the effective seismicity of the area together with the deformability and the strength mechanical characteristics of the materials.

7.1 *Preliminary static analysis*

The static analysis of the dam has been developed using a 2D model in plane deformation with elasto-plastic behaviour of the materials, taking into account the temporal evolution of the geometry and of the contour conditions.

The mesh, which represents the maximum height section, is formed by 1476 elements interconnected in 1554 nodes and has been drawn reproducing accurately the geometric and geotechnical features of the embankment.

In the numerical model the sequence of the phases has been reproduced distinguishing the construction of the original body and that of the other zones of the new embankment until the crest elevation. Due to the watertight upstream face, the impound effect has been introduced through simple nodal forces applied at the upstream contour.

7.2 *Dynamic geotechnical parameters*

The speed values Vs obtained with the MASW tests have been worked out for the existing embankment. As the new shells present a bigger stiffness, in their case at the same stress conditions an increase of about 15% of the Vs has been assumed.

For the foundation the Vs measures executed in the down-hole test have been used.

In absence of laboratory tests results, the materials have been divided in two categories (granular and cohesive), adopting literature G/Go and damping D curves versus shear strains.

7.3 *Linear equivalent dynamic analysis*

Firstly the dynamic analysis has been developed with a linear equivalent model in full reservoir conditions, using the same mesh as in the static simulation.

The application of the reference motion with 2475 years return time determines peak values generally inferior to 0.5 g, with a maximum of 0.8 g near the crest.

A big reduction of the shear modulus is located in the shells, with 20% of the value of Go; in limited zones the G modulus drops near 10% of Go. In the pre-existing embankment they result 40-50% of the initial ones. With reference to the shear strains, besides the shells the isolines

0.20% and 0.30% interest a more consistent part of the dam and about at 1/3 of the maximum height strain values near 0.40% are reached in a relevant zone.

For that reason also a non-linear model was developed (ISHIHARA (1968)).

7.4 *Permanent displacements*

On the basis of the results of the linear equivalent model the permanent displacements of the embankment for the design seismic events have been calculated with NEWMARK (1965) method.For the seism with return time of 2475 years the maximum displacement along the face direction is about 1.9 m (vertical component 0.73 m). Those values concern the nodes near to the crest; more modest entities characterize other zones of the embankment.

7.5 *Non-linear dynamic analysis*

The estimates executed with the non-linear model for the same return time show a maximum permanent settlement of 2.0 m (1.3 m in vertical direction) only in the downstream node of the crest. For the upstream node a vertical settlement of about 0.6 m is obtained. In other zones of the embankment much lower values are determined.

Resulting the maxima displacements largely inferior to the available net freeboard of 3.45 m, the watertightness of the embankment is then ensured.

With regard to this, it is meaningful the about 0.5 m calculated value of the final settlement in the central zone of secondary waterproofing: the relative top elevation would pass from 150.00 m a.s.l. to 149.50 m a.s.l., still superior to the normal water level (149.15 m a.s.l.).

8 CONCLUSIONS

The planned co-ordinated realization of an Expansion Impound on Ombrone River in Primavera Lakes zone and rehabilitation and upgrade of Giudea Impound represent an interesting example of synergy on the territory in the direction of the works sustainability.

The rehabilitation design of Giudea Dam, besides to eliminate the contact of the basin with the clayey material of the upstream face, primary reason of the occurred failures, introduces the zoning of the embankment, realizing with the existing body, suitably raised, an auxiliary watertightness in the central part in case of breakage of the superficial geomembrane.

In the new asset all the elements of waterproofing are associated with proper draining systems and their hypothetical losses are checked inside a downstream cabin. It is also verified that the safety of the works is warranted also in the most severe seismic conditions.

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