Design and construction of reinforced walls in Italy in complex static and seismic conditions

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ABSTRACT: The present paper aims to present the design problems associated with reinforced walls in difficult static and seismic conditions, through the presentation of some of the most challenging projects built in Italy in the last years. The reinforced walls here presented were built in different Italian regions, with widely differentiated topographic, geotechnical and seismic conditions; for both retaining structures and preservation of historical sites. The wall projects are divided in categories, including green faced walls, concrete blocks faced walls, walls for preservation of historical sites, walls with pile bulkheads, calcium stabilized and reinforced soil structures. The paper reports the stability analyses in static and seismic conditions, the design layouts and the construction techniques, showing technical drawings, construction details and photos taken during and after construction, thus affording a clear picture of Italian engineering of reinforced soil walls.

Keywords: Reinforced soil walls, geogrids, seismic, case histories

1 INTRODUCTION

Since the early '80 of last century hundreds of reinforced soil structures have been built in Italy in the most diverse environmental conditions, thus allowing the development of design and construction techniques, and the growth of specialized engineering companies and contractors. Green faced structures make the bulk of the projects, but also several walls with concrete block and concrete panel facing have been built as well. The present paper aims to present the design problems associated with reinforced walls in difficult static and seismic conditions, through the presentation of some of the most challenging projects built in Italy in the last years. The use of pile bulkheads, for helping the global stability and for shortening the geogrid reinforcement, and the use of marginal soil fills, like calcium stabilized silt and clay or tunnel debris, is reported as well.

2 ITALIAN NORMATIVE FRAME FOR DESIGN OF GEOTECHNICAL STRUCTURES

All construction in Italy shall be designed according to the “Technical Norm for Construction”, usually called NTC 2008, which are fully conforming to EN 1990:2002 (the so called EuroCode EC7), for which NTC 2008 is the Italian National Annex. Like in Eurocodes, reinforced soil structures are not directly addressed, hence design criteria need to be “extrapolated”.

Ultimate limit state analyses shall fulfill the condition Ed ≤ Rd, where Ed is a function of the characteristic values of each action multiplied by a partial amplification factor that takes into account the uncertainty in modeling, and Rd is a function of the characteristic values of the geotechnical system resistance divided by a reduction factor on resistance and by a coefficient of uncertainty in the modeling of the resistance.

NTC 2008 affords two types of design approaches for the ultimate limit states, but in case of retaining walls with anchors to the ground (hence also in case of reinforced soil structures), the analyses shall be made with reference to only Approach 1, which includes two different combinations of coefficients (A for amplification of loads, M for reduction of resistances, R for ultimate limit states verification purposes): Combination 1 (A1 + M1 + R1): more severe against the structural design; Combination 2 (A2 + M2 + R2): more severe towards the geotechnical design.

In practice the EC7 – NTC 2008 approach can be easily implemented by performing the “traditional” analyses, like sliding along a circular surface or a bilinear surface, bearing capacity, pullout, etc., but using as input values the factorized values of loads and geotechnical parameters. Analyses are satisfied when the equivalent minimum Factor of Safety (FS), now called Margin of Safety R1 or R2, is achieved; R1 and R2 are equal to 1.0 both in static and seismic conditions, but global stability analyses shall be carried out only with Combination 2 and a minimum FS value R2 = 1.10 shall be achieved.

For seismic analyses, the seismic motion at the surface of a site, associated with each category of the subsoil, is defined by the maximum acceleration (a_{max}) at the surface, which in turn depends on the maximum acceleration expected at the bedrock a_g: $a_{max} = (S \cdot a_g) = (S_S \cdot S_T \cdot a_g)$, where S_S, S_T are the stratigraphic and topographic amplification coefficients.

The horizontal and vertical seismic coefficients for pseudo-static analyses are: $K_h = (\beta_m \cdot a_{max} / g)$ and $K_v = (\pm 0.5\ K_h)$, where β_m (varying between 0.20 and 0.30 for a_{max} varying from 0 to 0.40) is the coefficient for reduction of the maximum acceleration at the site.

The coefficient S_S depends on the seismic soil category (A, B, C, D, E according to values of shear waves velocity in the first 30 m, $V_{s,30}$); the coefficient S_T depends on the category and features of the topographic surface (average slope, crest width, etc.).

Global stability analyses in seismic conditions (sliding along circular surfaces or rotational sliding; horizontal sliding or translational sliding) are usually carried out by adding a pseudo-static seismic horizontal force in the gravity center of each wedge, equal to: $F_{PS-h} = (K_h \cdot W_i)$ and $F_{PS-v} = (\pm K_v \cdot W_i)$, where W_i is the weight of i-th wedge.

3 GREEN FACED WALLS

One of the most challenging projects of reinforced soil walls with green facing is represented by the walls along the State Road Nr 28, closed to Imperia, in Northern Italy (Rimoldi and Intra, 2009), built by the Italian National Road Agency, with the aim of bypassing the town of Pieve di Teco. The project included a 2,0 km long tunnel, a bridge crossing the river valley and three roundabouts placed on the slopes along the course of river Arroscia. The three roundabouts were supported by reinforced soil walls, built using the wrap-around technique with sacrificial steel formworks, all with vegetated faces. The walls were reinforced by knitted polyester geogrids with 50, 60, 80, 100 kN/m tensile strength. For a better environmental blending the reinforced soil structures have been designed with tiered pattern, in order to match the old dry walls, made up of local stones, which cover all the slopes of the valley. Each reinforced soil structure is comprised of 80° sloped tiers and variable width horizontal berms. Seismic analyses had to be carried out for the peak bedrock acceleration $a_g = 0.15$ g. The most impressive reinforced soil structure, supporting the Northern roundabout, has the following characteristics: maximum height = 30.50 m; length = 260 m; 3 abutments of the bridge resting on top of the slope. Besides the reinforced soil structure, two concrete channels have been designed, carrying down the water of two creeks, the Rio Teco and the Rio Minore, whose natural courses perpendicularly cross the face of the reinforced soil walls: the channels follow the same tiered pattern of the wall, after passing below the new road stretch inside corrugated steel culverts. Figures 1 - 4 shows the design and construction of this very complex structure. The Acquetico roundabout has been built by filling the valley with coarse debris from tunnel excavation. The fill is supported by a tiered reinforced soil structure, with maximum height of 23.4 m. The Fosso S. Rocco creek, which was flowing through the small and steep valley, has been channelized: after crossing the roundabout inside a 3.20 m diameter corrugated steel pipe, it comes to light at the top of the reinforced soil structure, then it flows in a channel, made up of gabions, which follows the reinforced soil slope with several jumps; the final jump, almost 10 m high, is made up of huge stones, which also make the base of the reinforced soil structure. Figures 5 and 6 shows the design and construction of the wall. The gabion channel is waterproofed with 3 mm thick PVC geomembranes, protected by 500 g/m^2 nonwoven geotextiles, which run all around gabions. The Southern roundabout wall had to support a high slope which was cut to provide the space for accessing the 2.0 km long tunnel: it is 21.0 m high, 150 m long, and it extends above the tunnel entrance. Due to the very limited space available, behind the three tiers of the wall two pile bulkheads were built, in order to shorten the geogrid length without compromising the global stability of the structure. Figures 7, 8 show the cross-section of this wall and pictures during and after construction.

Figure 1. View of the reinforced wall of the Northern roundabout with the bridge abutments on top

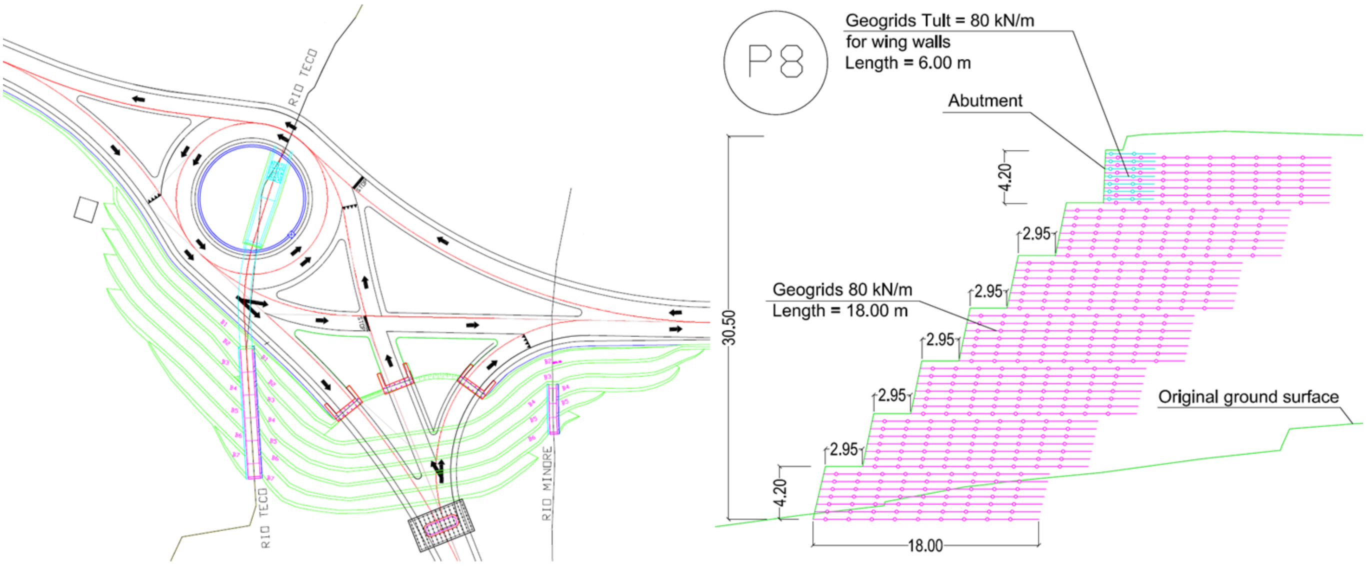

Figure 2. Plan view and cross-section, with bridge abutment on top, of the reinforced wall at the Northern roundabout

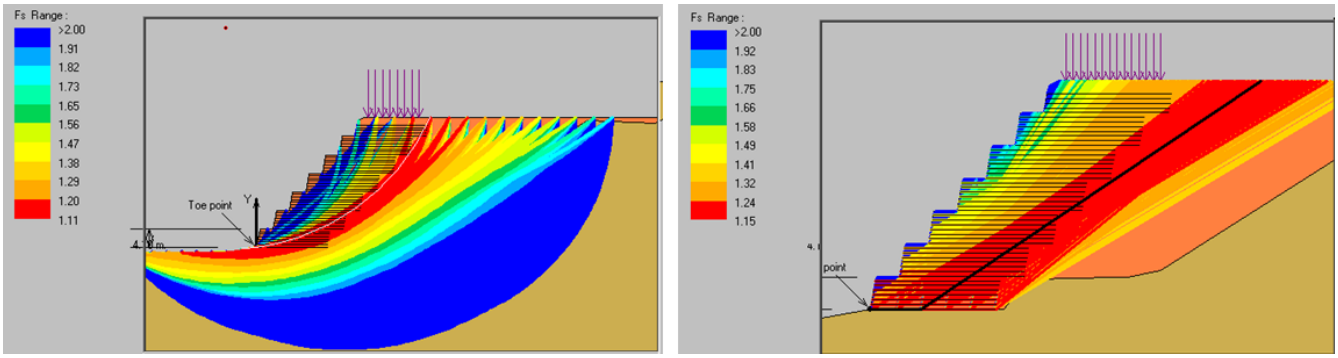

Figure 3. Rotational and translational seismic analyses for the section with bridge abutment on top

Figure 4. The wall under construction, showing the concrete channel for the Rio Teco creek, and the bridge abutments on top of the wall

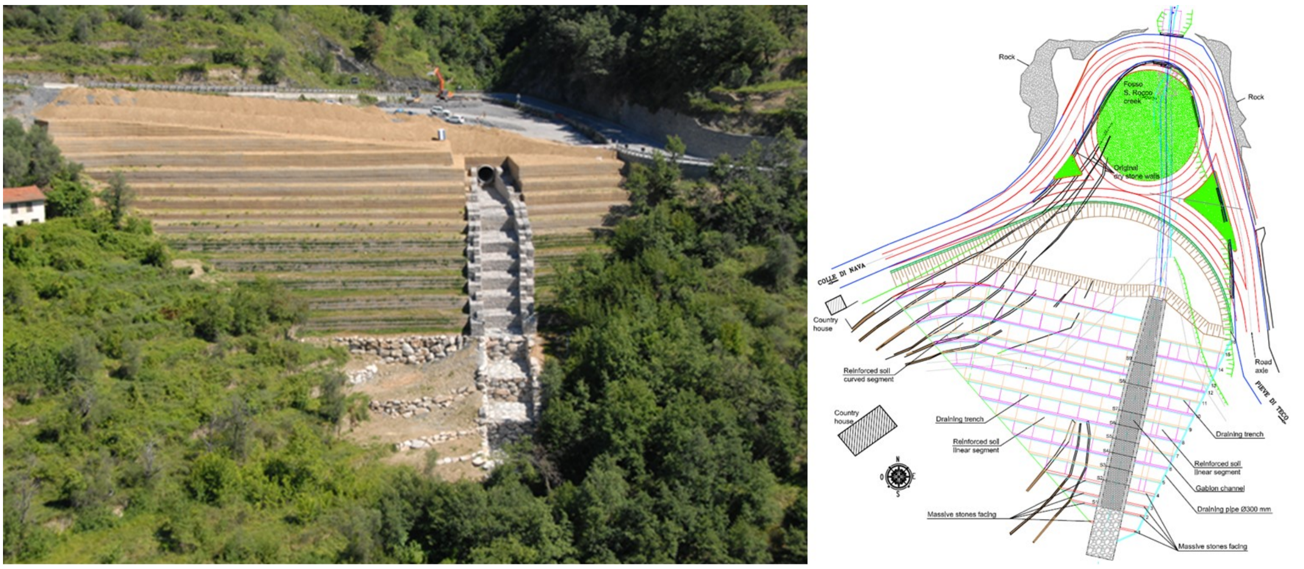

Figure 5. The completed wall with the gabion channel and the plan view of the Acquetico round-about

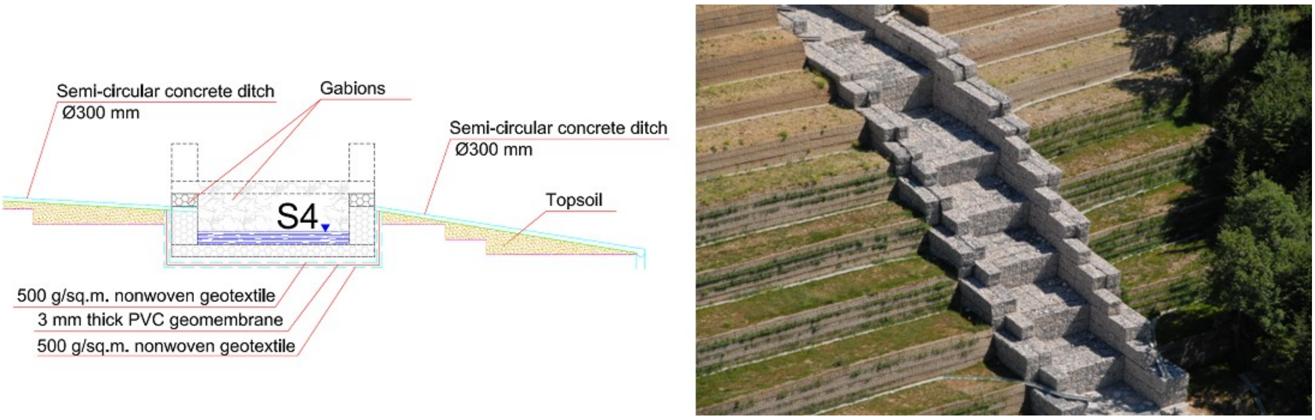

Figure 6. Cross section and picture of the gabion channel

Figure 7. Design cross section and view of the wall at the Southern round-about during construction

Figure 8. View of the completed wall at the Southern round-about and of the tunnel entrance

4 CONCRETE BLOCKS FACED WALLS

For walls with concrete block facing, the Ponte Prugneto project, near Modena in Northern Italy, is illustrated (Manni and Rimoldi, 2006).

The "Ponte Prugneto" historical arch bridge, originally built around 1850, on the Appennine mountain in the south of Modena in northern Italy, crosses the Scoltenna river along the Provincial Road SP30. The bridge is made up of sandstone masonry, with three arches of approximately 16 m span each, resting on 7 m high masonry abutments and piers, with 4 m high masonry foundations in the river bed. The bridge suffered heavy damage to the wing walls of the abutment on the right side of the river, due to a large upslope landslide (Fig. 9). The two wing walls, 7.0 m high, had the shape of a quarter circle and the face was made up of sandstone blocks. The design of the new wing walls was based on the technique of segmental concrete blocks for the face and high tenacity polyester geogrids for soil reinforcement. The concrete blocks were designed approximately with the same dimensions of the original sandstone blocks, with split face and yellow sandstone color to preserve the original external finish. To support the excavation of the unstable sand – lime soil, a micro-pile bulkhead wall, tied by steel tendons driven into the backfill, was designed. Since the bridge is located in a medium - high seismic area, according to Italian code, the horizontal acceleration $a_g = 0.09$ g was applied. The final layout of the reinforced soil retaining walls, 7,0 m high, with a 87° face inclination from the horizontal, required 14 layers of knitted polyester geogrids, spaced at 500 mm vertical centres. The facing system includes concrete blocks with sandstone yellow colour with a split face, plastic pins for block to block connection, HDPE bars for geogrid to block connections inserted into a groove running along the top side of the blocks. The required length of geogrids was equal to 6.0 m, but the bulkheads were only 3.8 m from the face, next to the bridge. Hence a connection system between the micro-piles and the geogrids was designed, in order to anchor the geogrids where the available length was less than the design length. Such a connection includes a 20 mm diameter steel hook either placed in the connecting concrete beams or welded to the micro-pile casings, to which a folded steel mesh is then connected; geogrids were wrapped around the steel mesh and fixed into the previously compacted soil layer. In this way geogrids were connected all along the horizontal bar of the steel mesh and not through the apertures, thus avoiding any concentrated stresses and brittle rupture. The connections afforded the same design strength of geogrids. In-situ tensile testing of connections during construction confirmed the design assumptions. Since the wing walls make a quarter circle in plan view, with a 13 m radius, the static load scheme of a horizontal cross-section is a reverse arch with soil pressure from inside. This means that tangential tensile forces need to be resisted by the geogrid reinforcement, in order to avoid the potential failure of the walls by breaking vertically and opening up. The tangential reinforcement has been designed according to the method proposed by Rimoldi et al. (1989), which convert the reverse arch to an equivalent thick horizontal plate subjected to external radial stresses. As a result of radial and tangential forces to be resisted, the geogrids were specified with 200 kN/m tensile strength in machine direction and 150 kN/m tensile strength in cross-machine direction. For providing the internal drainage of the fill, subject to periodical flooding of the river, the design included drainage strips, 300 mm wide at 1.0 m horizontal spacing, laid radially at each half centre between geogrid layers. The strips were cut from a geocomposite with a tri-planar HDPE geonet core. Figures 10 – 13 show construction details and pictures of this very complex project.

Figure 9. The Ponte Prugneto historical arch bridge and the failure of the upstream wing wall

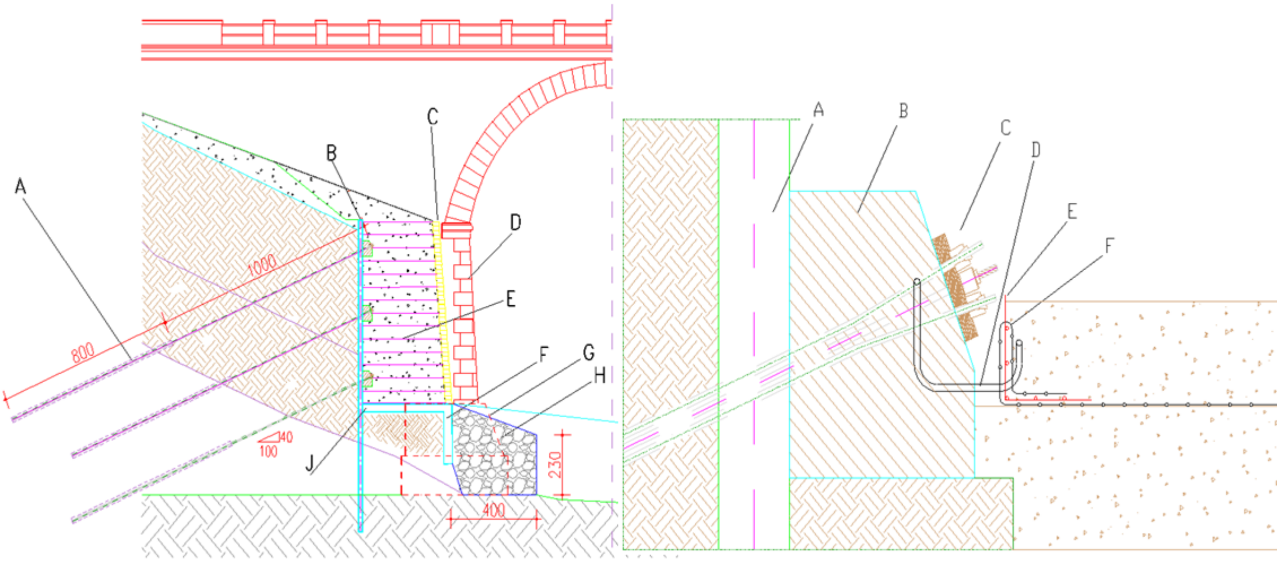

Figure 10. Left: final design layout: A) steel tendons; B) micro-piles; C) concrete block face; D) bridge abutment; E) geogrids; F) front concrete key; G) scour stone embankment H) original abutment foundation; J) foundation concrete slab; K) river bed. Right: the geogrid – bulkhead connection: A) micro-pile; B) concrete beam; C) steel tendon; D) steel hook; E) welded wire mesh; F) geogrid

Figure 11. The segmental concrete block facing system with the plastic pins and the groove for connector bars

Figure 12. **G**eogrids being connected to concrete blocks (right); geocomposite drainage strips (left)

Figure 13. The concrete block facing and the almost completed downstream wing wall

5 WALLS FOR PRESERVATION OF HISTORICAL SITES

Reinforced soil walls have been used several times in Italy for preservation of historical sites, particularly when churches or other historical building were built on top of hills whose slopes have become unstable during the centuries.

Such application is illustrated through the project in Genzano di Lucania, close to Potenza in Southern Italy: here the 12^{th} century Annunziata Church and the Monastery of the Clarisse nuns, resting on top of a weakly cemented sand hill, was at high risk due to the formation of large caves in the slopes underlying the constructions and the degradation of the sand cementation, which triggered many small landslides leaving almost vertical slopes just below the foundations. Part of the external wall of the Monastery had already collapsed. Fig. 14 shows a 3D reconstruction of the Church – Monastery complex and the highly degraded state of the slopes with the formation of caves.

Finally, the Municipal Administration of Genzano entrusted the execution of extraordinary maintenance works for the stabilization of the slopes underlying the Church and the Monastery.
Based on geological surveys and technical considerations based on the geometry of the sites and on the geotechnical characteristics of the concerned soils, the Designers decided to build a reinforced soil structure to stabilize the north and northwestern slopes below the Monastery: the reinforced soil structure, over 16 m high, consisted of tiered wall with 1.50 m wide horizontal berms, with 0.6 m constant spacing of reinforcement layers, made up of uniaxial HDPE extruded geogrids with tensile strength of 90 kN/m. The reinforced soil wall was built with the wrap-around technique and steel mesh formworks, with vegetated face to prevent erosion. The fill consisted of high quality sandy gravel from a nearby quarry.
The reinforced soil structure has the task of providing the Safety Factors required by the Technical Norms, so as to ensure the stability of the slope; in addition, the reinforced soil structure will ensure the permanent coverage of the slopes, in order to prevent the degradation of the geotechnical characteristics of the in-situ soil and thus maintain the current cementation.
Stability analyses were complicated by the complex geological stratification of the slopes, consisting of several layers of weakly cemented sands with clay interlayers, and the presence of the large caves, which forced to analyze dozens of different cross-sections; moreover, according to the Geotechnical Report, seismic analyses had to be carried out with maximum acceleration at the surface $a_{max} = 0.15$ g (no reduction coefficient β_m was applied, hence $K_h = 0.15$). Fig. 15 shows two of the seismic analyses for slopes in very different conditions. All the construction was carried out just in three months, before the next rainy season. Fig. 16 shows the reinforced soil wall during construction and the final vegetated structure, which perfectly blends with the surrounding landscape.

Figure 14. 3D reconstruction of the Church – Monastery complex and pictures showing the highly degraded state of the slopes with the formation of caves just below the foundations

Figure 15. Two of the seismic analyses for slopes in very different conditions (A = caves)

Figure 16. The reinforced soil wall during construction and the final vegetated reinforced soil structure

6 WALLS WITH PILE BULKHEADS

In situations where the available length for reinforcement is not enough and/or the deep seated failure cannot be contrasted with the reinforced soil structure alone, the design may include one or two pile bulkheads at toe and top. This solution, which has been used in many projects in Italy, is illustrated through the reinforced soil wall built along the Strada degli Inglesi road in Farfa, close to Rieti in central Italy. Here a 220 m long stretch of the road was destroyed in 2004 by a circular failure of the downstream slope, as shown in Fig. 17. The design of the reconstruction works of the road stretch had to face the complex geological situation (including irregular layers of gravel, sand, silt, clay, old fills), the water table few meters inside the slope, the limited available space due to an existing pile bulkhead (600 mm diameter) at top of the failed slope which were built to support the buildings just above, as shown in Fig. 18 left. Moreover the design peak seismic acceleration was ag = 0.175 g. It was clear that a reinforced soil structure alone would not have for provided stability against deep seated failure. Hence one more pile bulkhead at toe of the reinforced wall was tentatively introduced. Pile diameter and length of the bulkhead were set through stability analyses in static and seismic conditions (Fig. 18 right) by trial and errors until satisfactory Factors of Safety (FS) were achieved. Seismic coefficients were K_h = 0,072 and Kv = 0,036. The two bulkheads were modeled in the stability analyses as an equivalent soil with the following properties: unit weight = 25 kN/m^3; friction angle = 45°; cohesion = 1.100 kPa. The required FS were achieved by setting pile diameter = 1,000 mm at 2.0 m centers, and depth = 11.5 m. The wall was designed with polyester woven geogrids reinforcement, having tensile strength of 35, 55, and 80 kN/m. The final design layout is shown in Fig. 19.

Figure 17. Failure of the road in Farfa and subsequent excavation for the reinforced soil structure

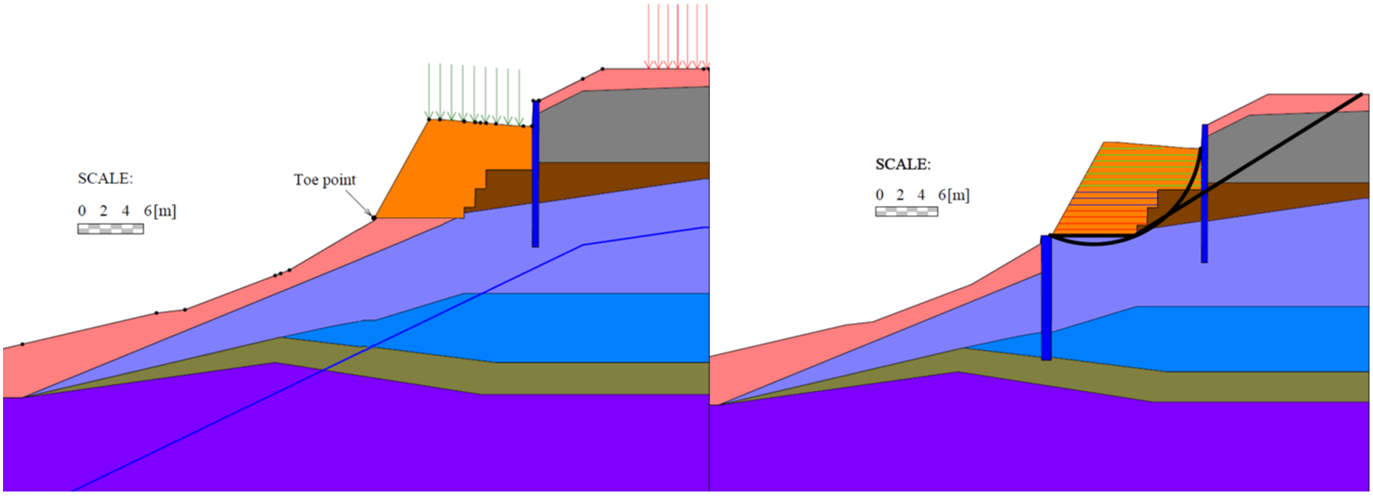

Figure 18. The complex design situation in Farfa and the stability analysis in seismic conditions with pile bulk-heads at toe and top of the reinforced soil structure

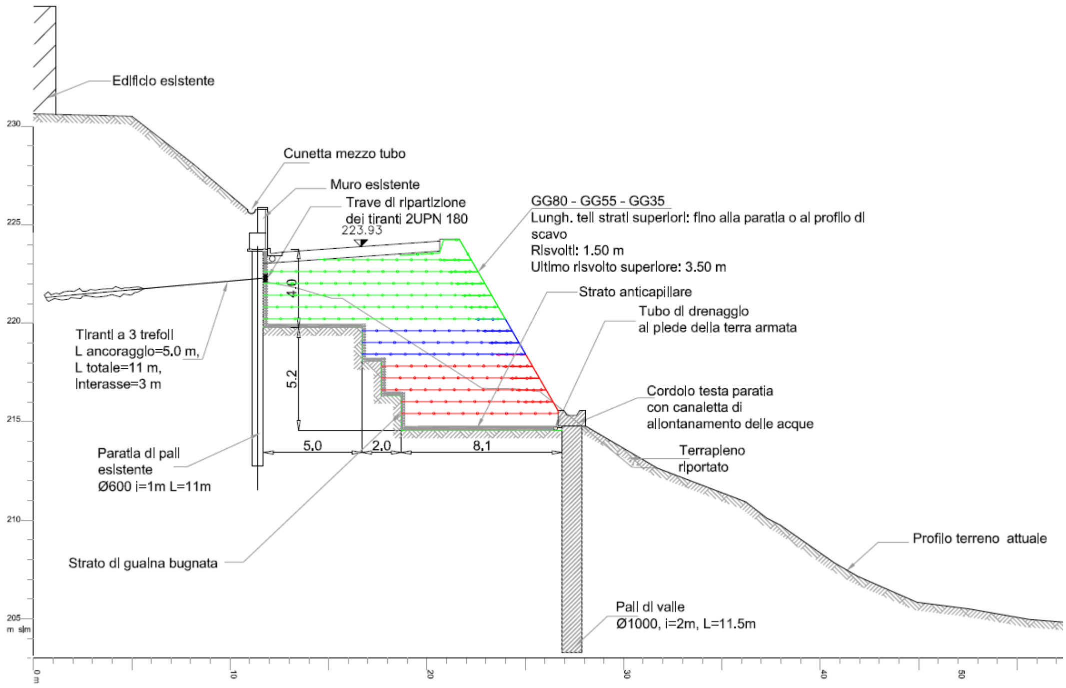

Figure 19. The final layout of the reinforced soil walls with bulkheads in Farfa

7 CALCIUM STABILIZED AND REINFORCED SOIL STRUCTURES

In many areas of Italy, and often in highly seismic areas, there is no or very little availability of granular soils: hence, for avoiding the cost and environmental impact of sourcing sand and gravel from very long distance, embankments and retaining structures are often built using the locally available fine soil. For improving the geotechnical characteristics of such soils and/or for building steep faced structures, it is possible to use the technique of calcium stabilized and reinforced soil. Rimoldi and Intra (2008) provide a detailed analysis of such technique, which is illustrated through the project of the Provincial Road Ex SS 277 "Trasversale Alta Basentana – Bradanica", close to the town of Grassano (Matera Province) in Southern Italy (Rimoldi and Intra, 2009): the project included tall geogrid reinforced embankments, with total length of 840 m, height between 2.10 m and 9.30 m, for a total of almost 8.000 m^2 face in vertical projection. The cross- section includes 65° geogrid reinforced walls, on both sides of embankments, a 2.0 m wide horizontal berm at crest, and on top a 5.0 m high unreinforced embankment with 2V:3H (34°) side slopes, which carries the road structure, providing 20 kPa uniform surcharge. All embankments had to be built with the locally available soil, that is silt and clay with variable sand content. The project is located in a highly seismic area: the design acceleration was $a_g = 0.156$ g. As shown in Fig. 20, finally the embankments were designed with a calcium stabilized and geogrid reinforced lower body, while the top unreinforced embankment is made up of compacted silty sand. Figure 20 also shows a picture of the Bradanica highway project during construction.

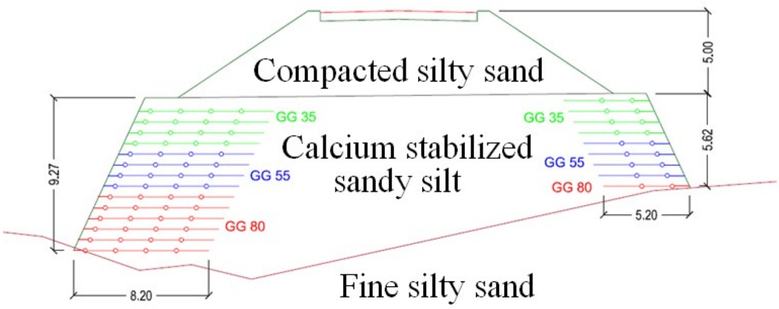

Figure 20. Design cross-section and picture of the Bradanica highway project during construction

8 CONCLUSIONS

Reinforced soil walls have been designed and built in Italy for solving difficult geotechnical problems in static and seismic conditions.

The paper has introduced the Italian normative frame for design, and has illustrated different types of reinforced soil walls built in Italy, including green faced walls, concrete blocks faced walls, walls for preservation of historical sites, walls with pile bulkheads, calcium stabilized and reinforced soil structures.

It can be concluded that reinforced soil walls in Italy represent an example of engineering excellence, which will continue to provide trustable and affordable solutions to the difficult geotechnical problems caused by the complex geological, geographical, topographical, seismic conditions of Italian territory.

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