Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)

Geotechnical and historical aspects on the collapse of the Tiber embankment walls in the centre of Roma (1870–1900)

F. Casini, A. Pucci, I. Giannetti & G. Guida
Dipartimento di Ingegneria Civile e Ingegneria Informatica (DICII)
Università degli Studi di Roma Tor Vergata (IT)

ABSTRACT: This paper deals with the issues related to the construction of the Tiber's embankment walls between years 1870–1926. The embankment walls (*muraglioni)* were designed by Raffaele Canevari to mitigate the effects of the river inundation in the city centre of Roma. After the flood of December 1900, several portions of the Anguillara and Alberteschi sections collapsed.

The aim of this work is to investigate whether the causes of the collapse can be traced back to design approaches of the time, lacking from a point of view of the hydro-mechanical interaction of the soil in the evaluation of the total earth pressure. In particular, designed calculations are also revised accounting for more advance soil phenomena laws, based on Terzaghi effective stress and the effects of scouring and erosion. Some assumptions have been made on the mechanical characteristics of the backfill soils and on the relying on foundation materials.

1 INTRODUCTION

The second part of the 19th century saw the construction of several urban river defence works in European cities such as Paris (Sein River, Lestel et al. 2020), London (Thames, Porter 1998), Vienna (Danube, Hohensinner et al. 2013), Budapest (Danube, WHC 1987). The new infrastructures were built according to the methods available at that time, in particular computing the earth pressure on the retaining walls were based on graphical methods developed by Rebahn (Rebahn, 1871) and Culmann (Culmann 1864–66).

Several urban history related studies (Segarra Lagunes 2004) report the stages that lead to the construction, starting from the year 1870, of the Tiber embankment walls as flood-control system for the historical centre of Roma. However, a proper geotechnical critical analysis, especially related to the issues related to the collapse of some sections of the embankments, is still missing in the technical literature. This paper aims at providing a contribution for bridging this gap, focusing on the description of the collapse events occurred during the exceptional Tiber flood of 1900. The study is based on the archive documents produced by the *Ufficio Speciale per la Sistemazione del Tevere* (Special Office for the River Tiber), conserved in the Rome State Archive within the Genio Civile collection (Giannetti & Casini 2021).

In the following the design and the construction history of the embankment walls are summarized with emphasis on the sections damaged by the 1900 flood, followed by a description of the collapse as reported in the historical sources. Finally, the geotechnical ultimate limit states (SLU-GEO) are evaluated based on the NTC2018 and on the D.M. 1988 in order to retrace the possible causes that induced collapse.

 DOI 10.1201/9781003308867-97

2 DESIGN OF THE TIBER'S RETAINING WALL

In the late December 1870 an inundation hit the centre of Rome, the water level of 17.22 m above the 0 was measured in the Ripetta gauge. Thus, a technical committee has been established to regulate the river floods led by the Engineer Carlo Possenti (1806–1872), inspector of the Genio Civile and vice president of the *Consiglio dei Lavori Pubblici* (Italian High Council of Public Works) . The members of the committee were the engineers Davicini, Barilari, Betocchi, Turazza, Armellini, Glori, Tatti, Partini, Canevari, Branchini and Castellini. Finally, after 19 meetings, the committee agreed on Raffaele Canevari's proposal for the canalization of the river (Canevari 1875). The latter included, in the urban area – from Sassi di S. Giuliano to S. Paolo – the construction of embankment walls (*muraglioni*) of 17 m high, the tuning of the riverbed at a constant width of 100 m, the construction of two underground tunnels functioning as sewer collectors and large docks, that ran parallel to the walls. The project also provided for the removal of the ruins and other obstacles existing in the riverbed, the embankment of the upper Tiber to the Sassi di S. Giuliano, the removal of one of the two branches of the river at the Tiberina island (as shown in Figure 1).

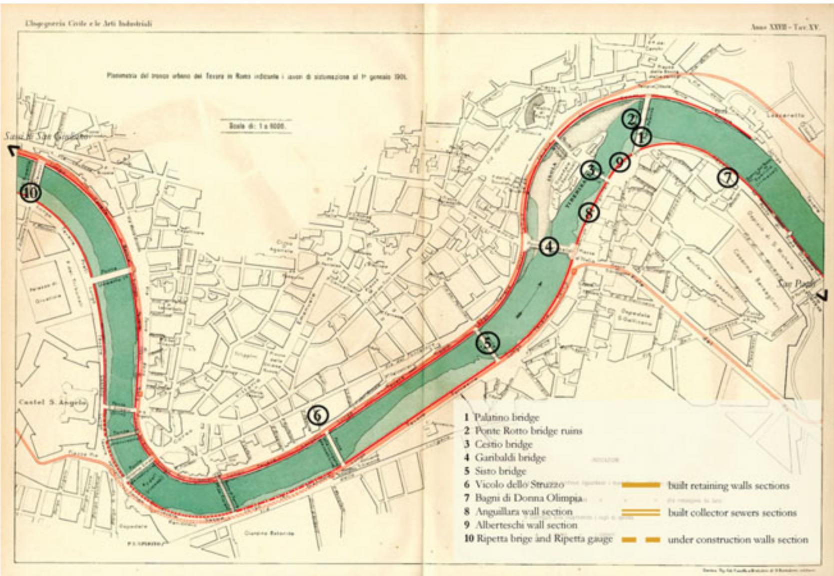


Figure 1. General plan of the Tiber embankment walls and the section between Ponte di Ripetta, on the left, and Ponte Palatino, on the right (L'Ingegneria Civile e le Arti Industriali, 1901) (after Giannetti & Casini 2021).

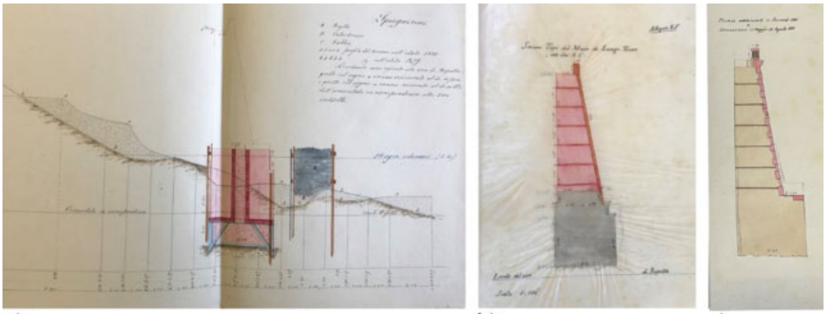
After years of debates and discussions, on November 29th, 1875, the definitive project for the complete settlement of the urban Tiber river section (Figure 1) has been approved by the High Council of Public Works. The project kept the Canevari conception of the river canalization (high embankment walls, large sewers collectors and docks), introducing two branches of the river around the Tiberina island: the right one width of 70 m and the left width of 60 m (Canevari 1875).

At the end of January 1876, the Special Office for the River Tiber was set up within the Genio Civile with the aims of supervise the project, and coordinate the construction sites (Consiglio Superiore dei Lavori Pubblici 1876).

The works began in the early months of 1877, with the first removal of the ruins and other obstacles existing in the riverbed, in the section between Ponte Sisto and Ponte Rotto (Figure 1), where the water downflow conditions were the most critical. Later, on February 13th, 1878, a further Committee (Commissione di Vigilanza 1877) was nominated to supervise the construction sites, writing an annual report for the Ministry of public works (Canevari 1879).

2.1 *Embankment walls design (1876–84)*

The preliminary design of the wall envisaged a height of 17.60 m, composed of an out-of-water masonry trapezoidal portion, which featured the external wall-line with a slope of 80.54° and a rectangular concrete foundation block. The masonry was composed of tuff blocks, with pozzolanic mortar joints, while the wall external cladding was in bricks (Figure 2a).



a) b) c)

Figure 2. a) study for the use of pneumatic foundations, 1877; b) first design of the retaining walls with bricks coating, 1876; c) execution design of the retaining walls with travertine coating and pneumatic foundations, 1882 (courtesy Rome State Archive, Genio Civile collection).

The foundations of the retaining walls were built adopting the compressed air technology, with large wrought-iron caissons, 2 m high, then filled with concrete (Biadego 1866; Bruno 1895) (Figure 2b). In 1882, the Higher Council of Public Works prescribed the adoption of this foundation technology with minimum deep of −1 m, measured from the 0 of the Ripetta water gauge (Consiglio Superiore dei Lavori Pubblici 1882). Further, the Higher Council of Public Works (Consiglio LLPP 1879) modified the construction details of the standard cross-section of the retaining wall. As shown in Figure 2, masonry composed of tuff blocks with pozzolanic mortar joints were adopted for the whole retaining walls' structure, built on the foundation caissons ceiling. For the external wall-line, a travertine cladding replaced the original design brick coating (Giannetti & Casini 2021).

A lot of the work from *Vicolo dello Struzzo*, on the left riverside, and *Bagni di Donna Olimpia*, on the right riverside (Figure 1), were carried out by the Swiss firm Cornad Zchokke. In December 1900, straight after the work has been completed, a massive river flood occurred, reaching 16.17 m above the 0 of the water Ripetta gauge. During the water level drawdown, large sections of the retaining wall – located in the right riverside of the so-called Anguillara area – collapsed into the river, while deep cracks, mostly vertical, occurred in the nearby retaining wall section (Alberteschi area, Figure 4) and the northern one (Mellini area).

The Anguillara and Alberteschi sections are comprised in the area most damaged by the flood. That portion of the retaining walls ran between Garibaldi and Palatino bridges for about 350 m: the Anguillara section, located between Garibaldi and Cestio bridges, was 240.86 m-long; the second, between Cestio and Palatino bridges, was 111.76 m-long (Figure 3).

The Anguillara and Alberteschi sections are comprised in the area most damaged by the flood. That portion of the retaining walls ran between Garibaldi and Palatino bridges for about 350 m: the Anguillara section, located between Garibaldi and Cestio bridges, was 240.86 m-long; the second, between Cestio and Palatino bridges, was 111.76 m-long (Figure 3).

The geometry of the masonry retaining wall was the same for both the Anguillara and the Alberteschi sections, with small dimensional variations. The walls featured a concrete basement (filling of the caisson) and a rectangular masonry portion located below the standard water level (+5 m on the 0 of the Ripetta water gauge), and a trapezoidal elevation with the external wall line's slope of 80.54° (θ) (respect to the horizontal base-line): the height (h) ranging from 10.61 m to 12.07 m, width at the base (s) ranging from 3 m to 4 m, and width at of top ranging from 1.5 to

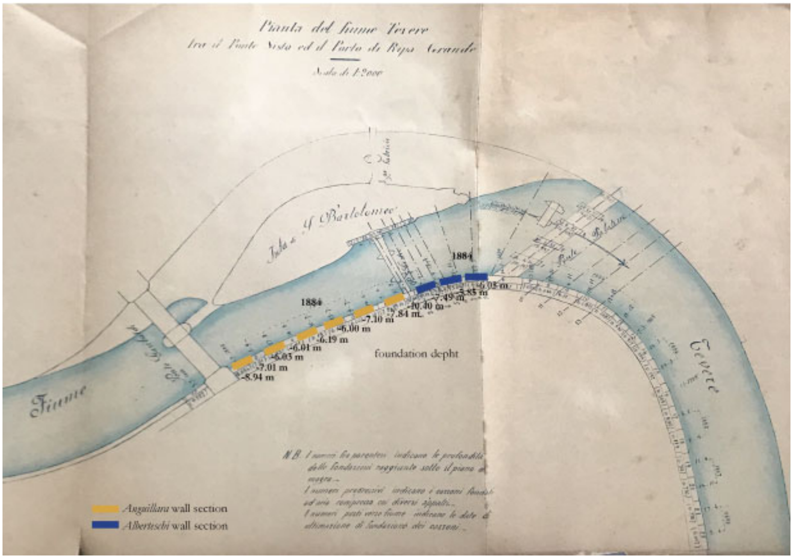


Figure 3. The Alberteschi and the Anguillara retaining walls: plan showing foundation deep and date of construction (courtesy Rome State Archive Roma, Genio Civile collection).

1.8 m (s_1). The foundations of the Anguillara section were laid between −6 m and −7.84 m below the standard water level, reaching the depth of 8.94 m, at the Garibaldi bridge. The foundations of the Alberteschi section featured depths, ranging from 6.00 m to 7.49 m (Figure 3). The masonry wall was composed of tuff blocks with pozzolanic mortar joints, while the inclined external wall-line was coated with squared travertine blocks, with an average thickness of 30 cm. Both the wall cornice and the parapet were in travertine, while the base and the cover of the parapet were in granite (Giannetti & Casini 2021).

3 THE FLOOD EVENT AND THE COLLAPSE OF THE ANGUILLARA RETAINING WALL (1900–01)

A flood with a capacity of 4200 m^3 (second only to the flood of 1538, Bencivegna et al. 1995) hit the historical centre of Roma on 2nd December 1900 at 2 p.m., with a peak height of 16.17 m above the 0 of the Ripetta water gauge. A 10-metre-diameter depression occurred behind the wall at the Cestio bridge axis, along with the flood event. On December 3rd, another depression occurred in the backfilling of the retaining wall, between the Garibaldi and Cestio bridges, that spread from upstream to downstream.

On the 4th December, at 7:24 a.m., when the river waters measured only 10.50 m above the 0 of the Ripetta's water gauge, a first section of the retaining wall – about 15 m long – overturned towards the river.

About three hours later, the next 110 m section of the Anguillara wall, located from 73 m downstream to 37 m upstream of the Garibaldi bridge, collapsed into the river in "three enormous blocks", when the water level, rapidly decreased, measured 9.25 m above the 0 of Ripetta's water gauge.

The Technical Committee of 10 members appointed after the flood, led by engineer and professor Luigi Cremona (1830–1903), was expected to fulfil the following three main tasks:

1) to investigate the accidental or lasting causes of the retaining wall collapse and of all structural damages that occurred during the flood;

2) to study and propose appropriate design strategy for damage repairing and for preventing future structural fails in the embankment walls;
3) to ascertain responsibilities in the design and the construction, by designers, contractors, and supervisors.

The Technical Committee on March 4th 1901 attributed the main causes of the collapse to the undermining of the retaining walls: "From the proof of the details of the disaster it is evident that the ruin of the Anguillara retaining wall is exclusively due to undermining, following the erosion of the foundations (…)" (Cremona 1901).

3.1 *Geotechnical Ultimate Limit Checks before, during and after the flood*

The stability conditions of the embankment walls are evaluated adopting the schematic cross section reported in Figure 4, representing the typical cross section of the Anguillara section.

The soil parameters of the backfilling assumed are a friction angle of $\varphi' = 33°$ and a unit weight $\gamma = 16$ kN/m^3. The active earth coefficient $k_a = 0.27$ is evaluated according to Lancellotta (2007), and by considering an interface friction angle soil-wall of $\delta = 2/3\varphi'$. the horizontal and vertical component of the active thrust coefficient equal to $k_{ah} = k_a \cos\delta = 0.25$ and $k_{av} = k_a \mathrm{sen}\delta = 0.101$ are respectively obtained. For the soil interacting with the foundation of the wall is assumed a unit weight of $\gamma_f = 19$ kN/m^3, an effective cohesion $c'_f = 40$ kPa and a friction angle $\varphi'_f = 40°$. The soil properties adopted agree with the literature data available (Cremona 1901).

The retaining height of the wall is $H_m = 18.26$ m, the width is $B = 4.90$ m, the foundation height $h_f = 2$ m and the service height of the river is $h_w = 6.02$ m from the base of the foundation. The geotechnical ultimate limit states (GEO), consisting of sliding, bearing capacity and overturning verifications, are checked in the following case:

1) standard operation condition, in which the water height is the same both upstream and downstream the wall and equal to $h_w = h_{wud} = 6.02$ m (see Figure 4a, PRE-FLOODING);
2) at the peak of the flooding, assuming $h_w = h_{wud} = 17.17$ m (Figure 4b, MAX FLOODING LEVEL);
3) drawdown to the level of the collapse, with $h_w = h_{wud} = 11.50$ m (Figure 4c, POST FLOODING);
4) drawdown to the level of the collapse with the scouring of the foundation $h_w = h_{wud} = 11.50$ m (Figure 4d, POST FLOODING Scouring), where d_r and e_r are the depth and the width of the scouring;
5) rapid drawdown to the level of the collapse in the river and filtration from the upstream to the downstream with a $\Delta h_w = h_{wu} - h_{wd} = 17.17 - 11.50 = 5.67$ m (Figure 4e, POST FLOODING Seepage).

Depth and width, $d_r = 1.7$ m and $e_r = d_r \cdot \tan(25°) \cong 0.80$ m respectively, of the scouring under the embankment wall foundation are evaluated according to Equation (1) after Froehlich (1989), obtained by analysing 170 live-bed scour measurements in laboratory flumes.

$$d_r = 2.27 \cdot K_1 \cdot K_2 \cdot y_a \cdot \left(L'/y_a\right)^{0.43} F^{0.61} \tag{1}$$

in which $L' = 4.9$ m is the length of active flow obstructed by the retaining wall, $y_a = 11.5$ m is the average depth of the flow, $F = 0.078$ is the Froude Number of the approaching flow upstream the wall, $K_1 = 0.55$ is a shape coefficient and $K_2 = 1$ is the coefficient for the angle between the retaining wall and the flow direction . In this case $d_r = 1.70$ m.

Finally, the effect of seepage is evaluated with a hydraulic head difference $\Delta h_{w_{u,d}} = 5.67$ m and a hydraulic gradient, $j = \Delta h_{w_{u,d}} / \left(h_{w_{up}} + B\right)$ evaluated considering a linear hydraulic head dissipation along the upstream side $h_{w_{up}}$ and the base B of the embankment wall. This induces an upstream distribution of the porewater pressure that is less than hydrostatic along $h_{w_{up}}$.

The stability analyses of the five cases reported in the bullet list are checked according to the past Italian code D.M. 1988 based on global safety factors and to the actual Italian code NTC2018 (DA2-A1+M1+R3) based on partial safety factors. The results are summarized in table 1.

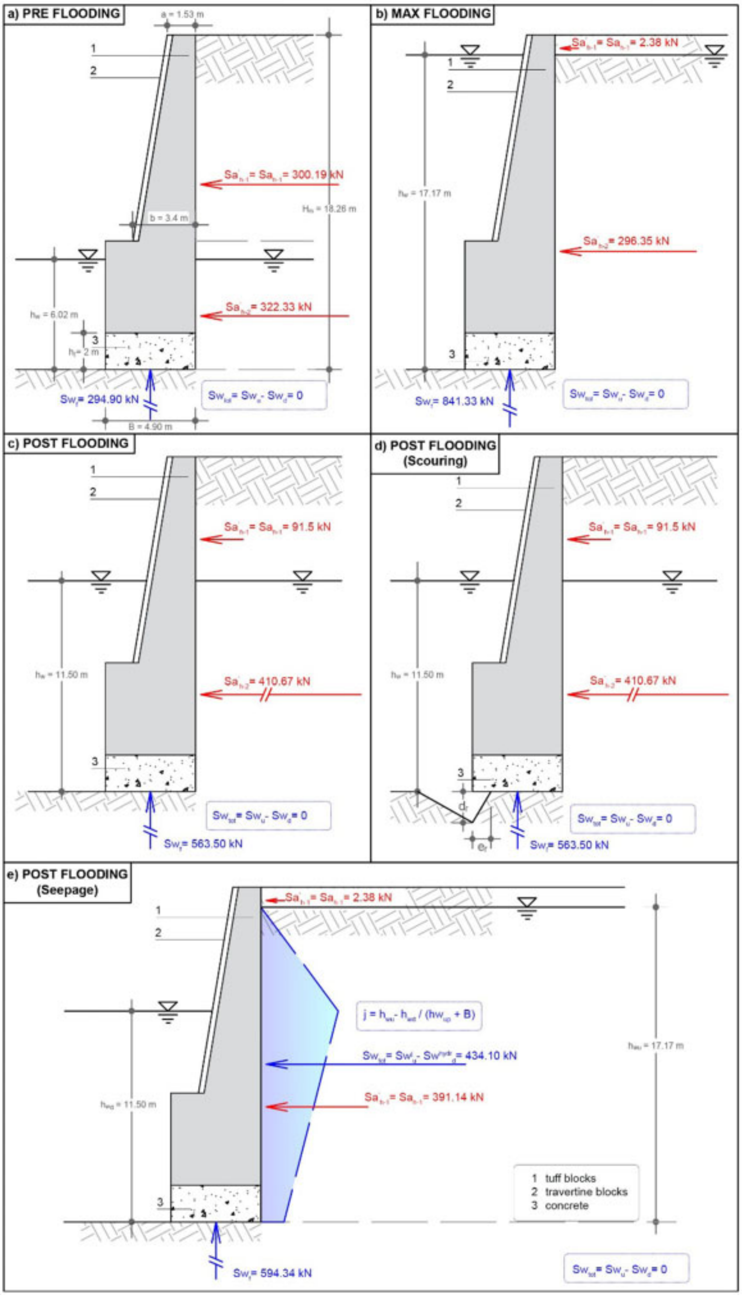


Figure 4. SLU-GEO performed with different h_{wd} from the base of foundation: (a) PRE FLOOTING; (b) MAX FLOODING; (c) POST FLOODING; (c) POST FLOODING Scouring; (d) POST FLOODING Seepage.

The sliding verification consists of checking if the sliding force induced by the active earth thrust is balanced by the friction force at the base of the foundation:

$$F_{stab} = \left(W_{wall} + S_{a,v}\right) \cdot tan\left(\phi'\right) + c' \cdot B, \quad F_{instab} = S_{a,h} \tag{2}$$

Table 1. Summary of SLU-GEO checks in accordance to D.M.1988 and NTC2018 italian codes.

		PRE FLOODING	MAX FLOODING LEVEL	POST FLOODING	POST FLOODING (Scouring)	POST FLOODING (Seepage)	
SLIDING	$SF = \frac{F_{stab}}{F_{instab}} \geq 1.3$	VERIFIED $FS = 2.23$	VERIFIED $FS = 4.28$	VERIFIED $FS = 2.78$	VERIFIED $FS = 2.72$	VERIFIED $FS = 1.58$	D.M. 1988
BEARING CAPACITY	$SF = \frac{q_{BC}}{q_{serv}} \geq 2$	NOT VERIFIED $FS = 1.02$	VERIFIED $FS = 8.37$	VERIFIED $FS = 2.78$	NOT VERIFIED $FS = 0.65$	NOT VERIFIED $B' < 0\,m$	
OVERTURNING	$SF = \frac{M_{STAB}}{M_{OVER}} \geq 1$	VERIFIED $FS = 1.00$	VERIFIED $FS = 1.01$	NOT VERIFIED $FS = 0.99$	NOT VERIFIED $FS = 0.88$	NOT VERIFIED $S = 0.55$	
SLIDING	$SF = \frac{R_d}{E_d} \geq 1$	VERIFIED $FS = 1.56$	VERIFIED $FS = 2.99$	VERIFIED $FS = 1.95$	VERIFIED $FS = 1.90$	VERIFIED $FS = 1.11$	NTC 2018 (DA2 - A1+M1+R3)
BEARING CAPACITY		NOT VERIFIED $FS = 0.56$	VERIFIED $FS = 4.60$	VERIFIED $FS = 1.53$	NOT VERIFIED $FS = 0.36$	NOT VERIFIED $B' < 0\,m$	
OVERTURNING		NOT VERIFIED $FS = 0.67$	NOT VERIFIED $FS = 0.67$	NOT VERIFIED $FS = 0.66$	NOT VERIFIED $FS = 0.55$	NOT VERIFIED $FS = 0.37$	

where W_{wall} is the weight of the wall, $S_{a.v}$ and $S_{a.h}$ are the vertical and the horizontal components of the active earth thrust.

The bearing capacity verification has been carried out as the ratio between the soil bearing capacity $q_{BC} = q'_{BC} + u_w$ and $(S_{a,v} + W_{wall})/B_r$, where u_{w} is the pore pressure acting on the foundation base. The q'_{BC} is evaluated with the Terzaghi's formula:

$$q'_{BC} = F_\gamma N_\gamma \sigma'_v (B_r/2) + F_c N_c c'_f \tag{3}$$

where $B_r = B - 2\,e$ is the reduced base size due to the eccentricity of load correction $e = M/N$, and $N_c\,(40°) = 75.31$, $N_\gamma\,(40°) = 106.05$ are the bearing capacity factors. The other corrective factor to be considered is the obliquity of the loads, thus $F_c = \xi_c$ and $F_\gamma = \xi_\gamma$.

Finally, the overturning verification consists of checking if the stabilizing moments evaluated around the downstream foot of the wall are balanced by the un-stabilizing moments due to the active earth thrust and to the water pressure. Each force was multiplied by the corresponding arm as follows:

$$M_{STAB} = W_{wall} \cdot B_{wall} + S_{a,v} \cdot B_{a,v}, \text{ and } M_{OVER} = S_{a,h} \cdot B_{a,h} + S_{w,f} \cdot B_f + S_w \cdot B_w. \tag{4}$$

As reported in Table 1, in the pre-flooding case, the retaining wall was in condition of imminent collapse: only two over three limit states are fulfilled with D.M.1988 (only sliding with NTC18). The max flooding case, upon the peak height of the flood, is the most favourable condition to geotechnical ultimate limit states, due to the stabilizing effects of the pore water pressure downstream: the three verifications are all satisfied in accordance with D.M. 1988, but the overturning check is not satisfied in accordance with NTC18, as it provides for a higher level of safety. In post flooding the limit state are comparable to the pre-flooding condition, except for the bearing capacity check which is satisfied.

Including scouring or upstream seepage, the situation further degrades. Scouring, indeed, reduces the size of the foundation plane reducing the frictional resistance to sliding and the bearing capacity. In addition, it moves the rotational point for the overturning check more upstream, decreasing consequently the stabilizing moment produced by dead loads. Finally, the presence of seepage induces uniquely un-stabilizing effects especially due to the unbalanced resultant of water pressure.

4 CONCLUSIONS

The paper traces Tiber's embankment walls construction stages, needed to mitigate the effects of flood in the historical centre of Roma, after the 1870 flood making use of an in-depth historical research based on the literature available at the Genio Civile in Roma. A critical technical analysis of the collapse event involving the Anguillara section of the embankment wall is also provided. The latter took place on 4th December 1900 when the river waters measured only 10.50 m, after a rapid drawdown that followed a peak of 17.60 m of water height above the 0 of the Ripetta's water gauge.

The safety conditions of the collapsed wall are analysed based on D.M.1988 and NTC2018 in five different conditions of upstream/downstream water levels. Only the maximum flooding conditions fulfils the ultimate limit state according to D.M.1988, while none of the cases analysed resulted fully verified according to the more restrictive NTC2018 code. The final three cases in exam are related to post flooding with same level of water upstream and downstream, post flooding with scouring and post flooding with seepage. In presence of scouring and seepage the embankment wall shows the worse conditions.

From the survey carried out in the work it emerges that the possible cause of the collapse of the Anguillara section may be due to the achievement of the overturning ultimate limit state capacity, which in fact turns out to be never verified.

ACKNOWLEDGEMENTS

The financial support of LazioInnova through the project 'Tiber's' is acknowledged (project number A0375-2020-36632, 22/07/2021). The second author acknowledges the MUR for the financial support of her PhD fellowship through the PON/DM 1061 (10/08/2021)

REFERENCES

Biadego, G. 1866. *Fondazioni ad aria compressa: ponti metallici*. Camilla e Bertolero, Turin, Italy.

Bruno, G. 1895. *Le fondazioni pneumatiche e quelle profonde*. *Appendice al corso di costruzioni idrauliche*. Pallerano, Naples, Italy

Canevari, R. 1875. *Studi per la sistemazione del Tevere nel tronco entro Roma*. Tip. e Lit. del Giornale del Genio Civile, Rome, Italy.

Canevari, R. 1879. *Relazione della Commissione di Vigilanza sui lavori di sistemazione del Tevere intorno all'andamento dei lavori a tutto l'anno 1878*. Tip. e Lit. del Giornale del Genio Civile Rome, Italy.

Consiglio Superiore dei Lavori Pubblici, 1876. *Sedute del 25–29 novembre*. Archivio di Centrale dello Stato, Fondo Ministero dei LLPP, busta 30 / inventario 30/03, Rome, Italy.

Consiglio Superiore dei Lavori Pubblici, 1882. *Sedute del 10 settembre*. Archivio di Centrale dello Stato, Fondo Ministero, busta 30 / inventario 30/03, Rome, Italy.

Culmann, C. 1866. *Die Graphishe Statik*. Meyer & Zeller, Zurich, Swisse.

Giannetti, I. & Casini, F. 2021. The construction and the collapse of the Tiber retaining walls in Rome, Italy (1870–1900). *Proc.of the Institution of Civil Engineers – Engineering History and Heritage*, in press.

Hohensinner, S. Lager, B. Sonnlechner, C. 2013. Changes in water and land: the reconstructed Viennese riverscape from 1500 to the present. *Water Hist* 5: 145–172,

Lancellotta, R. 2002. Analytical solution of passive earth pressure. *Géotechnique* 52(8).

Lestel, L. Eschbach, D. Meybeck, M. Gob, F. 2020. *The Evolution of the Seine Basin Water Bodies Through Historical Maps*. In The Seine River Basin. Springer, Berlin, Germany.

Porter, D.H. 1998. *The Thames Embankment, Environment, Technology and Society in Victorian London*. University of Ackron Press, Ackron Ohio, US.

Rebhann, G. 1871. *Theorie des Erddruckes und der Futtermauern*. C. Gerold's Sohn, Berlin, Germany.

Segarra Laguenes MM (2004) *Il Tevere e Roma. Storia di una simbiosi*. Gangemi, Rome, Italy.