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Scour and foundation damage at theVespucci Bridge on the Arno River in Florence (Italy)

Érosion et dammages des fondations du pont Amerigo Vespucci sur l'Arno à Florence (Italie)

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ABSTRACT: The Amerigo Vespucci Bridge on the Arno River in Florence (Italy) was built in the 50's of the last century. The bridge has three spans and a total length of 155.5 m. The deck is in pre-stressed reinforced concrete, the piers, the abutments and the foundations are in reinforced concrete. The foundations of the piers consist of caissons supported by bored piles, with diameter 0.40 m and length 15 m. The piles are weakly reinforced only in the first 3 m from its head. At the time of the construction of the bridge, the subsoil stratigraphy consisted of a surficial alluvial layer of sand and gravel with a thickness of 10-12 m overlying a deep layer of overconsolidated clay. The bridge is located immediately downstream of a hydraulic weir which is heavily inclinated with respect to the water flow direction. Such inclination causes a deviation of the water flow and situations that can be very different from each other even within a few tens of meters of distance. In particular, the right pier of the bridge is affected by a conspicuous deposition phenomenon while close to the left pier the riverbed has lowered causing a deep scour around and below the caisson foundations. At present the depth of the erosion is variable and has a maximum value of about 7.85 meters. The lowering of the riverbed has brought to light the foundation piles, exposing them to the erosive action of the water and the transported debris. Therefore, many piles appear to be damaged, broken or even absent. The phenomenon described was highlighted by surveying the riverbed and the foundation structures by multi-beam technology. In this paper the bearing capacity reduction of the pier foundation is estimated.

RÉSUMÉ: Le pont Amerigo Vespucci sur l'Arno à Florence (Italie) c'est une œuvre realisée dans les années 50 du siècle dernier. Le pont a trois baies et une longueur totale de 155.5 m. Le plancher du pont est en béton armé précontrain; les piles, les culées et les fondations sont en b.a. Les fondations des piles sont constituée de caissons en b.a. reposant sur des pieux forés d'un diamètre de 0.40 m et d'une longueur de 15.0 m, faiblement armés seulement dans les 3 premiers mètres. Au moment de la construction du pont, le profil de sol de fondation des pieux se composait d'une première couche alluviale de sable et de gravier pour une épaisseur de 10-12 m situèe au dessus d'une couche d'argile consistante et surconsolidée. Le pont est situé immédiatement en aval d'une traverse hydraulique qui présente une forte inclinaison par rapport à la direction du courant. Cette inclinaison a déterminé une déviation du flux du courant d'eau qui a crée dans quelques dizaines de mètres des situations localisées très différentes les unes des autres. En particulier, la pile droite du pont est affectée par un phénomène de dépôt visible alors que, sur la pile gauche, le lit a été érodé, ce qui a provoqué une déchaussement de la base de la pile elle-même. La profondeur de l'érosion dans l'état actuel est variable et a une valeur maximale d'environ 7.85 mètres. L'abaissement du fond du lit de la rivière a mis au jour les pieux de fondation, les exposant à l'action érosive de l'eau et des débris transportés. Par conséquent, beaucoup de pieux sont endommagés, interrompus ou même absents. Le phénomène décrit a été mis en évidence en examinant le fond du lit de la rivière et les structures de fondation au moyen de la technologie multi-beam, et à l'aide d'inspections sous-marine et sonar de la pile. Dans cet article, la réduction de la capacité de charge des fondations de pieux est estimée.

Keywords: Scour, bridge, pier foundation, multi-beam technology

1 INTRODUCTION

The technical regulations on road bridges (e.g. in Italy, Ministerial Circular No. 34233 of 25.02.1991) prescribe periodic and systematic checks on the static conditions and good conservation of bridges. Inspections are normally visual and, only if the work shows signs of serious anomalies, special investigations and controls are required.

Foundations are a non-visible part of the bridge, so it is difficult to control its state of damage. If the foundations are seriously damaged, but the structure in elevation and therefore the visible portion of the construction does not show signs of serious anomalies, there is an effective risk of ignoring the real conditions of danger.

The scour of the riverbed in correspondence of the piers cannot be detected by a visual inspection of the static condition of the structure, while it constitutes the most frequent cause of bridges collapse. It has been estimated that 60% of the collapses of bridges are caused by the scour (FHWA, 1988; Brandimarte et al., 2012; Briaud et al., 1999).

The bridge pier scour is associated with different mechanisms, which can also occur simultaneously: the general scour, which results in the evolution of the riverbed by natural and/or artificial causes and is independent from the presence of the pier, and the contraction scour, due to the reduction in the channels cross-sectional area due to the the presence of the pier itself, and to local scour that occurs around individual bridge piers (Brandimarte et al., 2012; Federico et al., 2003; Prendergast and Gavin, 2014).

The Amerigo Vespucci Bridge on the Arno River in Florence is apparently a stable structure, but in reality in precarious static conditions.

The three-dimensional relief of the riverbed and of the submerged works in the urban stretch of the river, carried out on behalf of the Municipality of Florence, highlighted a phenomenon of strong erosion close to the left pier and serious damage to its foundation system.

2 BRIEF DESCRIPTION OF THE BRIDGE

The Amerigo Vespucci Bridge was built in the 50's of the last century. The bridge has three spans with width 22.0 m and total length 155.5 m (Figure 1). The deck is in pre-stressed reinforced concrete, the piers, the abutments and the foundations are in reinforced concrete. The static scheme of the structure is rather complex, since it consists of a sequence of three independent portals. Each upright is obtained by coupling a tie rod and a strut, that is obtained with the ribbing of the pier and (Figure 2).

Figure 1. The Amerigo Vespucci bridge in Florence. View from a point upstream.

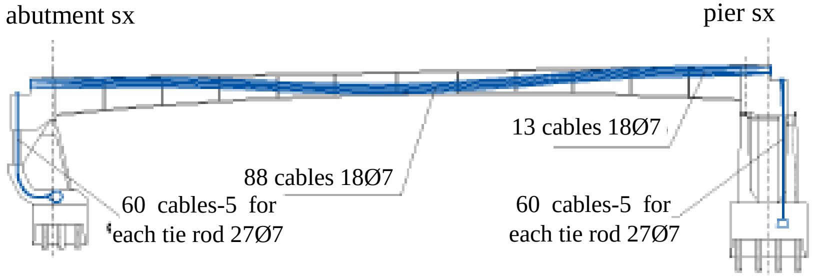

Figure 2. The static scheme of a span (from Aprigliano (2017))

Each pier supports two successive spans, therefore they receives moments of opposite sign from the two beams. Each moment is singularly relevant, but they mutually elide each other. The high degree of hyperstaticity, resulting from the particular joint between pier and spans, makes the framework particularly sensitive to the settlements of the foundation system.

The project documentation revealed that the foundations of the piers and of the abutments consist of caissons in reinforced concrete, subsequently filled with concrete, lying on a group of bored piles (Figures 3). In particular, the caissons of the piers have length 34.40 m, width 5.10 m and total height 3.25 m. At the time of construction, the caissons were sinked for 4.50 m within the riverbed and supported by the underlying sandy-gravelly soil and 106 cast in place concrete piles. The piles are uncased, have a diameter of 0.40 m, a length of 15.00 m and are armed with 4Φ16 of longitudinal and Φ6/25 cm transverse reinforcement bars only for the first 3 m from its head.

3 THE OBSERVED PHENOMENON AND ITS CAUSES

In 2016, the Municipality of Florence commissioned to DICeA[1] a study to investigate the conditions of the riverbed and of the structures in it in the urban stretch of the Arno River. During this study, which also included

[1] DICeA is the acronym of the Department of Civil and Environmental Engineering of the University of Florence

surveys of the riverbed with multi-beam and laser scanning technology, some critical issues emerged, the most serious of which concerned the left pier of the Amerigo Vespucci Bridge. The multi-beam technology and laser scanning use the forward and return sound waves of a signal to reconstruct the geometry of the riverbed and assess the conditions of the structures inside the riverbed. This very useful and cost-effective technology have been applied also to other fields, e.g. dredging project, coastal slope stability and hazard surveys, coastal engineering applications, working in high tidal variation etc.. (Lovelace, 2017; Mitchell et al., 2011).

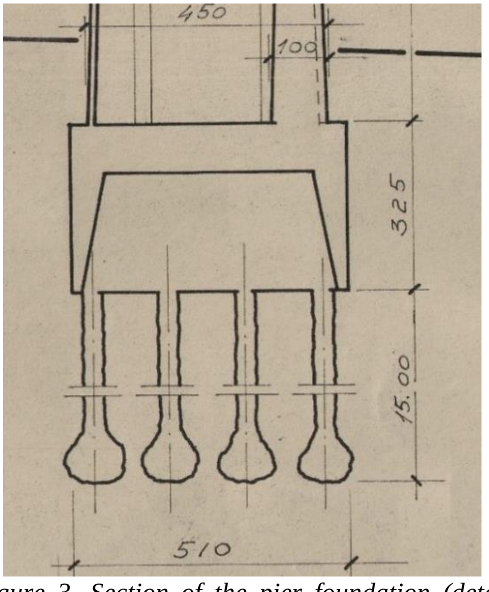

Figure 3. Section of the pier foundation (detail from a table of the original project)

The bathymetric relief around the left pier of the Amerigo Vespucci Bridge (Figure 4) highlighted a very marked erosion phenomenon on the right side of the pier, with a maximum depth of about 7.85 m.

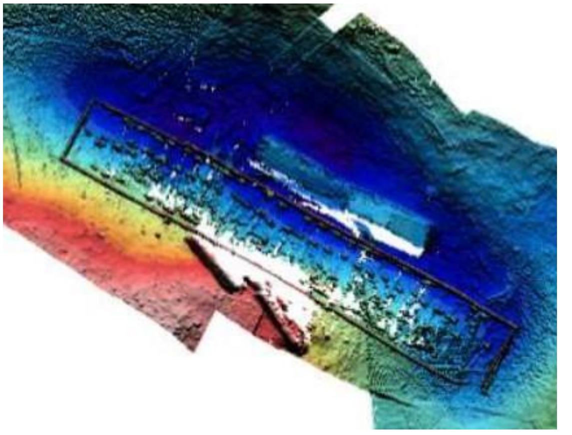

Figure 4. The bathymetric relief around the left pier of the Vespucci Bridge (from Hera Report, 2018)

The lowering of the riverbed resulted in the erosion of the soil at the intrados of the foundation block, which in part is currently supported only by the piles (Figure 5). In addition, some piles are damaged, broken or even absent. Figures 6 and 7 show images obtained with the multi-beam technology in which this phenomenon is particularly evident.

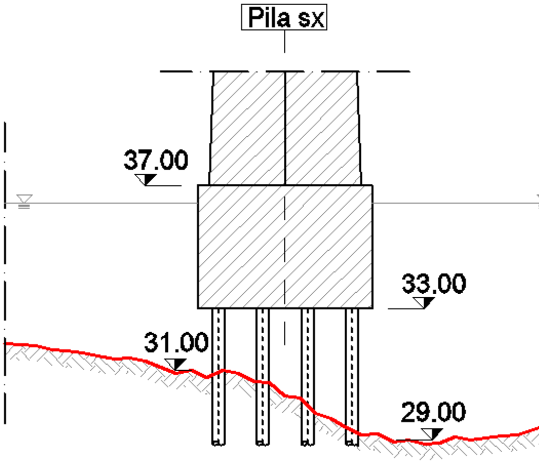

Figure 5. Reconstruction of the river bed profile in corrispondence of the left pier of the Vespucci Bridge (from Aprigliano (2017))

Figure 6. Reconstruction of the river bed profile from the bathymetric survey (from Hera Report, 2018)

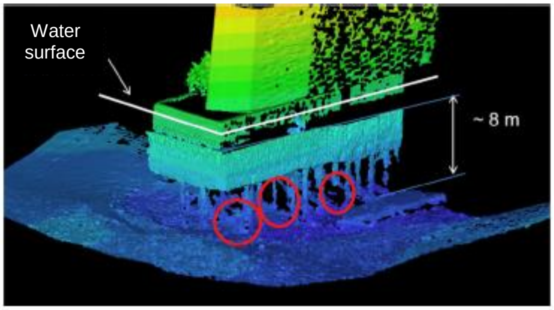

Figure 7. Longitudinal view of the foundation of the left pier, detected with multi-beam technology (from Hera Report, 2018)

The study on the morphological evolution of the Arno River in the period 1960-2015 showed a generalized lowering of the riverbed in the urban stretch of about 3.0 m, due to several causes. They include extractive activity, construction of dams and changes in land use. However, at the left pier of the Vespucci Bridge, the erosion depth is much greater due to a localized phenomenon attributable to a weir, called "Pescaia di Santa Rosa",located immediately upstream of the bridge (Figure 8). The sharp inclination of the weir (its axis has an inclination of 55° with respect to the axis of the bridge) caused a deviation of the streamflow, which caused very different localized situations even within a few tens of meters. In particular, the right pier of the bridge is affected by a significant deposition phenomenon while the riverbed has lowered at the left pier, causing sapping at the base of the pier itself. The plan of the foundation piles of the left pier of the Vespucci bridge and their state of consistency are shown in Figure 9.

Figure 8. Aerial view of the Amerigo Vespucci bridge and of the Santa Rosa weir

4 STRATIGRAPHIC CONDITIONS AND PILE BEARING CAPACITY

The stratigraphic conditions at the time of construction of the bridge (1955) can be deduced both from a borehole carried out where the pier was located and from , also from the booklet of measures written during the construction of the foundation piles, on which the changes in depth of subsoil layers were noted for each pile. At that time, the altitude of the riverbed was at + 37.00 m above sea level. Under the left pier, the stratigraphic profile consisted of a surficial layer of gravel and sand overlying a layer of very consistent and over-consolidated silty clay that extends to the bottom of the borehole (at nearly 30 m from the riverbed). The bottom of the layer of gravel and sand was located between 10.0 and 12.4 m from the riverbed with an average value of 11.75 m and a standard deviation of 0.43 m.

In 2017 a new geotechnical borehole, whose position is indicated by the yellow dot in Figure 8, was performed. From the stratigraphic profle, the riverbed resulted at + 29.15 m above sea level. Thus, the thickness of the upper layer of gravel and sand was reduced to 3.70 m.

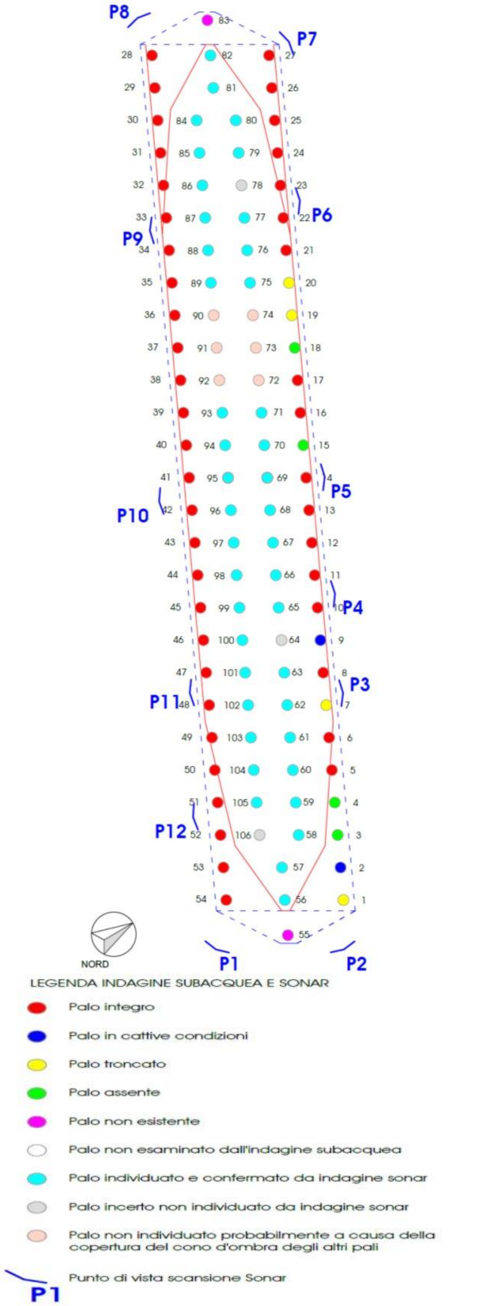

Figure 9. Plan of the foundation piles of the left pier of the Vespucci bridge and their state of consistency (june 2018) (from Hera Report, 2018)

The layer of silty clay resulted to have a thickness of 20.20 m, while a layer of gravel that extends to the bottom of the borehole was encountered at greater depth (Figure 10).

If an erosion of the gravel layer of almost 8 meters is taken into account, the subsoil profile deduced from the survey carried out in 2017 has a good agreement with that inferred from the historical survey of 1955.

During the drilling of 2017, SPT tests were carried out at different depths, undisturbed samples were extracted from the silty clay layer for laboratory analysis and several measures of undrained resistance were made by using a pocket penetrometer and a pocket vane tester.

At present, the piles of the Vespucci Bridge on which the left pier is founded show many differences with respect to the orginal project. Some piles have not been carried out, some other are sheared and totally ineffective or they are partially emerged from the ground to a different extent depending on the varying depths of the erosion (Figure 9).

The estimates of the vertical and horizontal bearing capacity of the single pile that were evaluated under the minimum and the maximum erosion conditions are given in Table 1.

Table 1. Estimates of the vertical and horizontal bearing capacity of the single pile under minimum and maximum erosion conditions

Bearing capacity	**Minimum erosion**	**Maximum erosion**
Vertical [kN]	1155	940
Horizontal [kN]	68	0

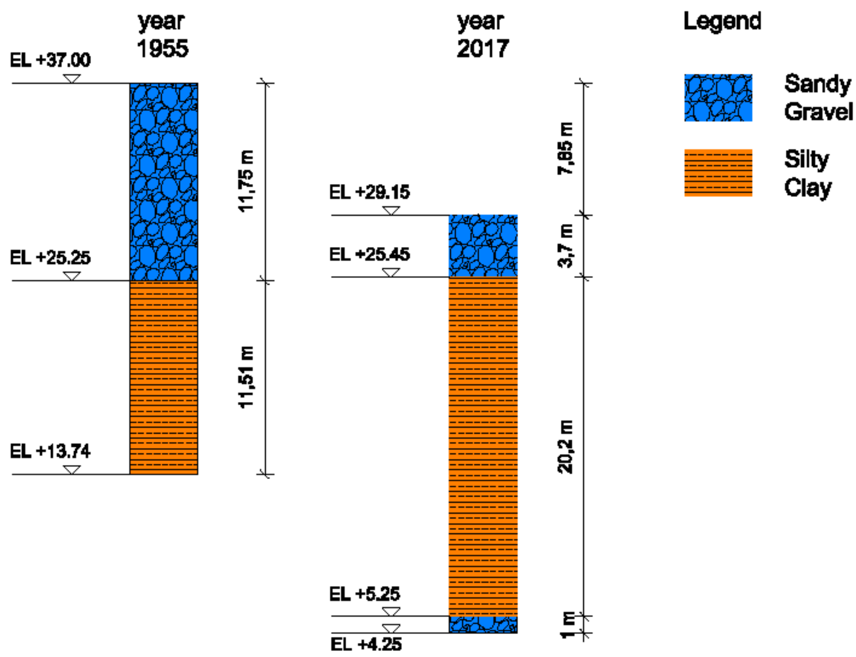

Figure 10. Stratigraphies in correspondence of the left pier in 1955 and in 2017.

5 ESTIMATED VERTICAL LOADS ON THE PILES

The total loads transmitted to the foundation system, if the most heavy loading condition is considered, are as follows:

Steady load: $N_p = 44.316$ MN
Live load: $N_{acc} = 4.959$ MN
Total load: $N_{tot} = 49.275$ MN

It can be noted that the live load represents only about the 10% of the total load.

The foundation block of the pier has an area of about 192.7 m^2. The intrados of the foundation block is at level +34.0 m a.s.l. Assuming that the minimum water level at the pier is +37.0 m a.s.l, the hydraulic upward thrust is: $S_w = 5.671$ MN.

If all the piles of the group were intact and of equal stiffness to the vertical translation, the average effective load transmitted at the top of each pile would be: P = (49.275-5.671)/106 = 0.411 MN.

Under current conditions, the lack of bearing capacity of a certain number of piles (from 15 to 21) leads to an increase of the loads supported by the remaining piles, that is also due to the resulting eccentricity of the load with respect to the centre of gravity of the active piling (Table 2).

6 CONCLUSIONS

The analyses performed on the foundation system point out the high vulnerability of the foundation of the left pier of the Vespucci Bridge in Florence.

In case of an earthquake, even of moderate severity, the risk of collapse is very high. In fact, even neglecting the soil-structure kinematic interaction, the horizontal inertial actions would induce the collapse of the piles emerged from the ground and this would produce a sharp increase in the resulting eccentricity and consequently the collapse of the other piles as well.

In addition, in the absence of a timely intervention of restoration of the foundation system, the stability conditions of the bridge could further worsen due to those same causes that have produced the current instability.

Therefore, a process for the design and the execution of the restoration works of the foundation system of the left pier of the Vespucci bridge is just started as a matter of urgency.

Table 2. Estimates of the loads on the foundation piles of the left pier of the Vespucci bridge in the most heavy load condition

No of ineffective or absent piles	15	21
No of existent and efficient piles	91	85
Eccentricity of the resultant load in the x direction [m]	0.244	0.261
Eccentricity of the resultant load in the y direction [m]	0.356	0.382
Maximum vertical load on single pile [kN]	619	666
Average vertical load on single pile [kN]	479	513
Minimum vertical load on single pile [kN	354	378

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