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Original

Renovation of quay walls to meet more demanding requirements: Italian experiences / Ruggeri, Paolo; Fruzzetti, Vivienne Marianne Esther; Scarpelli, Giuseppe. - In: COASTAL ENGINEERING. - ISSN 0378-3839. - 147:(2019), pp. 25-33. [10.1016/j.coastaleng.2019.01.003]

Availability:

This version is available at: 11566/263865 since: 2022-06-03T13:02:12Z

Publisher:

Published

DOI:10.1016/j.coastaleng.2019.01.003

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note finali coverpage

(Article begins on next page)

AUTHOR'S ACCEPTED MANUSCRIPT

The definitive Publisher's version is available:

<https://doi.org/10.1016/j.coastaleng.2019.01.003>

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Reference: CENG 3458

To appear in: *Coastal Engineering*

Received Date: 9 October 2018

Revised Date: 21 December 2018

Accepted Date: 18 January 2019



Please cite this article as:

Paolo Ruggeri, Vivienne Marianne Esther Fruzzetti, Giuseppe Scarpelli,
Renovation of quay walls to meet more demanding requirements: Italian experiences,
Coastal Engineering, Volume 147, 2019, Pages 25-33, ISSN 0378-3839,
<https://doi.org/10.1016/j.coastaleng.2019.01.003>

1 **RENOVATION OF QUAY WALLS TO MEET MORE DEMANDING**
2 **REQUIREMENTS: ITALIAN EXPERIENCES**

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7
8 **ABSTRACT**

9 Existing port structures often need to be upgraded to meet more demanding operational requirements caused
10 by increasing ship size, deepening of the seabed and increasing crane dimensions and storage loads. When
11 ports expand, upgrading is often preferable to the rebuilding of infrastructures in term of costs; however, the
12 design of such works must take into account that the reliability of the existing structures is often inadequate
13 according to the current codes, due to the low mechanical properties of the original materials and to their
14 aging in the highly aggressive marine environment. The geotechnical engineering literature rarely addresses
15 the problem of upgrading existing quay walls, even though such geotechnical structures are extremely
16 challenging. This paper discusses the main issues involved in the geotechnical design for upgrading existing
17 quay walls , through the presentation of some case histories drawn from past experiences in Italy.

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21 **Key-words:** geotechnical engineering, port structures, enhanced quay walls, ground improvement, seismic
22 upgrading, retrofitting

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29 1. INTRODUCTION

30 Globalization of trade and the integration of faraway economic markets are recognised trends of the last two
31 decades. Such evolution has been made possible by the astonishing development of maritime shipping,
32 thanks to the low cost of transport per weight unit over long distances. It has been observed that the
33 progressive reduction in the cost of transport is traceable to the rapid increase in the size of container vessels
34 (Lane and Meret, 2014), favoured by the recent deepening of the Suez Canal, which can now host vessels
35 with 20 m draughts. Such rapid development has led to competition among the ports, making it necessary to
36 upgrade quays to host the new larger vessels.

37 The evolution of port infrastructure has been always linked to the characteristics of the ships, as is clearly
38 shown by Figure 1, in which historical development of the container capacity of vessels is compared with
39 their draught.

40 A modern quay structure employed for cargo handling requires a seabed depth ranging from 12 m to 20 m
41 and a deck height ranging from 2.5 m to 5.0 m above sea level. Current cranes can be mounted on rails or
42 self-propelling, depending on the main use of the quay. Large quays specialized in handling containers (i.e.
43 container terminals) are usually equipped with Ship-to-Shore gantry cranes (STS cranes) on rails. The typical
44 span between the rails of such cranes will range from 20 m to 30 m, but cranes with gantry span up to 50 m
45 have been recently built.

46 The surface load on the platform also depends on the type of terminal involved. The overload for container
47 terminals may vary from 40 kPa to 60 kPa, while the figure can rise as high as 300 kPa in the case of ore
48 terminals (De Gijt, 2010). In any case, the effects on quay wall depend on the distance between the storage
49 zone and the wall.

50 Considering the large number of existing ports in Europe, and the fact that it is difficult to find a different
51 site on which to plan a new one, solutions must be found for upgrading existing structures to meet new
52 requirements. This is particularly true of Italian ports, which were usually constructed in centuries past and
53 are part of very large urban zones, where the possibility of expansion into new areas is minimal.

54 The upgrading of a quay wall is a challenging topic for port engineers, requiring consideration of a large
55 number of factors, including the deepening of the seabed, increased terrain loads, the use of large cranes –
56 quite often heavy mobile cranes – and the availability of strong mooring bitts. In spite of the importance of

57 the topic, it has rarely been addressed in the literature, and typically from the maritime point of view alone
58 (Franco, 1994). Only recently have some Authors begun to consider the problem from a broader perspective.

59 Among others, Bauduin et al. (2017) classify the entity of upgrades by distinguishing between:

- 60 - refurbishment, in which the existing structures are essentially re-used;
- 61 - medium upgrade, in which the existing structures are still used, but it is necessary to supplement
62 them with new structures;
- 63 - intensive upgrade, in which the existing structure is fully disregarded and the new structures have to
64 sustain the full impact of all actions.

65 A relevant aspect, that goes beyond the scope of this paper, is the costs of the upgrading works. Recently,
66 Goldbohom et al. (2018) presented a flow-chart to evaluate the opportunity to invest public resources in the
67 management of inner-city quays. As order of magnitude, the experiences of the authors suggest that the cost
68 of a medium upgrade work in Italy span between 10,000 € to 30,000 € per meter of quay, while an intense
69 upgrade is often more expensive than build a new quay, with costs ranging from 30,000 € to 60,000 € per
70 meter of quay, depending on the performance required to the new structure.

71 Another significant aspect for design of upgrading works is related to the evolution of the Italian mandatory
72 codes for construction. Considering the increasing demand for safety in public infrastructures by the society,
73 always particularly sensitive to their performance during earthquakes (Scarpelli et al., 2011; Scarpelli et al,
74 2012), any new updating of the codes implies an increase, typically very significant, in the robustness of the
75 structures. Upgrading works on old structures thus become very expensive just because of the increasing
76 safety demand in technical codes, even in the absence of any change in the use of the infrastructure.

77 The mandatory nature of Italian code for public works allows to identify which of the issues of the code
78 (e.g.: Law 1967, Law 1974, DM 1988, DM 1996, DM 2008, DM 2018) held for any specific design, that is
79 one to one related to the construction period.

80 This paper aims at outlining the main issues to be addressed when designing renovation works of quay walls,
81 in particular for medium upgrading cases, that is a level of intervention that allows an increase of 2-3 m of
82 the depth of the seabed in front of the wall. In this framework, few cases of interventions on quay walls
83 carried out in Italian ports are illustrated and discussed.

84

85 2. CLASSIFICATION OF QUAY WALLS

86 According to [Tsinker \(1997\)](#) a berth (or dock) is a general term used to describe a marine structure for safe
87 mooring of a ship, accommodating cargo-handling equipment, the loading or unloading of cargo or the
88 boarding or disembarkation of passengers. Among the different types of docks, it is useful to distinguish
89 between:

- 90 - quays (or wharfs in old English): any structure of timber, masonry, cement or other material built
91 along the navigable waterway, able to offer a safe mooring to vessels;
- 92 - piers (or jetties): a construction work projected out onto the water and able to accommodate vessels
93 on one or both sides;
- 94 - dolphins: isolated marines structure for mooring vessels; to moor a vessel, more than one dolphin
95 must be used.

96 This paper refers to the quay wall, a marine structure subject mainly to actions that are geotechnical in nature
97 while mooring forces play a secondary role.

98 From a structural point of view, several authors have proposed different classifications ([Tsinkin, 1997](#); [De
99 Gijt, 2010](#)). For the purposes of the present paper, use is made of the classification recommended by
100 [Thoresen \(2003\)](#), which groups quay walls into two main categories:

- 101 - solid berth structures: a vertical front wall is constructed to resist both the horizontal load from the
102 fill and the live load on the apron;
- 103 - open berth structures: a load-bearing slab on columns/piles covers the slope between seabed and
104 apron.

105 Solid berth structures, in turn, may be divided into gravity-wall structures and sheet-pile-wall structures,
106 based on the principle that lends stability to the wall.

107 The gravity-wall structure balances the horizontal action with its own deadweight and bottom friction.
108 Typical solutions consist of concrete blocks or caissons that are floated in. Such solutions always require a
109 rubble rock-fill behind the blocks to limit the horizontal pressure of the soil. They are the primary option if
110 the foundation soil is firm and requires only modest maintenance, thanks to a massive structural section.
111 Moreover, it is the solution under which construction of an anti-reflective wave chamber is easiest.

112 Sheet-pile walls are relatively thin walls of steel, reinforced concrete or timber supported by anchors and
113 passive soil pressure in front of the wall. Anchors can transmit the tensile force directly to the soil (ground
114 anchor) or to other anchoring structures (e.g. deadman). Nowadays, steel-sheet piles are the most widely
115 used sheet walls, thanks to the highly adaptable profiles offered by industrial production. However, the
116 slenderness of the profiles calls for care to be taken in aggressive environments. Moreover, it is not easy to
117 build anti-reflective wave chambers.

118 The so-called “Danish quay wall”, consisting of a sheet-pile wall retained by a platform set on inclined piles,
119 may be included among solid-berth structures. Under this solution, the platform set on piles makes possible
120 the transmission of overloads on the deck to a deep bearing soil stratum, decreasing the soil pressure on the
121 wall. For this reason, such solutions are often referred to as sheet-pile walls with relieving platforms. This
122 approach, generally very expensive, is becoming increasingly widespread, given the possibility of
123 accommodating a very deep seabed, even at a site with poor geotechnical properties.

124 A second class of solution is represented by open-berth structures (or jetties). This approach splits the
125 berthing actions in two parts: the seabed is shaped in a slope, to remove the horizontal soil pressure on the
126 structures, while a concrete slab set on piles is placed over the slope, providing the berth for vessels. A
127 similar solution makes it possible to obtain the deepest possible seabed, performances well in the event of a
128 tsunami and can be designed for high-performance in the event of an earthquake as well, thanks to the
129 relatively light-weight structures utilised. What is more, the slope under the deck, protected by rocks, ensures
130 optimal absorption of the marine waves. On the other hand, the large number of structural elements exposed
131 to the marine environment, together with their slender construction, makes this solution sensitive to ageing
132 and difficult to maintain.

133 [Figure 2](#) illustrates some examples of the structural solutions described.

134 **3. DESIGN CONCEPTS FOR THE RENOVATION OF A QUAY**

135 The main circumstances that require a structural intervention to enhance the performance of a quay wall are:

- 136 1. deterioration of the structures;
- 137 2. deepening of the seabed;
- 138 3. increased berthing forces;

- 139 4. increased loads on the deck (caused by increased overloads or the use of heavy cranes);
140 5. changes in technical code requirements, especially with regard to safety standards for public works
141 and/or changes in the natural actions to be considered (i.e. seismic safety).

142 Point 1 regards the ageing of the works, points 2, 3 and 4 can be included under the topic of enhanced quay
143 performance, and point 5 is related to the increased standards of safety that accompany ongoing societal
144 development.

145 Case studies on some of the problems that can arise with the operation of quay walls due to aging can be
146 found in [Littlejohn and Mothersille \(2008\)](#) and [Ruggeri et al. \(2013\)](#).

147 Only a few publications offer systematic analyses of the renovation of existing quay walls, in particular from
148 a geotechnical perspective. Some technical books, such as *Recommendations of the Committee for*
149 *Waterfront Structures, Harbours and Waterways* ([EAU, 2012](#)), contains limited suggestions on this theme.

150 Examples of such interventions can be found in [Franco and Noli \(1985\)](#) and in [De Gijt e Broeken \(2013\)](#). A
151 classification of a series of conceptual options for the upgrading of quay walls is presented by [Douairi and](#)
152 [De Gijt \(2013\)](#). The World Association for Waterborne Transport Infrastructures (PIANC) also recognises
153 the considerable importance of the topic, as shown by its recent establishment of Working Group 164 on the
154 “*Upgrading of Port Berths by Increasing Dredged Depth*”.

155 Limiting the investigation to solid-berth structures, and recognizing that this class of quay wall is essentially
156 a retaining wall, three strategies of intervention to improve performance may be identified:

- 157 - strategy A: reduction of stress, especially horizontal soil pressure;
- 158 - strategy B: increase in strength resources in the passive zone;
- 159 - strategy C: strengthening of quay wall structures.

160 Typically, any enhancement work requires a combination of more than one strategy to obtain the best result.
161 Strategy A aims to reduce soil pressures and includes interventions geared towards transferring the surface
162 loads at a depth. Examples of this strategy include the relieving platform built behind the vertical wall and
163 soil-improvement treatments, such as jet grouting or deep-mixing columns installed in the active volume of
164 the wall. Stone-column treatments behind the wall can also be used to reduce the soil pressure exerted by
165 overloads or mobile cranes on the deck. A different way to reduce active soil pressure is substitution of the
166 first meters of soil beneath the deck with lightweight material (i.e. expanded clay aggregate).

167 Strategy B focuses on increasing the strength resources in the passive zone. Such strategies can also be used
168 for the foundations of the gravity retaining wall and the sheet-pile wall, but naturally they prove more
169 effective with embedded walls in which passive soil resistance is directly involved in the equilibrium of the
170 structure. Weighting of the soil at the toe with the addition rocks, or partially substituting soft soil with
171 gravel, or treating soil volume with jet grouting by means of deep-mixing techniques to enhance strength and
172 stiffness, are techniques typically utilised in such interventions.

173 Strategy C requires strengthening of the structures. Concrete blocks are frequently connected by vertical steel
174 rods, with an underpinning of micro-piles. in order to prevent displacement of the individual blocks and
175 improve the overall stability of the work.

176 For sheet-pile walls, the typical approach is to strengthen the anchoring systems by adding new anchors or
177 reinforcing the existing steel bars and retaining walls. Strengthening of the structural section of the main wall
178 can also enhance the performance of the retaining system.

179 It is interesting to observe that, in the case of embedded walls, the desired effect can be obtained by treating
180 either the active side (i.e. Strategy A) or the passive side (i.e. Strategy B), though it can be shown that
181 treatment of passive side is more effective than that of the active zone (Ou et al., 1996; Xie et al., 2000). This
182 is partly intuitive, considering the lesser volume involved on the passive side as opposed to the active zone,
183 but it should be noted that the construction process also plays a role. In fact, if an excavation is planned, then
184 pre-treatment of the soil beneath the dredging level is very effective to limit the increased stress on the
185 structures; on the other hand, the effect is less pronounced if plans call for the active zone to be filled.
186 Moreover, positioning of the treatment, as well as the choice of the size, shape and pattern of the treated
187 volume, so as to ensure a cost-effective solution, is no trivial matter (Xie et al., 2000; Ruggeri et al., 2014;
188 Ruggeri et al., 2016).

189 **4. EXAMPLES OF SOLUTIONS ADOPTED IN ITALY**

190 There follow a number of case histories of quay-wall renovation projects carried out in Italian harbours
191 during the last few decades. Observations are made on the geotechnical aspects, the complexity and
192 sturdiness of each intervention.

193 Examples of works involving gravity walls are:

- 194 - Port of Genoa – San Giorgio Pier
- 195 - Port of Messina – Peloro Quay
- 196 - Port of Naples - Flavio Gioia Quay
- 197 - Port of Ancona – Quays nos. 21 and 22

198 The renovations of sheet-pile walls considered are:

- 199 - Port of Ravenna - San Vitale Quay
- 200 - Port of Gioia Tauro – Eastern Quay

201 [Figure 3](#) shows a map of Italy with the locations of the structures considered.

202 *5.1 Port of Genoa – San Giorgio Pier*

203 The Port of Genoa is the leading Italian seaport, in competition with the ports of Marseille and Barcelona to
204 be the largest in the Mediterranean Sea. With a trade volume of 51.6 million tons, it is Italy’s busiest cargo
205 port in terms of tonnage.

206 The San Giorgio pier is a facility of the Port of Genoa that has been in operation for many years. Used for the
207 importation of coal, the quay was built in the 20’s, with vertical walls made of heavy concrete blocks able to
208 sustain a seabed depth of approximately 11 m. Planned development of the area calls for the seabed in front
209 of the wall to be dredged down to 14 m to allow for the berthing of larger ships.

210 From a geotechnical point of view, the seabed subsoil of the area is primarily coarse-grained, formed by
211 quaternary marine deposits. The new apron was built by filling the sea with rock and gravel taken from a
212 rocky hill in front of the port that was razed to the ground.

213 To enhance the existing structures, a structural intervention had to be carried out in 1998. As showed in
214 [Figure 4](#), the blocks were given an underpinning of jet-grouting columns down to a depth of 18 m, reinforced
215 by steel rods. These rods extend into the blocks, linking the blocks to one another. Moreover, to improve the
216 stability of the geotechnical system, active ground anchors were installed along the entire length of the pier.
217 Details of the intervention, and of the innovative monitoring of structural movements over an extended
218 period of time, based on fibre-optic linear deformation sensors, can be found in [Del Grosso et al. \(2007\)](#).

219 The solution adopted is designed to convert the gravity wall in place at the head into a massive embedded
220 wall. It presents some potential weaknesses, in particular the effective size of injected columns beneath the

221 concrete blocks, meaning that it can only be employed when the type of soil involved makes injection easy
222 (i.e. sand).

223 *5.2 Port of Messina – Peloro Quay*

224 The Port of Messina serves the city of Messina, Sicily, in southern Italy. The port sits on the western shore of
225 the Strait of Messina, consisting of the large inlet provided by a natural harbour. One of the oldest ports in
226 the Mediterranean Sea, its origins are tied to its natural configuration and deep seabed. Until 1905, the west
227 side of the port area was a simple beach without any facilities, apart from the sustaining walls of a coastal
228 road. In 1908, a severe earthquake, followed by a tsunami, greatly damages the city, causing the old walls
229 along the shoreline to collapse. The new regulatory plan drawn up for the port in the wake of this event
230 called for the construction of a quay wall along the west coast. This new quay was built in 50's, 10 to 20
231 metres further into the sea than the old shoreline, and it still provides the main quay walls on west side of the
232 port, under the names of “Rizzo”, “Peloro”, “Marconi”, “I Settembre” and “Colapesce”. Starting in 2000, the
233 quays presented signs of developing instability, and major reinforcement work was planned. Details can be
234 found in [Valore et al. \(2004\)](#).

235 It is worthwhile focussing on the work carried out on the Peloro quay, which reflects the interventions
236 carried out on several of the other quays.

237 Peloro quay consists of a precast concrete caisson 13 m high and 6 m long, with a width that ranges from 3.6
238 m at its head to 6.0 m at its base. The base has two prominent shear keys, one in the front and one on the
239 rear, to connect the structure with the subsoil. A massive concrete beam, 2.5 m in height, was cast on-site on
240 the heads of the caisson. [Figure 5](#) shows a schematic cross section of the Peloro quay, with the reinforcement
241 works highlighted.

242 Geotechnical surveying revealed an alarming situation, given that the caisson was filled with gravel (instead
243 of concrete), the rock-fill utilised was heterogeneous, consisting primarily of sand, plus some of the caissons
244 were separated from each other by tens of centimetres (causing problems of erosion problems and subsiding
245 of the paving) and scouring at the toe was widely observed.

246 From a geotechnical perspective, the foundations of the structures were found in the thick gravel and sand
247 deposit typical of the zone, belonging to the well-known Messina Gravel Formation (MGF). MGF is a coarse

248 deposit of medium pleistocene age (500,000 to 600,000 years old) which, geological and geophysical
249 investigations, showed to extend up to very large depth. Geotechnical properties of MGF were generally
250 good: unit weight $\gamma = 20\text{-}21 \text{ kN/m}^3$ and effective friction angle $\phi' = 37^\circ\text{-}40^\circ$. The backfill of the caisson is
251 constituted of heterogeneous coarse soil.

252 The reinforcement measures consisted of:

- 253 - underpinning the caisson with a set of micro-piles 26 m in length, arrayed in 4 lines with spacing of
254 1 m along the line, 2 positioned vertically and 2 inclined; each micro-pile was reinforced with a
255 steel pipe with a diameter of 139.7 mm and a thickness of 14.2 mm;
- 256 - two lines of vertical micro-piles, positioned about 5 m far from the caissons, with spacing of 1 m
257 along the line, reinforced with steel pipe with a diameter of 88 mm and a thickness of 8 mm, able to
258 sustain the crane rail and to enhance resistance to horizontal actions;
- 259 - a pair of micro-piles, inclined at 7° from the vertical, positioned at a distance of approximately 10
260 m from the caissons, with spacing of 1 m spaced along the line and reinforcement in the form of a
261 steel pipe with a diameter of 139.7 mm and a thickness of 10.0 mm;
- 262 - jet-grouting treatment of the backfill, with columns 800 mm in diameter and 6 m in length, arrayed
263 in a quincunx pattern with spacing of 2.15 m;
- 264 - a concrete slab 500-600 mm thick, to create a new deck able to join the caissons and the micro-
265 piles, set on a foundation of jet-grouting columns.

266 The solution adopted focussed on improving the load-bearing capacity of the caissons and reducing the
267 active thrust by transferring the overload to a depth and improving the properties of the soil in the active
268 zone.

269 *5.3 Port of Naples – The Flavio Gioia Quay*

270 The Port of Naples is one of the Italy's largest seaports. Located along the Tyrrhenian coast, in southern
271 Italy, its founding dates back to the period of Greek colonization, in the 9th century BC. During the 18th
272 century AD, under the Bourbon dynasty, the port was established as one of the best -equipped and strongest
273 in Europe. Indeed, in the September 27, 1818, it was the site of the launching of the first steamship in the
274 Mediterranean. After the unification of Italy, in 1861, the Port of Naples entered a period of decline. After

275 the First World War, the port experienced a new period of growth, gaining a large number of new
276 infrastructures, with the new operational quay expanding to the east. The wall of the quay named for Flavio
277 Gioia (the legendary inventor of the compass) was built during this period. A new structure able to sustain a
278 seabed depth of 11 m, it was made from a gravity concrete–block assembly whose cross-section is shown in
279 [Figure 6](#).

280 From a geological point of view, the Naples Bay is part of a belt of coastal tectonic depressions filled by
281 several thousand of meters of volcanic sediments erupted by the Vesuvius and/or products from Phlegrean
282 Fields. The gravity concrete-block assembly is founded on these pyroclastic sand deposits. At larger depth,
283 below several meters of such deposit, a layer of tuff is also encountered. A backfill of mainly coarse-grained
284 soil allows to build the terminal area. Geotechnical properties of pyroclastic deposits are generally good: unit
285 weight, $\gamma = 17\text{-}18 \text{ kN/m}^3$, effective friction angle, $\varphi' = 30^\circ\text{-}32^\circ$, operational stiffness, $E' = 30 \text{ MPa}$.

286 During the 1980's, to deepen the seabed to 14 m below sea level, extensive work was carried out using a new
287 technique patented in 1970 by engineer Fernando Lizzi in 1970: the “reticulated root pile” system (built
288 through the structure of the quay wall, with elements arranged at different angles of inclination, reproducing
289 a pattern similar to that of the roots of a tree). The system underpins the existing structures with two rows of
290 raked micro-piles:

- 291 - row “A”, formed by piles with a larger diameter (approximately 200 mm to 250 mm), whose
292 primary function is to absorb the bulk of the vertical load of the wall;
- 293 - row “B”, formed by piles of a smaller diameter (approximately 100 mm to 150 mm), whose
294 function is to complete the network and provide horizontal resistance to the soil pressure.

295 In addition, the above network, a screen of piles had to be built along the toe of the quay wall, to avoid
296 scouring. Moreover, in order to install a new crane rail, a row of raked micro-piles was built on the landside,
297 at a certain distance from the sea line. This structure was also anchored to upper portion of the quay wall to
298 improve its resistance to horizontal forces (i.e. mooring action on the bitts).

299 The solution was complex to plan and expensive to carry out, but considering that the quay has functioned
300 properly up to the present, there be no doubting its sturdiness and durability.

301

302 *5.4 The Port of Ancona – Quays nos. 21 and 22*

303 The Port of Ancona is located in a natural gulf along the Adriatic (east) coast of Italy. Archaeological
304 findings from the Mycenaean Era have been recovered in the area, demonstrating that there were commercial
305 trades with Greece as early as the 13th century BC. Later, the Dorians built the first docks and founded the
306 city named Ankòn (which means “elbow” in Greek), in reference to the profile of the shoreline. During
307 Roman period, under the Emperor Trajan, in the 2nd century AD, the port was expanded extensively. To
308 celebrate these works, the Roman Senate had a triumphal arch built, giving the port what still stands today as
309 its primary monument. In the 9th century, both the city and the port were almost destroyed by multiple
310 attacks by the Saracens. After these assaults, the harbour was fortified with stronger walls. Between the 13th
311 and the 14th centuries, Ancona became one of the most important harbours in the Adriatic Sea, second only
312 to Venice, which succeeded in stifling Ancona’s independence by ensuring that it remained under the control
313 of the Papal States. This period of peace did not last for long, as Ancona was a major centre of revolutionary
314 activity during the Italian Wars of Independence, and later, during World War II, the target of severe
315 bombing that destroyed several neighbourhoods and most of the port facilities.

316 Quays nos. 21 and 22 were part of a seaward expansion of the port undertaken during the 1930’s and 40’s
317 along the south breakwater. Later, in the 1980’s, the development of the port proceeded to the south, with the
318 construction of quays nos. 23-24 and 25.

319 Quays nos. 21 and 22 were built of concrete blocks, for a seabed depth of 8 m. For decades, they were used
320 mainly for the handling and storage of cereals in silos, by means of cranes operating on rails. Recently, a
321 portion of the silos was dismantled, with the quays converted to multipurpose uses employing mobile cranes.
322 In the course of their existence, the quays have undergone a number of reinforcement efforts, including the
323 two main initiatives described in what follows.

324 *5.4.1 Quay no. 21*

325 Quay no. 21 consists of a gravity quay wall built from 4 overlapping concrete blocks. The base of the wall
326 sits at a depth of 8.50 m, and the deck is located 1.90 m above sea level. Behind the blocks there is a rock
327 mound, and a sand refilling was also carried out. In 1970s, the depth of the seabed had to be increased to
328 10.5 m to upgrade the quay, and so plans were drawn up for the project.

329 Geotechnical surveying showed that the refill consisted of dredged material (mainly fine sand and silt), while
330 underneath the original seabed, below a layer of soft sandy silt, a thin stratum of sand was encountered,
331 followed by a firm bedrock of over-consolidated marly clay.

332 The structural solution adopted called for a new structure to be built in front of the existing wall.
333 Specifically, sheet pilings consisting of octagonal precast concrete columns (14 m in length, with a total
334 cross-section of 500 x 500 mm) were installed side-by-side in front of the blocks. Given the presence of the
335 over-consolidated clay deposit, the precast columns were positioned following preliminary boring of the soil,
336 with the column toes joined to the soil with concrete. The sheet pilings was then anchored, using horizontal
337 steel rods placed at 3 m intervals at the heads of the pilings, to a deadman consisting of a concrete block with
338 dimensions of 2.1x2.0x1.2 m (WxLxH) located at a distance of 15 m from the seaside. [Figure 7](#) shows the
339 cross-section of the quay following the upgrading work.

340 No structural use was made of the old facility, with the new work designed to be built atop the earlier
341 structures. Having been in place for 40 years now, recent surveying showed the sheet piling to be in good
342 condition, while the steel bars have been affected by a small amount of corrosive decay. It should also be
343 pointed out that the bars were given no protection (i.e. coating).

344 The solution adopted for Quay no. 21 it is very popular today, thanks to the widespread use of steel sheet
345 piling, though careful consideration should always be given to the intensity of the actions at the level of the
346 bases of the old blocks.

347 *5.4.2 Quay no. 22*

348 Quay no. 22 is a gravity quay wall formed by 4 overlapping concrete blocks. The structural section is very
349 similar to Quay no. 21, though the fact that the construction is older than the adjoining Quay means that the
350 dimensions of the blocks may differ. This quay has been used for decades without significant work being
351 done, except for restoration of the toe due to problems of scouring and renovation of the paving. The quay
352 was used for cereal-handling operations for a long time, and then, following removal of its silos, for
353 multipurpose operations.

354 In 2014 the quay was repurposed for container handling using new mobile cranes. After few months of
355 operations, the pavement began to show surface depressions and misalignment of the quay shoreline was

356 evident. The damages appeared so serious that the use of the quay was prohibited in the summer of the same
357 year. A multi-beam scan of the vertical wall proved extremely useful, with the details of this survey showing
358 the position of each block, together with its misalignment.

359 In light of the importance of Quay no. 22 to traffic at the port, the Port Authority financed a project of
360 upgrading. No technical documentation on the original design was available, so a survey of the soil and the
361 structures was planned. The results indicated that the base of the wall sat at -9.40/-9.50 m, while the deck
362 was positioned at +1.70 m above sea level. Geotechnical investigation allowed to identify the typical ground
363 stratigraphy. A borehole in the apron indicated that after the pavement, a backfill constituted of mainly a
364 fine grained soil was found up to the original seabed, at about 8.0 m below the sea level. Then, a layer of
365 3.0 m of sandy silt is encountered, followed by a thick layer of dense sand. At 19.0 m below the sea level a
366 thin layer of gravel indicated the passage to the bedrock, constituted by over-consolidated clay (Scarpelli et
367 al., 2003). In-situ and laboratory tests allowed to define the main geotechnical properties of the encountered
368 layers in terms of soil unit weight (γ), effective cohesion (c'), effective friction angle (φ') and operational
369 Young modulus (E'). For backfill: $\gamma = 17.5 \text{ kN/m}^3$, $\varphi' = 24^\circ$, $E' = 2 \text{ MPa}$; for sandy silt: $\gamma = 18 \text{ kN/m}^3$, $\varphi' =$
370 26° , $E' = 10 \text{ MPa}$; for dense sand: $\gamma = 18.5 \text{ kN/m}^3$, $\varphi' = 39^\circ$, $E' = 40 \text{ MPa}$; for over-consolidated clay:
371 $\gamma = 20 \text{ kN/m}^3$, $c' = 30\text{-}50 \text{ kPa}$, $\varphi' = 26^\circ$, $E' = 70\text{-}100 \text{ MPa}$.

372 Given the weaknesses of the existing structures, the elevated requirements of the Port Authority (i.e. 60 kPa
373 of over loads, the use of heavy mobile cranes, seabed down to a depth of 12.50 m) and the poor geotechnical
374 properties of the filling soil, it was decided to abandon the existing structures and build a new quay. Figure 8
375 shows the cross-section of the quay, following the renovation work.

376 The new quay is made of a concrete slab 1.0 m thick placed on a foundation of 4 rows of piles. The piles are
377 large-bored piles, 1.2 m in diameter, extending into the ground to -25 m below sea level. The seaward
378 alignment was carried out with a steel sheet piling wall consisting of tubular piling at a diameter of 914 mm
379 and a thickness of 20 mm, combined with a Z section (AZ12-770). With this solution, the new wall on the
380 seaside is able not only to serve as the foundation for the slab, but to balance the soil pressure as well. Both
381 the bored piles and the tubular steel piles extend down to the firm over-consolidated clay. The bored piles are
382 placed in an array of 6.0 m x 4.0 m, so that the distance is sufficient to cross the old blocks. Every 4.0 m,
383 there is also an inclined ground anchor 36 m in length, reinforced with steel rods 63.5 mm in diameter, in

384 order to provide the new structure with a horizontal restraint, especially necessary in the event of an
385 earthquake.

386 This solution, which entails a major effort, was adopted in consideration of its reliability under a number of
387 different aspects, and specifically:

- 388 - the high safe level of the new quay in terms of the use of mobile cranes;
- 389 - the long life of the paving, without upgrading of the filling materials;
- 390 - the use of widely known solutions, such as the bored piles and steel sheet piles, with a low risk of
391 unexpected problems during construction;
- 392 - the ductile response of the structure against seismic actions.

393 *5.5 The Port of Ravenna - San Vitale quay*

394 The Port of Ravenna is located along a channel on the Adriatic coast of Italy. By virtue of its strategic
395 geographic position, the Port of Ravenna is Italy's leading port in terms of trade with the markets of the
396 Eastern Mediterranean and the Black Sea (almost 40% of the national total, excluding coal and oil products),
397 also playing an important role with respect to trade with the markets of the Middle and Far East.

398 The port was created after World War II, when a large petrochemical complex was constructed along an old
399 channel. From the 1970's on, the port expanded its commercial operations to include the handling of grain,
400 fertilizers and mineral ores. After the year 2000, there was growth in the container handling and passenger
401 traffic as well.

402 Recently, a major renovation effort was planned to deepen the entire channel from 10 m down to
403 approximately 12.50 m, and as far as 14.50 m below sea level in front of some of the quay walls.

404 Focusing on the works already implemented, the solution employed to upgrade the facility known as the San
405 Vitale Quay to a seabed depth of 12 m is illustrated.

406 Built between 1964 and 1971, the old quay consists of a reinforced concrete diaphragm with a thickness of
407 0.6 m, extending down to -19.66 m from sea level. The head of the diaphragm is restrained by a ribbed
408 concrete slab sitting on a foundation of raked piles that serve as a horizontal restraint on the wall. They are
409 Franki piles measuring 420 mm in diameter and 9.5 m in length, arrayed in two lines, respectively 8.5 m and

410 9.5 m distant from the seaside. The quay was designed to sustain a seabed depth of 9.40 m and a terrain load
411 of 40 kPa.

412 The subsoil of the site is typical of the Port of Ravenna, having originated from a recent geological evolution
413 of the Po Plain caused by eustatic movements of the sea. Three main layers were identified in the area: the
414 first, at 13.50 m below sea level, is characterized by a sand layer representing the most recent phase of the
415 still active holocene regression; from 13.50 m down to 26 m below sea level, a layer of soft silty clay, with
416 small lenses of sand and silt deposited in the marine environment during the extension of the holocene
417 transgression, can be found. Below this layer are dense, grey sandy silts and silty sands that form the
418 beginning of the continental sequence.

419 The geotechnical characterization was based on cone-penetration testing (CPT), flat dilatometer testing
420 (DMT) and laboratory tests on undisturbed samples of the clay deposit. Details on the geotechnical
421 characterization of the port area can be found in [Segato et al. \(2010\)](#). The sand layer presents a friction angle
422 of 32-34° and a Young secant modulus at an operative strain level that ranges from 10 to 20 MPa. The clay
423 layer presents an effective friction angle of 26-28°, a Young secant modulus at an operative strain level of 5-
424 7 MPa and an undrained cohesion of between 30 to 50 kPa, progressively increasing as the depth becomes
425 greater.

426 In 2011, an innovative upgrading project based on underwater anchors was carried out. Specifically, a new
427 horizontal tie rod was built at 8.0 m below sea level using an innovative onshore technology thanks to which
428 all the work was performed by remote control. The anchors are 18.00 m long, being made of 6 modules that
429 are each 3.00 m in length. The anchor is reinforced with hollow-section steel rod with an external diameter
430 of 51 mm and an internal diameter of 33 mm. These rods are also used as drilling tools for installation of the
431 anchor and injection pipe to form the foundation of the anchor. The foundation is created by injecting a
432 cement mixture through the two nozzles at a pressure of about 400 bar. In practice, an advancing jet grouting
433 anchor installed by a robotic device is used. Details can be found in [Sciacca et al. \(2012\)](#).

434 New anchors positioned with a span of 2 m were able to provide a tensile load of a 630 kN. With this work,
435 the seabed was deepened to 12 m below sea level, as shown in [Figure 9](#).

436 The quay was upgraded with work consisting of structural reinforcement alone, for the purpose of limiting
437 the increase in the bending momentum on the wall caused by dredging. Such an approach requires careful

438 attention, seeing that it adds concentrated forces to structures not designed to handle them, with a decrease in
439 overall safety stability that can prove hazardous in situations where the soils at depth are poor.

440 *5.6 The Port of Gioia Tauro – the Eastern Quay*

441 The Port of Gioia Tauro, located along the Tyrrhenian coast of the Calabria region, in southern Italy, is
442 Italy's largest transshipment terminal and one of the most important hubs of container traffic in the entire
443 Mediterranean basin. It has a channel configuration that runs parallel to the coast, along a north-south axis,
444 for a length of approximately 3 km and a minimum width of 200 m. It has more than 5 km of docks. The
445 main quay walls were built on the east side of the channel, where space for large aprons was available. The
446 maximum operative depth is 18 m along what is known as the "Deep-Water Quay" on the south side of the
447 port.

448 The construction of the Port of Gioia Tauro took place in the first half of the 1970's as part of a special
449 infrastructure project for southern Italy. The size and structural characteristics of the work were determined
450 on the basis of its original functional purpose of serving the industrial installations planned by the
451 Government for the creation of Italy's 5th Steelworks Centre in the Calabria region. In the early 80's, the
452 crisis of the steel industry put a stop to the project, but with the port already completely built. Its
453 geographical position along the Suez - Gibraltar median through the Mediterranean Sea favoured conversion
454 to the transshipment of cargo units and containers in general.

455 The walls of the eastern quay walls are T-shaped diaphragms that extend for approximately 3000 m,
456 separated into four sectors: A, B, C, D. The quay subject to the upgrading work was that of sector D. Each
457 panel of this quay wall extends from the pavement surface (+3.5 m above sea level) to a depth of 24.0 m
458 below sea level; it was excavated in the traditional manner, using grab suspended by cables to a crane, with
459 bentonite suspension employed to ensure the stability of the excavation. The cross-section of the T-shaped
460 panel is 3.00 m wide, running along the direction of the quay, and 2.50 m high. Both the flange and the web
461 are 0.80 m thick. A massive concrete beam measuring 4.75 m x 2.35 m (BxH) joint the panels together at the
462 top, housing the heads of the steel bar anchors that link the wall to an auxiliary anchoring structure of piles.
463 This structure was positioned 15 m from the sea line and held the rails for the original crane. The quay wall
464 was originally designed for a seabed of 13.5 m.

465 The soil stratigraphy, for the entire depth surveyed (40 m), is characterized by the presence of granular soils
466 from a deposit of Quaternary-age continental sediments. Below a manmade backfill 1–2 m thick, is an initial
467 stratum of coarse sand and gravel. This layer ranges from 12–13 m below sea level and appears to be in
468 dense condition. Below this layer, and down to the maximum surveyed depth, is a dense, silty coarse sandy
469 layer, plus a sequence of fine sandy layers consisting of more or less silty components.

470 The geotechnical characterization of the mainly incoherent layers was based on the results of standard
471 penetration testing (SPT) and flat dilatometer testing (DMT). The soil density ranged from 60% to 80% for
472 the entire depth. The friction angle of the sand and gravel layer is greater than 40°, decreasing to
473 approximately 36-38° for the silty sand. The elastic properties of the soil, as shown by the DMT results,
474 result in a constrained modulus (M) ranging from 30 MPa to 60 MPa, with higher figures at greater depths.

475 Two quay walls of sector D underwent two major upgrade projects. The first one, needed to improve the
476 restraint of the head of the wall and make possible the use of larger crane rails, was carried out between 1994
477 and 1996. The works included (Figure 10):

- 478 - a sturdy steel frame made from HEB320 beams, to connect the wall and the rear portions of the
479 piles in order to prevent differential horizontal displacements between the rails of the crane;
- 480 - new crane rails with a span of 20 m, resting on a foundation of piles with a diameter of 1000 mm, a
481 length of 25 m and an interval along the line of 6 m;
- 482 - pre-stressed ground anchors reinforced with 8 strands of 0.6'', 25 m of free length and 15 m of
483 foundation, inclined at 30° to the horizontal, fixed to the beam holding the new crane rails;

484 Between 2014 and 2016, major new works were carried out on a portion of sector D 650 m in length, in
485 order to increase the depth of the seabed to 17.40 m below sea level and install the large cranes for handling
486 containers, with their rails presenting a span of 30.48 m. These projects included (Figure 10):

- 487 - jet grouting treatment of the soil in front of the wall; the treatment selected was for a wall 1.5 m
488 thick, 5 m in length and 7 m in height, facing towards the seaside, with a distance of 3 m between
489 the walls;
- 490 - reinforcement of the diaphragm through thickening of the existing wall with a new concrete wall
491 1.1 m thick;

- 492 - a massive beam to hold the new landside rails, resting on a foundation of concrete rectangular
493 diaphragms placed every 6 m and measuring 1.20 m x 2.80 m (W x L), extending down to 14 m
494 below sea level;
- 495 - a concrete slab, 0.40 m thick, to replace the old steel frame between the retaining wall and the raked
496 piles;
- 497 - horizontal steel rods to join the structures behind the head of the wall.

498 The recent works were complex and expensive, but it should be noted that the performance of the original
499 quay wall was greatly improved. The works both enhanced the passive resistance of the soil and strengthened
500 the structures, especially the head restraints of the wall.

501

502 **5. CONCLUDING REMARKS**

503 In the paper, the most common solutions for upgrading efforts are described with reference to a number of
504 Italian case histories, with discussion of the relevant aspects of each example. Some of the general
505 considerations highlighted are indicated below.

506 The deepening of the seabed in front of the gravity walls is always hard. The typical project meant to obtain
507 a medium upgrade depends on being able to move the sea-line edge of the apron. If it cannot be moved, the
508 major work is needed to install underpinnings of micro-piles or carry out jet-grouting. See the cases of
509 Genoa, Messina and Naples. On the other hand, it is standard practice to cover existing gravity structures that
510 are to be abandoned with a new wall made of sheet piles, as in the case of Ancona. It should be noted that,
511 from an economic standpoint, the covering solution is often less expensive.

512 For the most part, sheet-pile walls can be easily improved, either to increase the depth of the seabed or raise
513 the level of the terrain loads. A structural intervention can prove sufficient for minor upgrading (as in the
514 case of Ravenna), while combined interventions on both structures and soil can considerably enhance the
515 performance of an existing quay (as in the case of Gioia Tauro).

516 At present, jet-grouting and deep-mixing techniques represent valid solutions for improving the performance
517 of existing quay walls. In any event, density and patterns of treatment should always be designed with care,

518 especially as regards the expected effect in terms of the stiffening of the treated soil mass. Moreover,
519 extensive control of the geometry of the treatment is also necessary.

520 Re-use of existing structures may be limited by the poor mechanical properties of materials. This aspect may
521 be of crucial importance, considering the stringent requirements of recent technical codes when it comes to
522 durability.

523 The assessment of the seismic performance of an existing port structure deserves much greater attention than
524 in the past. With the intensity of seismic actions derived from the recent national seismic mapping, no design
525 can be conceived without the use of ductility resources, both of structural components and of the soil

526 Finally, considering that existing quay walls are complex structural systems, the schemes implemented for
527 their analysis should be simple, but not simplistic; such schemes should be able to capture the essential
528 behaviour of the structure in order to conceive the best design for its upgrading.

529

530 **ACKNOWLEDGMENTS**

531 Some results of the paper have been obtained thanks to the Research project PRIN 2008 (2008
532 WHMLBX_003) and ReLUIS 2011-2013/2014/2015. Port Authorities are greatly acknowledged for the
533 provided data.

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593 **FIGURE CAPTIONS**

594 Figure 1. Evolution of vessels TEU capacity and corresponding draught (Data from Hacegaba, 2014)

595

596 Figure 2. Classification of quay walls

597

598 Figure 3. Map of Italy with the location of the considered Port

599

600 Figure 4. San Giorgio Pier (Port of Genoa): cross-section of the quay and representation of the renovation
601 works

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603 Figure 5. Peloro quay (Porto of Messina): cross-section of the quay and representation of the strengthening
604 works

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606 Figure 6. Flavio Gioia quay (Port of Naples): cross-section of the quay and representation of the upgrading
607 works

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609 Figure 7. Quay wall n.21 (Port of Ancona): cross-section of the quay and representation of the upgrading
610 works

611

612 Figure 8. Quay wall n.22 (Port of Ancona): cross-section of the quay and representation of the upgrading
613 works

614

615 Figure 9. San Vitale quay (Port of Ravenna): cross-section of the quay and representation of the upgrading
616 works

617

618 Figure 10. Eastern quay – sector D (port of Gioia Tauro): cross section of the original quay and
619 representation of the renovation works carried out in 1994-1996 (left) and 2014-2016 (right)



















