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## RENOVATION OF QUAY WALLS TO MEET MORE DEMANDING REQUIREMENTS: ITALIAN EXPERIENCES

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#### ABSTRACT

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

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

#### 29 1. INTRODUCTION

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

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

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

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

The upgrading of a quay wall is a challenging topic for port engineers, requiring consideration of a large number of factors, including the deepening of the seabed, increased terrain loads, the use of large cranes – 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 64

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sustain the full impact of all actions.

intensive upgrade, in which the existing structure is fully disregarded and the new structures have to

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

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

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

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

84

#### 85 2. CLASSIFICATION OF QUAY WALLS

According to Tsinker (1997) a berth (or dock) is a general term used to describe a marine structure for safe mooring of a ship, accommodating cargo-handling equipment, the loading or unloading of cargo or the boarding or disembarkation of passengers. Among the different types of docks, it is useful to distinguish 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:
- solid berth structures: a vertical front wall is constructed to resist both the horizontal load from the
  fill and the live load on the apron;
- open berth structures: a load-bearing slab on columns/piles covers the slope between seabed and
  apron.

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

The so-called "Danish quay wall", consisting of a sheet-pile wall retained by a platform set on inclined piles, may be included among solid-berth structures. Under this solution, the platform set on piles makes possible the transmission of overloads on the deck to a deep bearing soil stratum, decreasing the soil pressure on the wall. For this reason, such solutions are often referred to as sheet-pile walls with relieving platforms. This approach, generally very expensive, is becoming increasingly widespread, given the possibility of 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).

Point 1 regards the ageing of the works, points 2, 3 and 4 can be included under the topic of enhanced quay performance, and point 5 is related to the increased standards of safety that accompany ongoing societal 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". Limiting the investigation to solid-berth structures, and recognizing that this class of quay wall is essentially 155

- a retaining wall, three strategies of intervention to improve performance may be identified:
- strategy A: reduction of stress, especially horizontal soil pressure;

- strategy B: increase in strength resources in the passive zone;

- 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.

Strategy A aims to reduce soil pressures and includes interventions geared towards transferring the surface loads at a depth. Examples of this strategy include the relieving platform built behind the vertical wall and soil-improvement treatments, such as jet grouting or deep-mixing columns installed in the active volume of the wall. Stone-column treatments behind the wall can also be used to reduce the soil pressure exerted by overloads or mobile cranes on the deck. A different way to reduce active soil pressure is substitution of the first meters of soil beneath the deck with lightweight material (i.e. expanded clay aggregate). Strategy B focuses on increasing the strength resources in the passive zone. Such strategies can also be used for the foundations of the gravity retaining wall and the sheet-pile wall, but naturally they prove more effective with embedded walls in which passive soil resistance is directly involved in the equilibrium of the structure. Weighting of the soil at the toe with the addition rocks, or partially substituting soft soil with gravel, or treating soil volume with jet grouting by means of deep-mixing techniques to enhance strength and 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.

For sheet-pile walls, the typical approach is to strengthen the anchoring systems by adding new anchors or reinforcing the existing steel bars and retaining walls. Strengthening of the structural section of the main wall 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 sustain a seabed depth of approximately 11 m. Planned development of the area calls for the seabed in front 208 209 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 concrete blocks, meaning that it can only be employed when the type of soil involved makes injection easy(i.e. sand).

#### 223 5.2 Port of Messina – Peloro Quay

The Port of Messina serves the city of Messina, Sicily, in southern Italy. The port sits on the western shore of 224 225 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).

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

Peloro quay consists of a precast concrete caisson 13 m high and 6 m long, with a width that ranges from 3.6 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 rear, to connect the structure with the subsoil. A massive concrete beam, 2.5 m in height, was cast on-site on the heads of the caisson. Figure 5 shows a schematic cross section of the Peloro quay, with the reinforcement works highlighted.

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

From a geotechnical perspective, the foundations of the structures were found in the thick gravel and sand 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 $\gamma = 20-21$ kN/m <sup>3</sup> and effective friction angle $\varphi' = 37^{\circ}-40^{\circ}$ . 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;

- a pair of micro-piles, inclined at 7° from the vertical, positioned at a distance of approximately 10
   m from the caissons, with spacing of 1 m spaced along the line and reinforcement in the form of a
   steel pipe with a diameter of 139.7 mm and a thickness of 10.0 mm;
- jet-grouting treatment of the backfill, with columns 800 mm in diameter and 6 m in length, arrayed
  in a quincunx pattern with spacing of 2.15 m;
- a concrete slab 500-600 mm thick, to create a new deck able to join the caissons and the micro piles, set on a foundation of jet-grouting columns.

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

269 5.3 Port of Naples – The Flavio Gioia Quay

The Port of Naples is one of the Italy's largest seaports. Located along the Tyrrhenian coast, in southern Italy, its founding dates back to the period of Greek colonization, in the 9<sup>th</sup> century BC. During the 18th century AD, under the Bourbon dynasty, the port was established as one of the best -equipped and strongest in Europe. Indeed, in the September 27, 1818, it was the site of the launching of the first steamship in the Mediterranean. After the unification of Italy, in 1861, the Port of Naples entered a period of decline. After the First World War, the port experienced a new period of growth, gaining a large number of new infrastructures, with the new operational quay expanding to the east. The wall of the quay named for Flavio Gioia (the legendary inventor of the compass) was built during this period. A new structure able to sustain a seabed depth of 11 m, it was made from a gravity concrete–block assembly whose cross-section is shown in Figure 6.

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

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

# row "A", formed by piles with a larger diameter (approximately 200 mm to 250 mm), whose primary function is to absorb the bulk of the vertical load of the wall;

row "B", formed by piles of a smaller diameter (approximately 100 mm to 150 mm), whose
 function is to complete the network and provide horizontal resistance to the soil pressure.

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

The solution was complex to plan and expensive to carry out, but considering that the quay has functioned 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 trades with Greece as early as the 13th century BC. Later, the Dorians built the first docks and founded the 305 city named Ankon (which means "elbow" in Greek), in reference to the profile of the shoreline. During 306 Roman period, under the Emperor Trajan, in the 2<sup>nd</sup> century AD, the port was expanded extensively. To 307 308 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 9<sup>th</sup> century, both the city and the port were almost destroyed by multiple attacks by the Saracens. After these assaults, the harbour was fortified with stronger walls. Between the 13th 310 311 and the 14<sup>th</sup> 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 activity during the Italian Wars of Independence, and later, during World War II, the target of severe 314 315 bombing that destroyed several neighbourhoods and most of the port facilities.

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

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

324 5.4.1 Quay no. 21

Quay no. 21 consists of a gravity quay wall built from 4 overlapping concrete blocks. The base of the wall 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 mound, and a sand refilling was also carried out. In 1970s, the depth of the seabed had to be increased to 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 steel rods placed at 3 m intervals at the heads of the pilings, to a deadman consisting of a concrete block with 337 338 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.

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

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

347 5.4.2 Quay no. 22

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

In 2014 the quay was repurposed for container handling using new mobile cranes. After few months of operations, the pavement began to show surface depressions and misalignment of the quay shoreline was evident. The damages appeared so serious that the use of the quay was prohibited in the summer of the same year. A multi-beam scan of the vertical wall proved extremely useful, with the details of this survey showing 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 upgrading. No technical documentation on the original design was available, so a survey of the soil and the 360 361 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 ( $\gamma$ ), effective cohesion (c'), effective friction angle ( $\varphi'$ ) and operational 369 26°, E' = 10 MPa; for dense sand:  $\gamma = 18.5$  kN/m<sup>3</sup>,  $\varphi' = 39^{\circ}$ , E' = 40 MPa; for over-consolidated clay: 370 371  $\gamma = 20 \text{ kN/m}^3$ , c' = 30-50 kPa,  $\phi' = 26^\circ$ , E' = 70-100 MPa.

Given the weaknesses of the existing structures, the elevated requirements of the Port Authority (i.e. 60 kPa of over loads, the use of heavy mobile cranes, seabed down to a depth of 12.50 m) and the poor geotechnical properties of the filling soil, it was decided to abandon the existing structures and build a new quay. Figure 8 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 large-bored piles, 1.2 m in diameter, extending into the ground to -25 m below sea level. The seaward 377 378 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:

- the high safe level of the new quay in terms of the use of mobile cranes;

- the long life of the paving, without upgrading of the filling materials;

- the use of widely known solutions, such as the bored piles and steel sheet piles, with a low risk of
   unexpected problems during construction;
- 392 the ductile response of the structure against seismic actions.

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

The Port of Ravenna is located along a channel on the Adriatic coast of Italy. By virtue of its strategic geographic position, the Port of Ravenna is Italy's leading port in terms of trade with the markets of the Eastern Mediterranean and the Black Sea (almost 40% of the national total, excluding coal and oil products),

also playing an important role with respect to trade with the markets of the Middle and Far East.

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

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

Built between 1964 and 1971, the old quay consists of a reinforced concrete diaphragm with a thickness of 0.6 m, extending down to -19.66 m from sea level. The head of the diaphragm is restrained by a ribbed concrete slab sitting on a foundation of raked piles that serve as a horizontal restraint on the wall. They are Franki piles measuring 420 mm in diameter and 9.5 m in length, arrayed in two lines, respectively 8.5 m and 9.5 m distant from the seaside. The quay was designed to sustain a seabed depth of 9.40 m and a terrain loadof 40 kPa.

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

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

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

attention, seeing that it adds concentrated forces to structures not designed to handle them, with a decrease inoverall 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

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

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

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

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

Two quay walls of sector D underwent two major upgrade projects. The first one, needed to improve the restraint of the head of the wall and make possible the use of larger crane rails, was carried out between 1994 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;

Between 2014 and 2016, major new works were carried out on a portion of sector D 650 m in length, in order to increase the depth of the seabed to 17.40 m below sea level and install the large cranes for handling 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.

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

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

For the most part, sheet-pile walls can be easily improved, either to increase the depth of the seabed or raise the level of the terrain loads. A structural intervention can prove sufficient for minor upgrading (as in the case of Ravenna), while combined interventions on both structures and soil can considerably enhance the 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, especially as regards the expected effect in terms of the stiffening of the treated soil mass. Moreover,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.

The assessment of the seismic performance of an existing port structure deserves much greater attention than in the past. With the intensity of seismic actions derived from the recent national seismic mapping, no design can be conceived without the use of ductility resources, both of structural components and of the soil Finally, considering that existing quay walls are complex structural systems, the schemes implemented for 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

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