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Safety appraisal and rehabilitation of a quay wall

Évaluation de sécurité et remise en état d'un mur de quai

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ABSTRACT
The case-history of a quay wall which went on the verge of collapse and was subsequently stabilised is reported in the paper. The main instability cause was the deepening of sea floor in front of the wall. Stabilising measures were selected taking into account the extreme sensitivity of the structure even to modest mechanical actions such those induced by construction equipment. They were implemented in successive stages specifically designed for avoiding critical stability situations. Frequent displacement measurements during work execution showed temporary marked increases of the rate of displacement. The stabilisation works were successfully completed and the quay was brought back into operation.

RÉSUMÉ
Dans cet article est rapporté le cas d'étude d'un mur de quai qui a été au bord de l'effondrement, et a été successivement stabilisé. La cause principale d'instabilité était l'approfondissement du fond sous-marin devant le mur. Les mesures stabilisantes ont été choisies tenant compte de la sensibilité extrême de la structure même aux actions mécaniques modestes telles que les vibrations induites des opérations de construction; elles ont été effectuées en étapes successives, spécifiquement pensées pour éviter des situations critiques de stabilité. Les mesures fréquentes de déplacement pendant l'exécution de travail ont montré des augmentations marquées provisoires de la vitesse des déplacements. Les travaux de stabilisation ont été terminés avec succès et le quai a été remis en service.

1 INTRODUCTION

The appraisal of safety conditions of existing structures requires, in principle, the knowledge of the present features and geotechnical characteristics of the ground-structure system, and of its stress and deformational history related to changes of loads and actions, dissipation of excess pore water pressures, boundary conditions, ageing and deterioration of materials.

However, many factors, such as the loss of design documents and the lack of records of observations on actual behaviour, concur in hindering this knowledge. As a matter of fact, it is not infrequent that the as-built state of even relatively recent constructions is not known, that relevant information concerning foundation soils as well as design hypotheses have sunk into oblivion.

It may well happen that the soil-structure system comes close to failure as a consequence of changes in use and of modifications of geometric features and boundary conditions. These problems are fairly well exemplified by the case-history of the Colapesce Quay Wall of Messina Harbour.

The features of this quay-wall, the appraisal of its stability conditions, the selection of corrective measures and their staged implementation, assisted by frequent surveys of movements, are discussed and reported in the paper.

2 CHARACTERISTICS OF THE SOIL-QUAY WALL SYSTEM

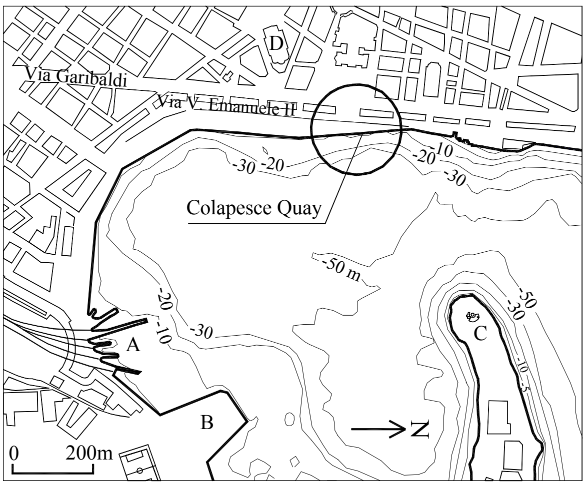
Colapesce quay was built about fifty years ago within the "Falcate – i.e. sickle-shaped – zone" of Messina Harbour (Fig.1). The stretch of quay wall referred to in this paper is 64.20m long and runs in the near vicinity of Vittorio Emanuele II street (Fig. 2). The minimum distance from existing buildings is 21m. A schematic cross section is shown in Fig. 3.

The wall is formed by 13m high reinforced concrete caissons filled with lean concrete. Each caisson is 6m long; the width varies from 6m a the base to 3.60m at the crest.

The caissons are joined at the top by a hollow reinforced concrete "beam", in which a service adit is housed.

The crest elevation of the wall is 2.13 m above mean sea level. The depth of the sea floor in front of the wall was originally 10m below m. s. l., while it was found at 13m below m. s. l. in 2000, when investigations were carried out.

The foundation soils have been explored through many boreholes and SPT tests; they mainly consist of dense, uncemented saturated gravelly sands with rare lenses of gravels and occasional small boulders.



A Ferry-boat terminal; B Norimberga warf;
C Madonna della lettera column; D Duomo.

Fig. 1. Messina Harbour. Plan of the "Falcate zone" and position of Colapesce Quay.

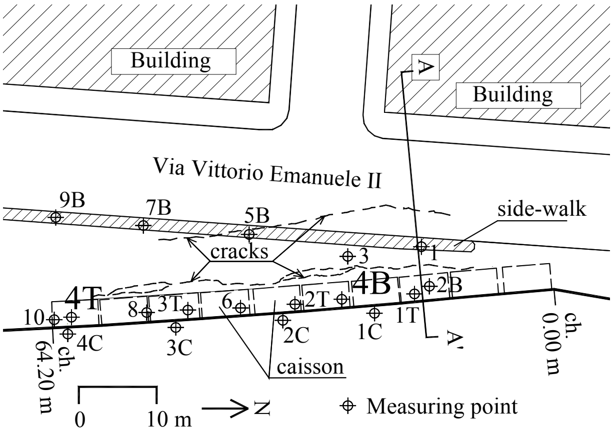


Fig. 2. Schematic plan of Colapesce Quay and location of measuring points for monitoring movements of caissons.

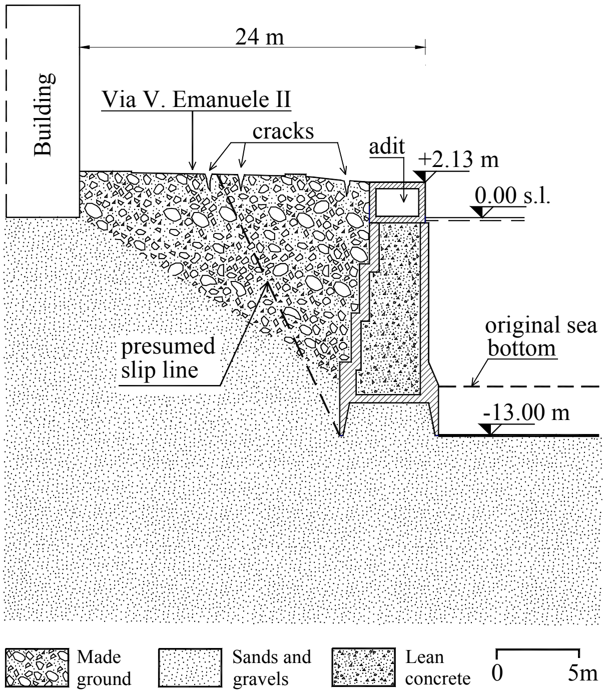


Fig. 3. Schematic cross section A-A′ of the quay wall, foundation soils and backfill material and backfill surface.

Geotechnical properties are summarized below:

specific weight $\gamma_s = 27$ kN/m^3;

saturated unit weight $\gamma_{sat} = 20\text{-}21$ kN/m^3;

angle of shear strength (peak) $\varphi' = 36\text{-}40°$.

The backfill is heterogeneous but prevailingly formed by masonry rubble and debris and occasional silty lenses; the unit weight of backfill ranges from 17 to 21 kN/m^3 with a mean value of 19 kN/m^3; cohesion intercept can be considered nil; the operative value of the angle of shearing strength is 38° and has been derived from a backanalysis of the quay wall under the hypothesis that the backfill attained the active state, congruently with the tilt undergone by the wall, which is leaning toward East.

The maximum horizontal projection of the upper edge of the caisson out of the perpendicular was 200 mm, corresponding to an outward rotation of arctg (200/1500)=0.76°, which results in fairly good agreement with the criteria for the attainment of active state (Terzaghi, 1934 and 1936; Clough and Duncan, 1991).

Some well developed tension cracks, almost parallel to the wall edge, were detected on the surface of the backfill behind the quay wall (Fig. 2).

The cracks showed vertical offset of a few centimeters and were approximately located within the active wedge; depressions up to 150 mm deep were also noted on the surface of backfill.

Neighbouring buildings did not exhibit any sign of distress.

The elevation of the groundwater table at about one hundred meters from the quay wall, on the landward side, is about 20-30 cm above m. s. l. due to obstruction of sewers' outlets.

3 RESULTS OF CONTROL MEASUREMENTS AND STABILITY APPRAISAL

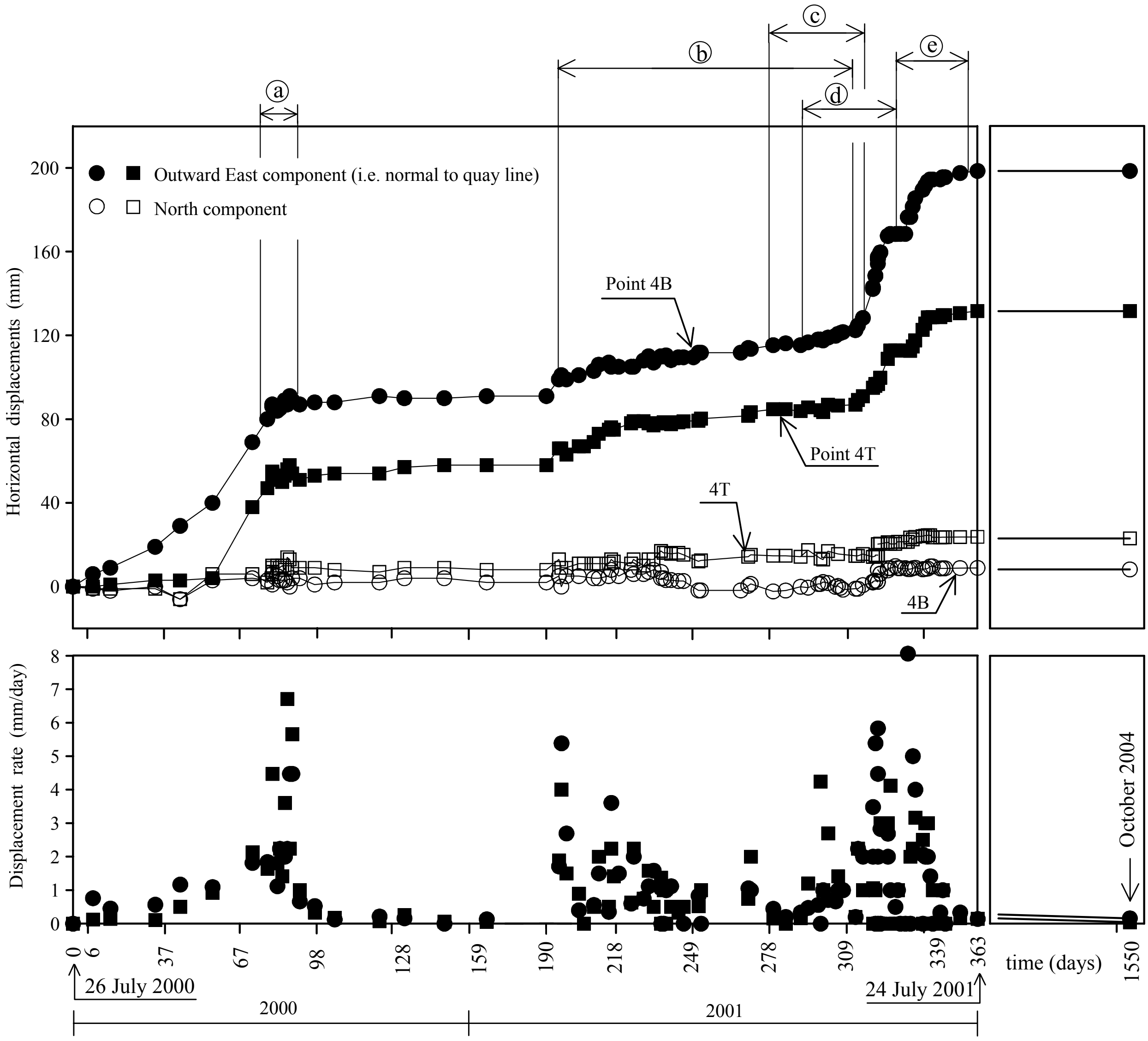
When it was realized that the quay wall tilted towards the sea and that the cracks on the surface of the backfill might have been indicative of the formation of a failure mechanism, the quay was put under control by monitoring its movements, and particularly the horizontal displacements, (Fig. 2), movements of the backfill surface as well as of buildings were also monitored. Operation of the quay was interdicted. A careful subaqueous inspection pointed out the existence of several cavities at the base of caissons. Moreover, it was readily apparent that the sea floor in the vicinity of the caissons was deeper than expected as a consequence of scour and of dredging operations, which however have not been recorded. The trend of horizontal outward displacements (Fig. 4 and Table 1) pointed out that collapse by overturning might have been impending, even in the absence of seismic actions.

Results of stability calculations based on limit equilibrium methods (Valore et al., 2004) confirmed this alarming conclusion derived from observational data.

Simulation of the process of deepening of the sea floor by means of the FEM Plaxis code (1998), also proved that the quay wall ought to be marginally stable even for erosion depths of the sea bottom lesser than the actual ones.

Table 1 – Intensity and rate of outward horizontal displacements (normal to the quay line) in relation to the implementation of corrective measures. (For the meaning of symbols see Fig. 4; start of displacement measurement: 21 July 2000).

Corrective actions	Measuring point (cfr. Fig.2)	Horizontal displacement (mm)		Max rate of displacement (mm/day)
		initial	final	
Before initiation of works	4B	60	80	1.8
	4T	40	45	2.1
ⓐ	4B	80	92	4.5
	4T	45	52	6.7
after ⓐ	4B	92	98	0.2
	4T	52	60	0.1
ⓑ	4B	98	121	5.4
	4T	60	90	4.1
ⓒ	4B	115	130	2
	4T	85	95	4.1
ⓓ	4B	113	170	5.9
	4T	86	112	4
ⓔ	4B	170	198	8
	4T	112	130	4.1
after ⓔ	4B	198	200	0.2
	4T	130	136	0.2



ⓐ Removal of upper 2m thick layer of backfill. ⓑ Construction of "micropile-trestles". ⓒ Installation and tensioning of temporary anchorages. ⓓ Partial filling up at caissons toe. ⓔ Construction of micropiles through caissons.

Fig. 4. Typical results of the survey of horizontal displacement of measuring points located on the crest of caissons in relation to stabilisation actions carried out.

4 SELECTION AND EFFECTIVENESS OF STABILISATION MEASURES

The choice of stabilisation actions in the case under discussion was considerably restricted due to serious concern for possible adverse effects on stability of moving the construction equipment necessary for carrying out the corrective measures themselves. A preliminary "first-aid" intervention was eventually deemed indispensable, and this consisted in the removal of the upper 2m thick layer of the backfill. This measure proved effective in slowing down the rate of horizontal displacement, as can be inferred from Fig. 4.

Subsequently, definitive stabilisation works were carried out according to a sequence aiming to reduce, as far as possible, the risk of overturning of the structure during the execution of the works. The corrective measures were implemented according to the following sequence (Fig. 5).

1 Construction of micropile "trestle" structure capped by a reinforced concrete beam, capable of withstanding horizontal loads. 2 Toe loading of the quay wall. 3 Temporary anchoring of the quay wall to the trestle structure. 4 Jet-grouting of the backfill. 5 Injection of cement grout in the cavities at the base of caissons. 6 Installation of micropiles through the quay wall down to foundation ground. 7 Construction of a reinforced concrete slab connecting the head of the quay wall to the "trestle structure", capable of transmitting tensile forces. 8 Placement of ballasted woven-non-woven protective mat at the toe of quay wall, against soil erosion. 9 Construction of a shallow drainage adit to avoid possible raising of groundwater table – as a consequence of the treatments of the ground (injections, jet-grouting) – which might adversely affect existing nearby buildings.

Micropiles were reinforced with steel tubes (outer diameter 139.7 mm, thickness 14.2 mm). Features of anchors were: total length 16.70-18.20 m; free length 13.00-13.50 m, ample enough for avoiding excessive overstressing as a consequence of anticipated outward movement of caissons; fixed length injected inside the caissons after placement of inflatable packer bags; two-strands tendon; steel bearing plates placed underwater on

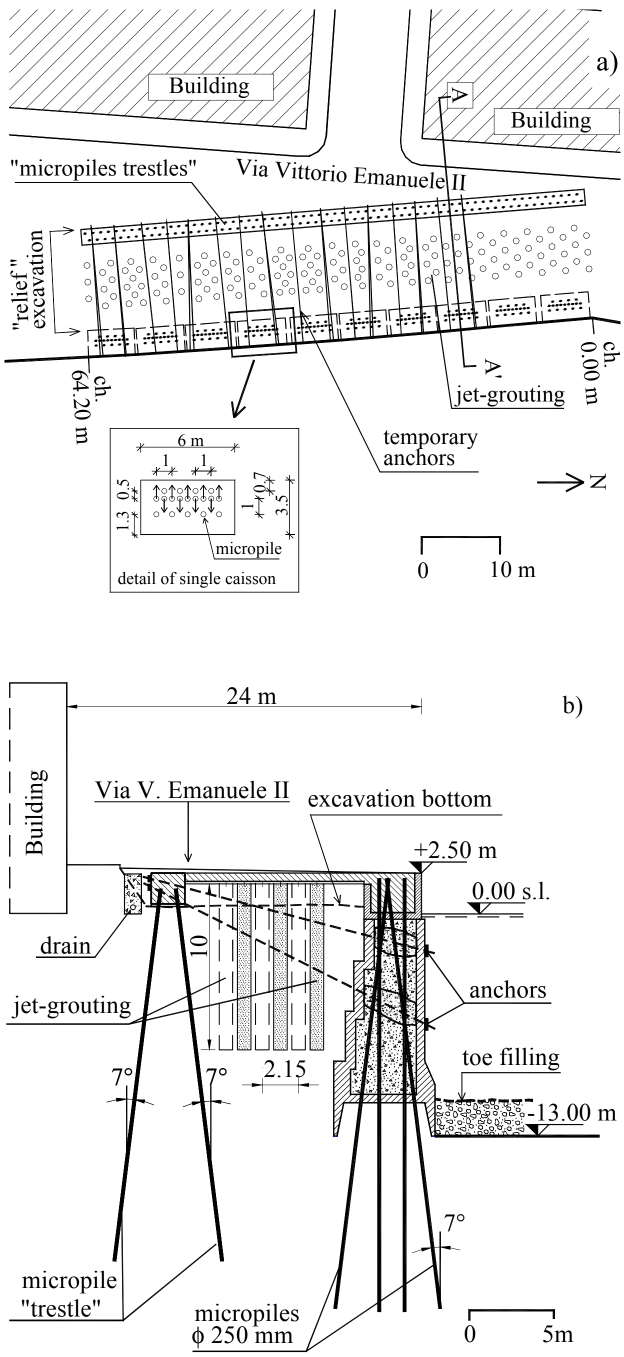


Fig. 5. Stabilisation measures. a) Planimetric layout; b) Vertical cross section A-A′.

the caisson outer wall and on the landward side of the trestle structure; initial stressing force 19.6 kN (2 metric tons).

The capability of a group of three micropiles capped by rigid reinforced concrete slab to sustain horizontal forces was preliminarly tested in situ (Valore et al., 2002). The horizontal load was 1180 kN for an horizontal displacement of 2.5mm (first loading phase); a limit horizontal force of about 1600 kN was obtained for a horizontal displacement of 10 mm.

Data plotted in Fig. 4 show that moving equipment near to the quay wall during installation of temporary anchors and the placement (from the crest of the wall) of filling material at the toe of the caissons caused resumption of horizontal movement, which, however, became almost imperceptible when the causative operation ceased. Movement was resumed again during the very initial phase of the installation of micropiles through caissons. One of the anchor was instrumented with a load cell; the tensile force evolved from 19.6 kN (2 t) up to 176.5 kN (18 t) during the execution of works. Movements of the wall slowed down and stopped after the completion of corrective works.

The stabilisation actions were fully successful, although not exempt from risks during their implementation as clearly pointed out by data in Table 1, from which the “reactiveness” of the quay wall to modest mechanical actions - usually taken as negligible – is evident.

5 CONCLUSIONS

Many structures are reputed, erroneously, safe simply because they do not exhibit signs of anomalous behaviour. In other cases, such as that of Colapesce quay wall, the significance of cracks and displacements is overlooked due to a lack of knowledge of the true actual state of the soil-structure system and of the changes it underwent from its construction, or merely because no one takes the duty of assessing the safety level during the lifetime of the structure, despite ageing, changes in use and in boundary conditions. Of course, original design hypotheses do not always hold true for ever.

Monitoring the movements of the structure can prove essential for the diagnosis of its safety condition. In the case of Colapesce quay wall only when results of displacement measurements became available was it fully realised that the structure was evolving toward collapse, and that stabilisation measures were urgently needed.

Finally, it must be stressed that corrective interventions must be scheduled and carried out taking into account possible adverse effects of constructive operations themselves, which may jeopardise the structure. Frequent measurements of displacements during work execution may greatly assist in adjusting the construction phases in order to avoid critical situations.

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