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Consolidation settlement of coastal areas of the Emilia-Romagna region from cone penetration tests

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ABSTRACT: This paper describes an attempt to develop and calibrate a simple tool to forecast the natural subsidence of coastal Holocene deposits. An empirical correlation has been calibrated between the penetration resistance measured by a static cone penetrometric tests and i) the normal compression line NCL of fine grained, coastal deposits ii) the current void ratio and iii) the void ratio on the NCL at the site effective stress. The comparison between the site void ratio and the normally consolidated void ratio can be used to roughly estimate if the soil is overconsolidated, normally consolidated or under-consolidated/structured and, in the latter case, if the fine layer is in the condition of further developing consolidation settlement to reach the self-weight equilibrium.

1 INTRODUCTION

The vulnerability of coastal areas to climate change and, in particular, to sea level rise, is a cause for alarm at an international level. The geological survey group of the Emilia-Romagna Region (SGSS), in Italy, has carried out a study to highlight the effect of on-shore subsidence on the potential sea transgression, and the action of subsidence has resulted decisive in some areas of the coast, where the altimetric altitude is close to zero. The origins and possible evolution of subsidence need to be evaluated to limit its impact on the risk of inland sea transgression. In this context, a study has been carried out to estimate the natural component of subsidence linked to the compaction of recent coastal deposits of fine grained soils. The research has been based on three main components: i) two near shore pilot sites, well characterized from a geotechnical point of view, where subsidence rate is monitored by means of assestimetric measures; ii) several site where both CPTUs and oedometric tests on fine grained samples were available, iii) a large database of CPTUs carried out in sites spread all along the Emilia-Romagna coast.

The results of CPTUs and oedometric tests on Holocene fine grained soils have been used to link the cone penetration resistance q_c to i) the compression index C_c; ii) the altitude e_1 of the 1-D compression line in the e-logσ'_v plane defined at $\sigma'_v = 1$ kPa; iii) the current void ratio e_c.

A tool has been calibrated which allows to derive from a q_c profile and for fine grained layers two relevant void ratio values: the current site void ratio e_c and the void ratio the soil would have at the site effective stress if normally consolidated e_{NC}. The comparison between these values roughly indicates if the soil is overconsolidated, normally consolidated or under-consolidated/structured and, in the latter case, allows to estimate the possible consolidation settlement the layer could still develop to reach the self-weight equilibrium.

The tool has been validated for the pilot sites and used to estimate the expectable natural subsidence of fine grained deposits at selected sites of the coastal areas where CPTUs were available.

2 GEOLOGICAL SETTING AND REFERENCE SITES

The study area belongs to the outer sector of the Pliocene-Quaternary Apennine foredeep (Ricci et al. 1986), progressively affected by recent phases of compressive deformation of the Apennine chain. The Quaternary succession is over 2000 m thick and records the gradual filling of the highly subsiding basin. The land lowering due to tectonics is still active and maximum rates have been estimated about 1 mm/y (Cuffaro et al. 2010). The most recent succession (Middle Pleistocene-Holocene) is

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characterized by the sedimentary cyclicity consisting of the metric alternation of sandy and highly compactable fine levels, induced by the glacial-eustatic fluctuations of the late Quaternary. The upper 30-40 metres of this succession, testify the transgressive-regressive Holocene cycle (Amorosi et al. 2003; Stefani and Vincenzi 2005,) characterized by paralic and marine deposits overlying the Pleistocenic alluvial plain in the lower portion and, in the central and upper portion, by a thick sedimentary wedge deposited by the deltaic and beach prograding systems.

From a lithological point of view, in the littoral sector, the shallowest succession is constituted by coastal and delta sands in the upper part and by thick prodelta and beach fine deposits in the lower part. The natural compaction of these recent fine deposits may be responsible for the observed subsidence (Teatini et al. 2011), that reaches maximum rates of 12 mm/year.

In the study area, sediment deposition during progradation took place through complex phases of feeding, switching and abandonment of the ancient Po delta branches; this has generated variable depositional history even for sediments that are very similar in appearance.

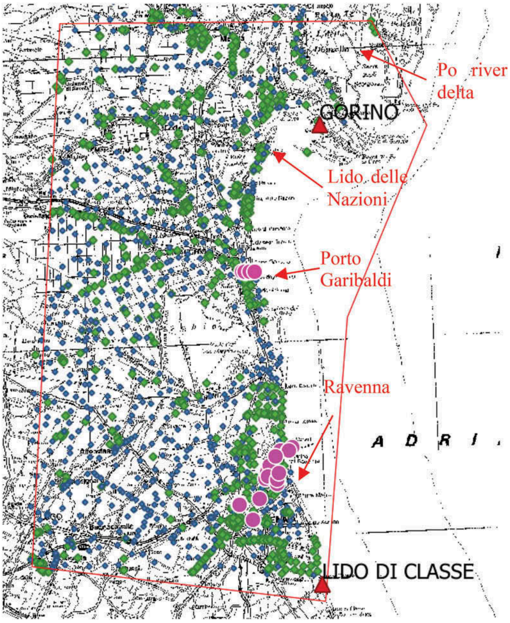

Figure 1. Location of pilot sites and available data: corings (green dots), CPTUs (blue dots) and selected tests (pink dots).

As part of the studies aimed at evaluating the natural subsidence of the superficial plio-quaternary deposits of the coastal areas, SGSS has selected two pilot sites evidenced in Figure 1 at the localities of Gorino (Ferrara Province) and Lido di Classe (Ravenna Province), where it is possible to exclude the occurrence of subsidence of anthropogenic origin. Both sites are characterized in the first 30 m of depth by Holocene deposits of clays, silts and sands. Gorino stratigraphy is representative of the coastal deposits originated by the Po river typical of the northern sector of the regional coasts; Lido di Classe soil profile is typical of the southern sector coastal deposits, originated by the activity of Apennine rivers.

Both sites were characterized by means of continuous core drilling and undisturbed sampling, CPTU and SCPTU tests, oedometric tests on undisturbed sample of fine soil. The boreholes were equipped with settlement gauges, anchored to the Pleistocene deposits deeper than 30 m and cemented to the hole, for monitoring the subsidence of the deposit over time. The analyzes carried out so far have shown in both sites a progressive lowering of about 1 mm/year.

Gorino site (q_c profiles in Figure 2) is characterized within the first 5-6 m of depth from the ground surface by a predominantly sandy layer with frequent alternations of finer soils, followed by a clayey silty stratum up to 27-29 m of depth. This layer, made of inorganic and medium to high plasticity fines, resulted mainly normally consolidated from oedometric tests and is followed by Pleistocene sandy deposits. The ground water table is in average 0.5 m deep.

At Lido di Classe, a superficial 8 - 9 m thick layer of clean sands is followed by a dense alternation of silty sands, sandy and clayey silts up to about 24 m of depth, then by silty clays. The fine grained layers, characterized by low plasticity, are slightly over consolidate from the ground surface to 9 m of depth, overconsolidated from 9 to 15 m of depth, normally consolidated at higher depths. The ground water table is 1.7 m deep.

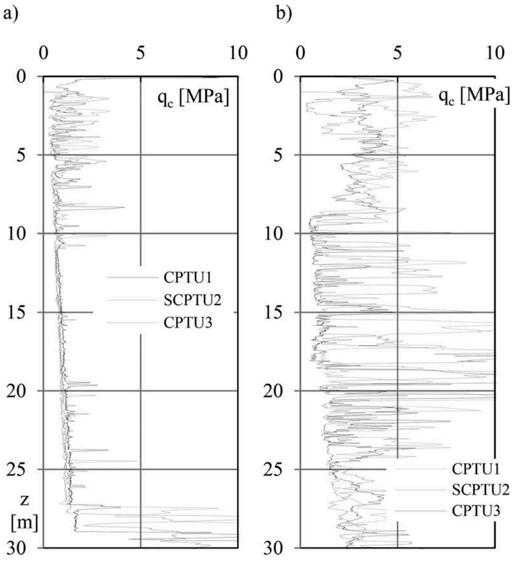

Figure 2. CPTSs at pilot sites, a) Gorino, b) Lido di Clsse.

In both sites, oedometric tests have been repeated also on reconstituted specimens. In some cases, the undisturbed oedometric curve lied above the intrinsic compression line (Burland 1990), indicating presence of structure, possibly due to flocculated deposition occurred in conditions of high sedimentation rates in the delta front and proximal prodelta environment. These results are consistent with the geological and depositional history of the sites.

In both sites, the void ratio at the depths of undisturbed sampling, computed as a function of the water content and specific gravity and assuming complete saturation, resulted in some cases higher than the void ratio derived from the oedometric curve at the specific vertical stress, indicating still in progress consolidation phenomena, accordingly with the estensimetric measures, or presence of structure.

In addition to the 2 pilot sites, 5 extra sites were considered in this study, 2 located in the norther sector of the regional coast at the locality of Porto Garibaldi, 3 in the southern sector, in the area of the city of Ravenna (Figure 1), all characterized by similar geological origin and stratigraphy as the two pilot sites. For all the sites considered, CPTUs and oedometric tests on undisturbed samples were available. Figure 3 reports the grain size fractions and plastic index as a function of depth measured on the undisturbed samples overall analyzed.

3 EMPIRICAL CORRELATION

From each oedometric curve available, the compression index C_c (slope of the normal compression line in the e - logσ'_v plane) and the void ratio e_1 (altitude of the normal compression line at σ'_v = 1 kPa) have been derived. Figure 4 shows the C_c measures vs. depth; in Figure 5 e_1 is plotted versus C_c. A linear relation exists between C_c and e_1, which can be expressed as:

$$e_1 = 4 \cdot C_c + 0.3 \tag{1}$$

The site void ratio at the sampling depth has been derived as a function of the measured water content w and specific gravity G_s as:

$$e_c = w \cdot G_S / S \tag{2}$$

where the degree of saturation S has been assumed equal to 1.

From the CPTU carried out nearest to the borehole from which the undisturbed samples tested in oedometer came, an average q_c value was derived at the depth of sampling. Figures 6 and 7 show the compression index C_c and the site void ratio e_c plotted versus the average q_c normalized over the atmospheric pressure p_a. C_c is in the range 0.25 – 0.5 when q_c/p_a is between 5 and 15 and decreases as the normalized cone resistance increases, indicating a decrease of compressibility as the soil resistance increases.

Despite the significant dispersion in Figures 6 and 7, and acknowledging the rather low correlation coefficients, a power function and an exponential function have been drawn to try to link C_c and e_c to the normalized cone resistance:

$$C_c = 0.48 \cdot (q_c/p_a)^{-0.167} \tag{3}$$

$$e_c = 1.127 \cdot e^{-0.015 \cdot q_c/p_a} \tag{4}$$

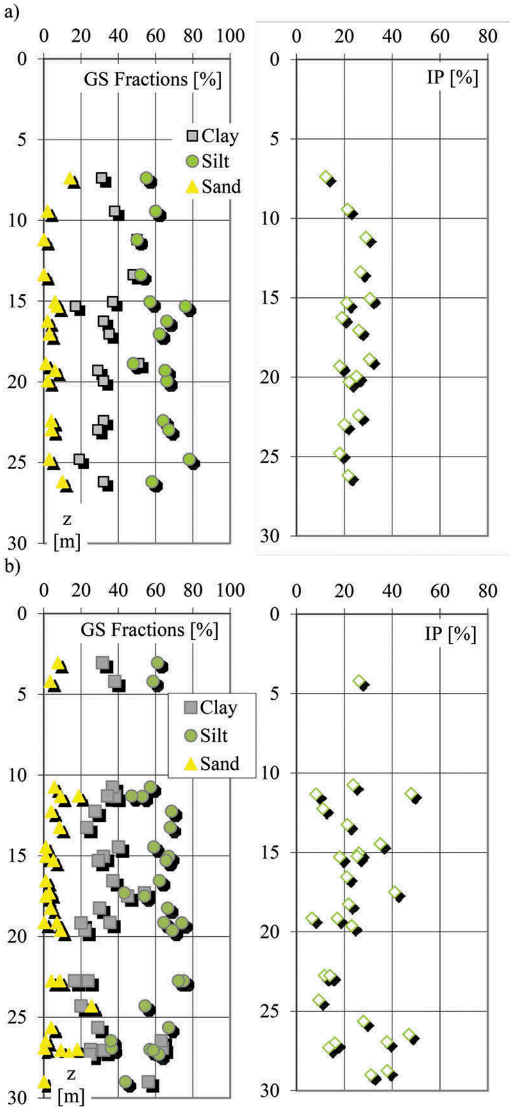

Figure 3. Grain size fraction and plastic index, a) Norther sector, b) Southern sector.

These tentative relations allow, given a generic q_c profile, to derive, for fine grain layers, C_c, e_c and e_1 according to eqs. 1, 3 and 4. The computed site void ratio e_c, compared with the normally consolidate void ratio e_{NC}, allows to establish if the layer is normally consolidated, overconsolidated or underconsolidated; e_{NC} can be computed at a certain depth, known e_1 and C_c, as:

$$e_{NC} = e_1 - C_c \cdot \log(\sigma'_v) \tag{5}$$

For the pilot sites, C_c and e_1 are measured quantities; e_c was computed via eq. 2 from w and Gs measured on undisturbed samples.

Figure 8 compares, for the site of Gorino:

- the profile of e_{NC_lab} computed via eq. 5 and using e_1 and C_c from laboratory measures;
- the site void ratio e_{c_lab} at sampling depth from eq. 2;
- the profile of e_{NC_CPT} computed via eq. 5 and using e_1 and C_c estimated from q_c via eqs. 3 and 1;
- the site void ratio e_{c_CPT} at sampling depth from eq.4.

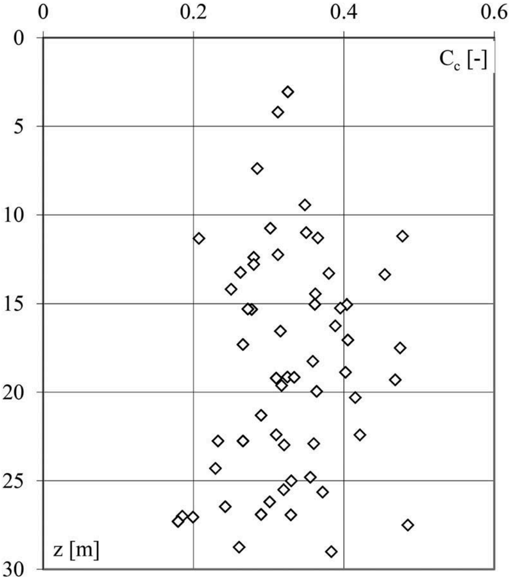

Figure 4. Compression index as a function of depth.

The discontinuities which characterise the e_{NC_lab} profile (black line) are due to change in C_c and e_1 derived from direct measures on undisturbed samples. On the other hand, the profile e_{NC_CPT} (green line) is more regular, as it mirrors the q_c profile. The comparison between e_{c_lab} value and the e_{NC_lab} profile shows that from 6 to 10 m the soil is slightly over-consolidated; between 10 and 14 m the ground is normally consolidated; at greater depths the current void ratio is greater than the normally consolidated value, indicating either that the ground on site is still subject to consolidation compression or that it is slightly structured. In the first case, subsidence settlement due to the one-dimensional compression of the layer present between 14 and 27 is of the order of 50 cm. This value is obtained as integral of the difference $\Delta e = e_{c\_lab} - e_{NC\_lab}$, at the depths where $e_{NC\_lab} > e_{c\_lab}$.

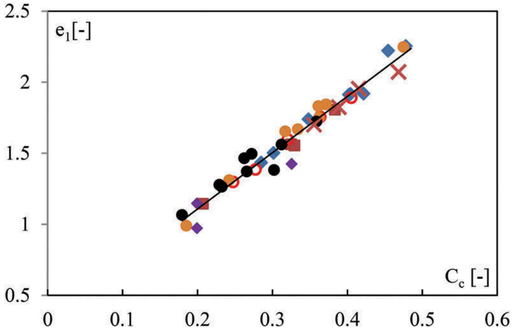

Figure 5. Altitude of the normal compression line e_1 vs. C_c.

Regarding to the profile e_{NC_CPT} (obtained via Eq. 4) it can be noted that although it differs from e_{NC_lab} profile, it is in relation to e_{c_CPT} similarly to the lab profiles. In this case, the possible consolidation settlement is of the order of 74 cm.

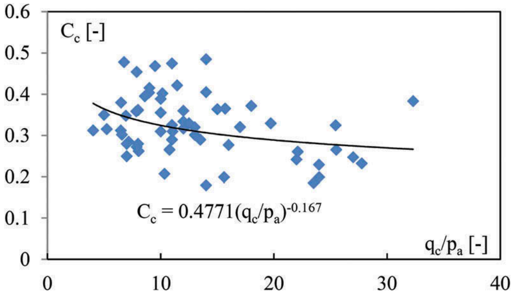

Figure 6. Compression index C_c as a function of q_c/p_a.

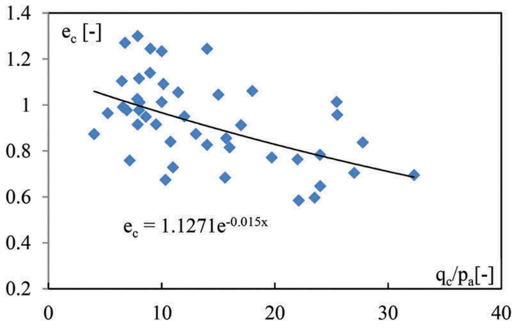

Figure 7. Site void ratio e_c as a function of q_c/p_a.

4 LARGE SCALE APPLICATION

The procedure described above was applied to CPTUs selected from the SGSS database and located in the two sectors of the regional coast evidenced in Figure 1 (blue dots). Figure 9 shows for one of the test sites (where a silty clay layer, with frequent sandy intercalations, is present from 14 m to 30 m of depth from the ground surface, topped by a sandy deposit), the measured tip resistance q_c, lateral friction f_s, interstitial overpressure u_2, the estimated hydrostatic profile u, the profiles of the normal consolidated void ratio e_{NC_CPT} and the current void ratio e_{c_CPT}. From the large scale application resulted that the settlements estimated for the norther sector are lower than those expected in the southern area (average value of 0.38 m in the Ferrara area and 0.58 m in the Ravenna area).

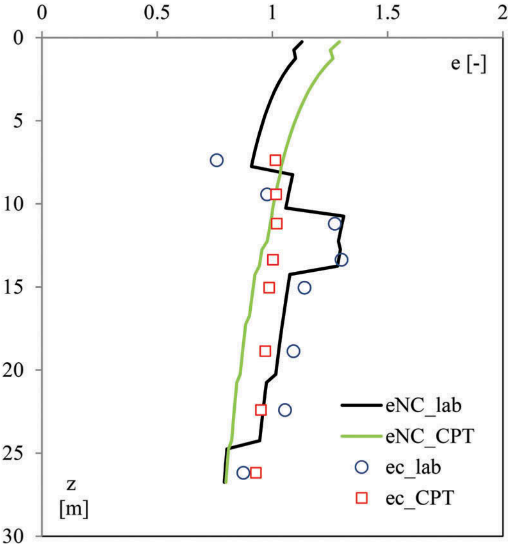

Figure 8. Gorino site: computed and measured void ratio.

Higher thickness of the layers of fine-grained soil returns higher estimated settlements. The local values of estimated consolidation settlement have been interpolated over the areas of interest to derive a map of expectable subsidence.

The function was tested to the CPTs in the northern coastal sector, between Casalborsetti and Lido di Volano. The potential settlement values for each point were interpolated with the inverse distance weighting method, obtaining the map shown in Figure 10. The spatial distribution and the range of settlements are consistent with the subsoil nature, characterized by a marked lithological heterogeneity. The lowest settlements are expected near the Reno river mouth and between Porto Garibaldi and Lido delle Nazioni where the delta and the coastal sandy deposits are thick. On the other hand, in the areas affected by the highest settlements, prodelta clays, lagoonal silts and marsh peat are prevailing.

The map provides important information to interpret the subsidence monitoring data and it also supports spatial planning, highlighting the areas most vulnerable to coastal risks, such as marine submersion due to land lowering.

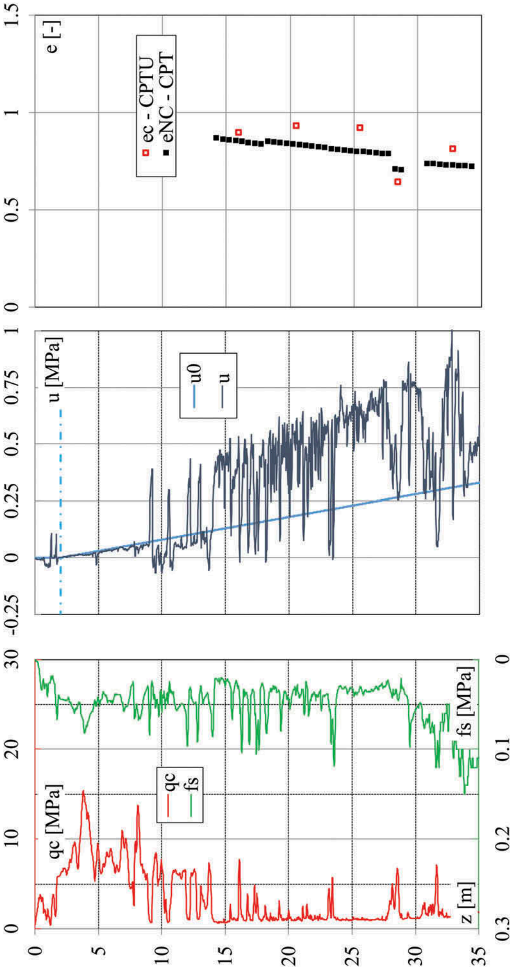

Figure 9. Application of the correlation to a CPTU.

5 CONCLUSION

The results of a significant number of CPTU and laboratory tests (particle size analyzes, Atterberg limits, oedometric tests) carried out in coastal sites characterized by the presence of recently deposited, fine-grained soil deposits, have been analyzed and interpreted to calibrate a semi-empirical correlation between the compressibility of fine grained soils and the results of static penetrometric tests.

The interpretation of all the available data allowed the elaboration of correlations between:

- the tip resistance q_c measured by a CPTU and the compression index C_c measured during the oedometric tests;
- the resistance q_c and the site void ratio e_c;
- the compression index C_c and the altitude e_1 of the normal compression line in the e-logσ'_v plane.

These correlations, even if characterized by significant dispersion, have been used to elaborate

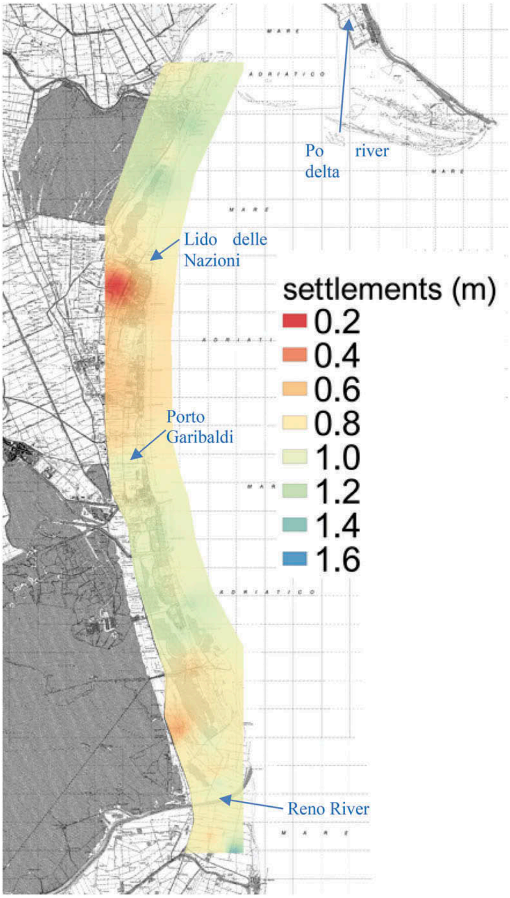

Figure 10. Map of expectable settlements in the coastal sector between Casalborsetti (RA) and Lido di Volano (FE).

a procedure that allows to evaluate, starting from the results of a CPTU, the site void ratio profile e_c of the fine-grained layers and the voids ratio profile that the fine soil would have if normally consolidated, e_{NC}. The comparison between the two profiles allows to establish if the fine soil layer is:

- overconsolidated ($e_c < e_{NC}$);
- normally consolidated ($e_c \approx e_{NC}$) or
- it has yet to reach the condition of equilibrium due to its own weight, or the soil has a structure or microcementation ($e_c > e_{NC}$); at present it is not possible to distinguish the two different conditions.

In the first two cases the layer is stable and no subsidence is expected in the absence of lithostatic load variations. In the third case, the difference between the current void index and the normal consolidated theoretical one allows to estimate any settlements that the deposit has yet to/could show due to consolidation or destructuring.

The procedure elaborated has been used to compute the possible subsidence settlement at selected sites along the Emilia-Romagna coast and to derive expected subsidence map, which provides important information to interpret the subsidence monitoring data and supports spatial planning, highlighting the areas most vulnerable to coastal risks, such as marine submersion due to land lowering.

It should be pointed out that

- the estimated settlements is probably an upper limit, as it's not possible to distinguish underconsolidation from structuring, and its course over time is not known;
- if the difference between the current site void ratio and the normal consolidated void ratio were due to cementation or the presence of a structure, in the absence of variation in the lithostatic conditions, the soil would be stable and would not show spontaneous subsidence;
- the calibrated correlations are based on a limited sample, albeit significant, of geotechnical data that must be integrated to allow for a refinement of the proposed equations;
- nevertheless, the database employed is the first attempt of systematical collection, analysis and interpretation of compressibility data in area strongly affected by subsidence of natural and anthropic origin;
- in the definition of the empirical correlations, only coastal sites located along the regional coast were taken into consideration, therefore the calibrated equations could only have local validity and should be used only in contexts similar to those studied;
- the calibrated equations should be used only for large-scale areal considerations; for local assessments at the scale of the artefact, alternatives to the necessary geotechnical investigations on site and in the laboratory cannot be considered;
- refinement of calibrated correlations through the execution of test fields and site and laboratory geotechnical investigations is desirable.

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