Assessment of effect on climate change on structural behaviour of corroded sheet-piles in harbors

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ABSTRACT: Corrosion and water levels changes due to the tide affect the reliability of steel sheet-piles in harbors by changing both the resistance and the loading. Corrosion of steel components in marine environment is highly dependent on the characteristics of the exposure environment: temperature, availability of oxygen, pH, nutrients that characterize the type of exposure (submerged, tidal range, etc.), etc. Climate change in coastal regions affect mainly these structures in two ways: the change of water temperature and pH that govern the kinetics of the corrosion and the sea level rise that modify the stability of the sheet-pile. Moreover, the effect of rising water levels is felt on two levels: stability and location of the maximum corrosion zone. The main objective of this paper is to assess the effects of climate change on the reliability of sheet-piles structures prone to corrosion. First effect of corrosion and sea level rise are analyzed separately and deterministically. Then phenomena are coupled with climate projections from general circulation models for several climate change scenarios (existing database). Influence of corrosion and rising water levels on the reliability of a wharf are illustrated on a design located Saint Nazaire, France.

1. INTRODUCTION

Civil engineering infrastructures occupy an important place in our society and fully contribute to its sustainable development: Energy infrastructures (nuclear, hydraulic, wind, etc.) and Transport infrastructures (maritime, river, railway, tunnels). Today, due to strong economic pressures, the useful life of civil engineering structures is often extended (50 or even 100 years), in service conditions that can sometimes be worse than those foreseen in the design phase. Harbor infrastructure managers are facing this problem and they therefore have to guarantee long-term operation of an heterogeneous set of structures, in optimal conditions of safety and serviceability, respecting the environment (Boéro et al., 2009). Consequently, managers are therefore led to answer two main questions: ”What are the risks associated with the structures in service?” and ”What are the actions to plan to control these risks? (Fulmer, 2009). Among harbour infrastructures, steel sheet pile seawalls are the structures most at risk, in particular with regard to hazards related to corrosion and the role they play in modern harbors.

Steel sheet-piles are very vulnerable because of the risk of perforation and leakage of the embankment (Boéro et al., 2012). Corrosion and sea level adversely affects mechanical behavior and structural safety and is evaluated mainly with respect to the limit state “structural flexural strength of the sheet piling wall”. Corrosion of steel components in marine environment is highly dependent on the characteristics of the exposure environment: temperature, availability of oxygen, pH, nutrients that characterize the type of exposure (submerged, tidal range, etc.), etc. Since the 50’s many papers have studied the corrosion processes in marine environment (Melchers,

2014) and stochastic models are reviewed in (Schoefs et al., 2020). Climate change in coastal regions affect mainly these structures in two ways: the change of water temperature and pH that govern the kinetics of the corrosion and the sea level rise that modify the stability of the sheet-pile. Moreover, the effect of rising water levels is felt on two levels: stability and location of the maximum corrosion zone.

The main objective of this paper is to assess the effects of climate change on the reliability of sheet-piles structures prone to corrosion.

Climate change in coastal regions affect mainly these structures in two ways: the change of water temperature and pH that govern the kinetics of the corrosion (Klinesmith et al., 2007) and the sea level rise that modify the stability of the sheet-pile. Moreover, the effect of rising water levels is felt on two levels: stability and location of the maximum corrosion zone (Orcesi et al., 2022). Chaves et al. (2016) developed a model for accounting of climate change effects on the corrosion of steel structures in marine environment due both to the change of physical parameters of the sea water and to nutrient pollution. In all these studies, the effect of sea level rise was not considered. However, the stability of bottom fixed marine structures is affected by the water level and the profile of corrosion with depth. Sea level rise will change these two factors. The most sensitive steel structure to these effects is the sheet pile (Boéro et al., 2009; Schoefs et al., 2012).

First effect of corrosion and sea level rise are analyzed separately and deterministically. The corrosion mechanisms modelled by introducing effect of climate change on an existing model. Then phenomena are coupled with climate projections from general circulation models for several climate change scenarios (existing database). Influence of corrosion and rising water levels on the reliability of a wharf are illustrated on a design placed in Saint Nazaire, France. Effect of climate change on the corrosion process itself is not accounted for.

2. CORROSION MODELLING

The complexity of steel corrosion mechanisms in the marine environment results from the simultaneous effects of a large number of metal-specific parameters (strong local variations) and the attack environment (physical, chemical, biological, mechanical). The most influential are the physico-chemical parameters: temperature of the water, pH, salinity and dissolved oxygen. The changes of these parameters with time, their seasonal and random nature, especially in harbors and the competitions between the mechanisms makes it very difficult to model parametrically over the long term. Most of the models aim at capturing the trend with more and use more or less parameters (Schoefs et al., 2012). That is why a statistical model, based on the observation of thousands of data for structures up to 50 years old, was developed for North Atlantic and Mediterranean Sea (Schoefs et al., 2012). Built on the statistical analysis of the data contained in the Euromarcor database, developed within the GEROM research project (Boéro et al., 2009), it capitalizes over 34,000 measurements of residual steel thickness collected on 23 port facilities on 4 French ports. Inspections in general are affected by uncertainties and errors even if inspection protocols currently allow them to be overcome (Schoefs et al., 2009). The predictive model of corrosion is based on the general assumption that corrosion is considered a phenomenon decoupled in the R^2 plane of a structure, that is, along its length x and along its depth z (according to the exposure zone). Schoefs et al. (2020) modeled the loss of thickness (mm) as follows:

$$c(x, Z_E, t, \theta) = T(x, Z_E, t) + c(Z_E, t, \theta) \qquad (1)$$

where T (x, Z_E, t) is the deterministic trend with respect to an average value of constant thickness loss along the x direction while c(Z_E, t, θ) is the random variable along the z direction that follows a gama pdf.

Z_E denotes the corrosion zone. Each zone is bounded either by a peak in the corrosion profile or a change in the slope [5]. The five zones are:

- Splash zone (ZS): it is a wetland where a continuous water film is maintained on the surface of metal exposed to the atmosphere.
- Tidal zone (ZT): this zone is located between the average level of high tides and the aver-age level of low tides and is alternately submerged and emergent.
- Low seawater level zone (ZL): the area of lower waters lies just below the average level of lowest tides
- Immersion zone (ZI): this area is located between the area of lowest waters and the mud area. The metal is in permanent contact with seawater and macro-fouling will colonized and growth.
- Mud zone (ZM): this buried area corresponds to the buried parts of a metal structure. The feedback shows that this area usually requires very little maintenance.

Rise in sea level, has two main effects: sheet pile stability (it decreases stress because it balances the pushes of the soil) and the change of the exposure area (moving of Z_E with time). We consider in this paper the worse scenario of IPCC with an extreme sea level rise of 1.1m in 2100 according to RCP 8.5. the effect on the stability is analyzed.

As for the exposure zone change, let’s examine a point at 6.3m on the sheet pile (red disk on the figure). Figure 1-up shows the rise in sea level. By using the mean trend of RCP 8.5, this point being in ZT at building date in 2025, moves to ZL in 2065 (40 years of exposure) and ZI in 2082 (57 years of exposure) (Figure 1-down). According to this trend we write:

if $0 < s < 0.3m$ then $M \in ZT$
if $0.3 < s < 0.5m$ then $M \in ZL$
if $s > 0.5m$ then $M \in ZI$

where s denotes the sea level rise in [m].

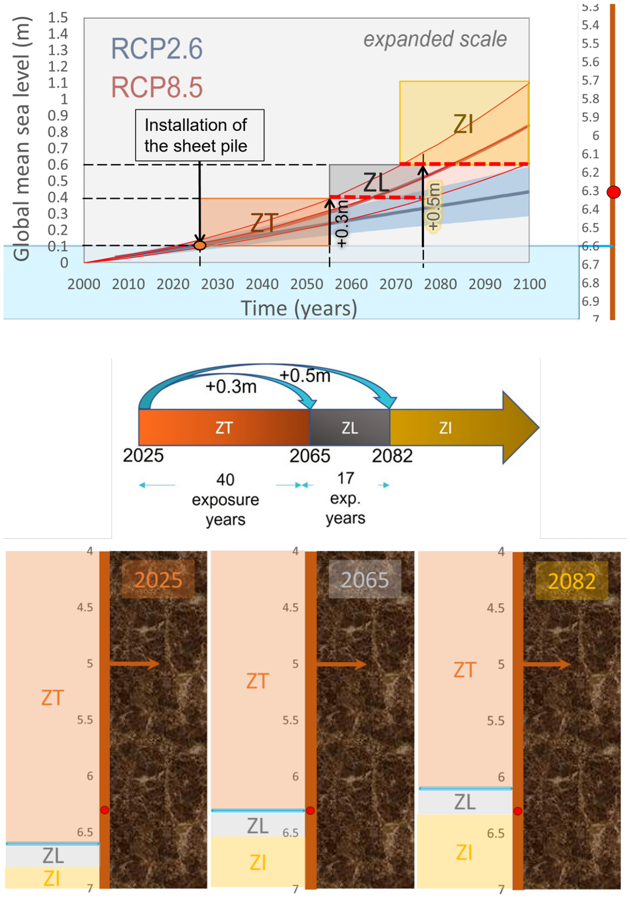

Figure 1: Effect of sea level rise on a sheet pile (up) and changes of the zones (down).

3. DESIGN AND DETERMINSITIC ANALYSIS

3.1. Design of the sheet pile

To be representative of a realistic sheet-pile, the design follows engineering principles and is not optimized with a sophisticated finite element computation. The structure analyzed is the configuration below and no effect of climate change is accounted for at the design stage (Figure 2). A PU 32^{+1} of class S240GP section is selected.

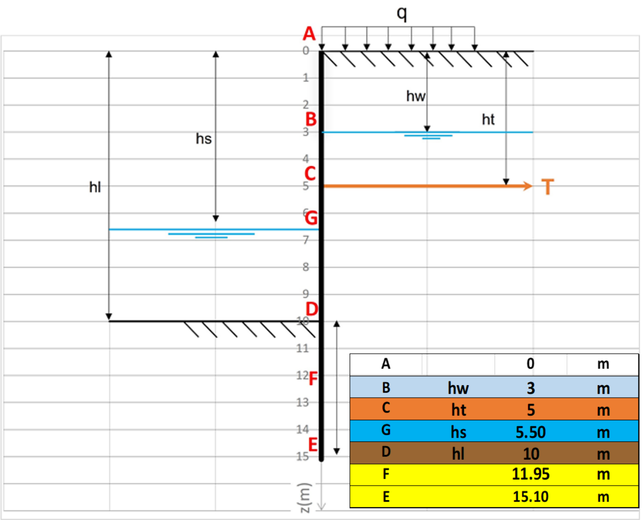

Figure 2: Initial configuration of the designed sheet pile walls (q: service loading, T: toe-rod).

3.2. *Effect of corrosion.*

Corrosion leads to a decrease of thickness and, as a consequence, a decrease of the inertial. Maximum stress thus increases in the sheet pile; its profile for the mean corrosion is given on Figure 3 after 75 years of exposure in 2100.

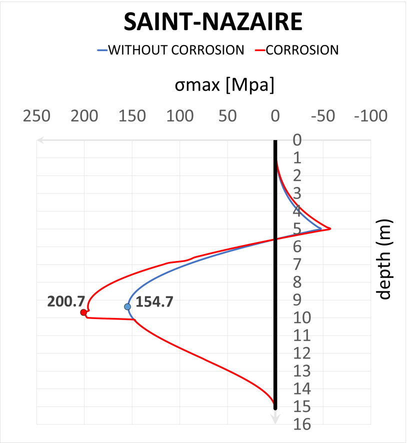

Figure 3: Effect of corrosion on the profile of stress.

3.3. *Effect of sea level rise.*

We consider a sea level rise of 1.1m in 2100 (hs=5.5m see Figure 4-left). This increase generates a decrease in the bending moment and of the maximum stress which profile is given on Figure 4-right. This decrease is caused by the increase in stop stresses due to the effect produced by the higher water pressure. This decrease is also caused by the increase in stop stress. The maximum stress along the profile experiences a decrease of 26%.

The rise in sea level will benefit the structure because the bending moment and the stress will decrease. That is to say, the probability of failure will decrease since at the end of its service life the structure will withstand a lower load than at the beginning.

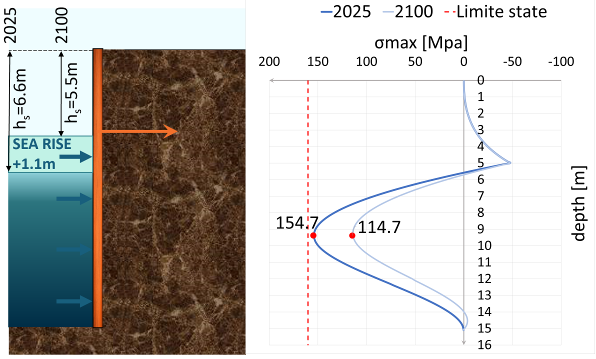

Figure 4: 1.1m (2100) Sea Rise configuration (left); Profile of the maximum stress at building stage (2025) and at year 2100 (right).

3.4. *Effect of the sea rise level and corrosion.*

In this section, we analyze the effect described in section 2. Using the mean value of the corrosion (1) without acceleration due to climate change and the mean value of sea level rise with time (RCP 8.5) at point 6.3 [m] (Figure 1), the corrosion process will change with time because the point will move from zone Z_T, to zone Z_I via zone Z_L. Quantitatively in 2100, it is shown in Figure 5, on this point, that the thickness loss will increase to 8.4mm instead of 3.4mm. This phenomenon will depend on the position of the point along the pile:

- Points in the immersion area will stay in this place
- Points like 6.3 [m] point will experience 3 zones
- Points higher in altitude will experience spay and tide zones.

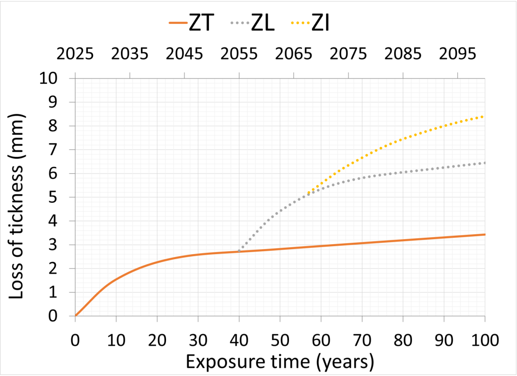

Figure 5: Evolution of the mean loss of thickness with time on point 6.3 m due to a change on the exposure area for St Nazaire site.

Note that, when moving from an exposure zone to another point at time t_c ('c'= change) the corrosion process doesn't start at t=0. Indeed, corrosion products act as a protection of the steel with time. We assume here that a given thickness of steel converted in a given thickness of corrosion products has the same property whatever the exposure zone where it was created. As a consequence, the equivalent time of loss of thickness t_{eq} as to be computed. For instance, on Figure 5, between 40 (t_c=40) and 56 years, the loss of thickness is computed following equation (2):

$$c(t, \theta) = c(Z_T, t_c, \theta) + c(Z_T, t_{eq}+(t - t_c), \theta) \quad (2)$$

Figure 6-left gives the profile of mean corrosion after 75 years (in 2100) for 5 quantiles of sea level rise and Figure 6-right gives the evolution with time for the most critical scenario (RCP 8.5, 95%).

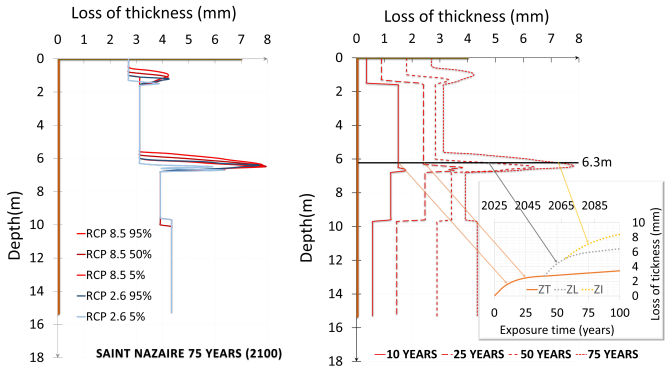

Figure 6: Profile of corrosion for 5 quantiles of sea level rise in 2100.

4. PROBABILISTIC MODELING: RESULTS

4.1. Probabilistic modeling of sea rise and tide

From uncertainty of the prediction models used by IPCC, we model 's' (section 2) as a random variable normally distributed. It was possible to know the probability, for each year of exposure, with which the 6.3 m point is in a given exposure area. The analysis was done through the study of the cumulative probability distribution and the normal distribution and later it will be shown only the year 2085 (60 years of exposure). The Monte Carlo simulation is performed through Latin Hypercube Sampling (LHS) by divided this interval into 10 intervals. Each of these quantiles lead to a scenario of change of Z_E for each point along the pile, at each time step. Figure 7 (down) illustrates the distribution of the MLWS tide level depending on the sea level rise. MLWS is the lower bound of the most critical zone: Z_L (Figure 2). For a sake of illustration, we illustrate the effect of the rise of this boundary on the corrosion process. Figure 7 (down) plots the distribution of this boundary at time 2056 and 2022 for which point 6.3 m experiences a probability of being in Z_L or lower (Z_I) of 5 and 95 % respectively. On this figure, the curves linking each of the 3 quantiles 5, 50 and 95% of sea rise level with time is plotted. From this computation, the times $t_{5\%}$, $t_{50\%}$ and $t_{95\%}$, corresponding to the quantiles of the distribution of the time of being in Z_L are computed. Then the start of corrosion model in Z_L begins according to (2) (Figure 7-up); the same for Z_L.

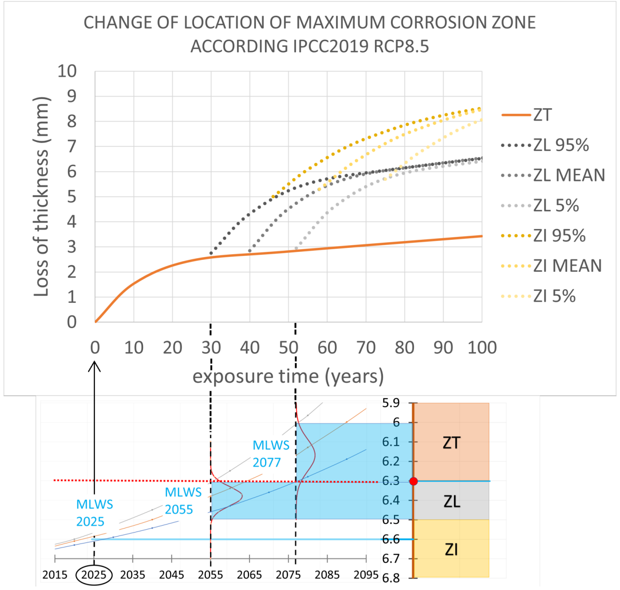

Figure 7: Mean, 5% and 95% quantiles of sea level rise and their effect on the change in exposure zone.

The French Naval Hydrographic and Oceanographic Service (SHOM) provides historical data for tide level at each port (https://maree.shom.fr/). In Saint Nazaire, 13442 data from 2000 to 2020 were analyzed. Even if Loire river is closed to the harbor, the tide was shown to follow a normal distribution. Because of the astronomical source of the tide generation, the distribution is supposed to be the same in 2100. Figure 8 plots these distributions in 2025 (date of building of the sheet pile and 2100). That allows, for each

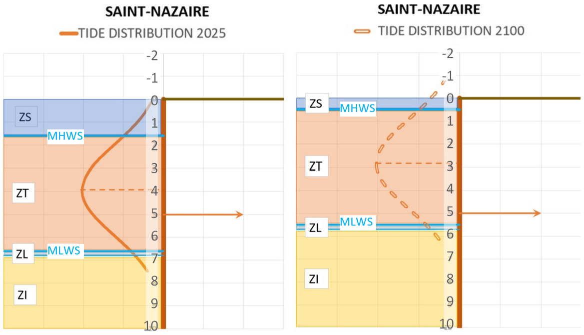

Figure 8: Normal distribution of the tide in the studied configurations (2025-2100).

4.2. Probability of belonging to an exposure zone

From the previous section, at each time and for each point, the probability of belonging to an exposure zone can be computed. Then two possibilities can occur: the point stay in the same exposure zone and continue to corrode with the same process or the point moves to another zone and it adopts the corresponding corrosion model. For instance, after 60 years of exposure, probability of point 6.3 m for being in each zone is given from Figure 9. This point was in Z_T at the building time and experiences a probability of 1.1% to stay in this position, and 33.3% and 65.6%, to move in Z_L and Z_I respectively.

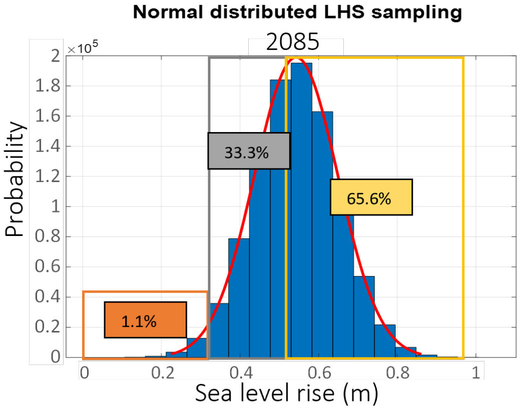

Figure 9: Distribution of sea level rise and position of each bound of the zones.

Figure 10 gives the marginal distribution of loss of thickness in each zone and the total pdf of the loss of thickness 60 years after building at the same point.

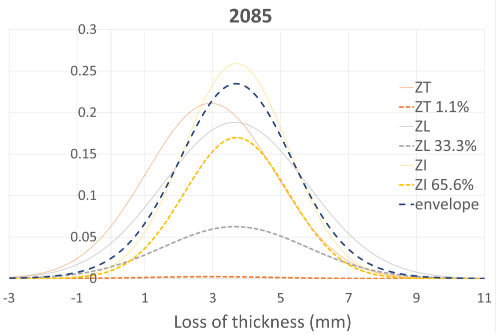

Figure 10. Marginal and total distribution of the loss of thickness at point 6.3 m and 60 years after building.

4.3. Probabilistic modeling of corrosion

Knowing the probability of belonging to an exposure zone from the previous section, the suitable kinetics of corrosion can be selected.

Then the probability of corrosion is obtained by using the conditional probability of corrosion in the given zone.

No corrosion model includes a complete time-variant stochastic modelling including the autocorrelation in time. We follow here the key principles given by Melchers (2014) by using increasing functions of loss of thickness with time: according to LHS principles, the support of the Gama pdf is subdivided in N intervals $I_{i,\, i\in[1,N]}$ of probability $p_i=1/n_i$. Each j^{th} trajectory is obtained by linking the points of the same interval I_j for each time step. In the following, and to avoid any explosion of numerical cost, we use N=10. Such trajectories are given for Z_T on Figure 11.

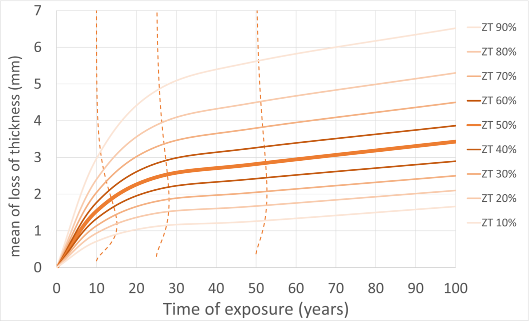

Figure 11: Trajectories built with LHS for Z_T.

Moreover, we assume that a given trajectory is representative to a given intensity of the corrosion process (material vulnerability + environmental aggressivity) and the change of zone doesn't change the relative change of intensity. In other words, when a point experiences a change of zone, the j_{th} trajectory in the previous is followed by the j_{th} trajectory in the next one. Figure 12 is the probabilistic transformation of Figure 5: it presents this phenomenon for the point at 6.3 m belonging successively to Z_T, Z_L and Z_I.

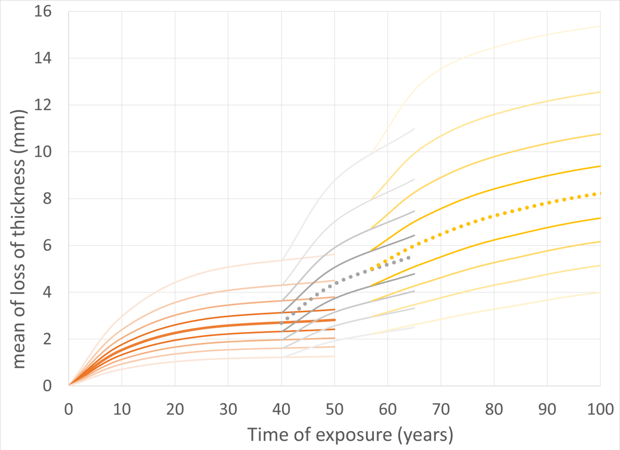

Figure 12: Corrosion quantiles as a function of time for point 6.3 m belonging successively to Z_I, Z_L and Z_T .

Each occurrence of corrosion at a given time has a probability of occurrence of 10%. Then for each situation of level rise, the stress evolution with depth can be updated.

Figure 13 gives this profile for 3 quantiles that covers a large range of sea level rise: +0.2, +0.5 and +1.1 m for quantiles 5 and 95% for RCP 2.6 and 95% for RCP 8.5 respectively.

It is shown that corrosion and sea rise lead to less unfavorable situation than with corrosion only (Figure 3) for which corrosion exceeds 200 MPa. The more the sea level rise, the less the maximum stress.

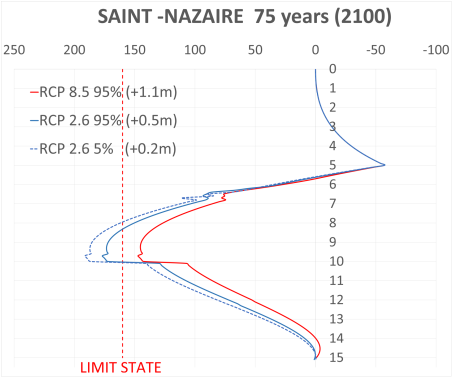

Figure 13: Profile of mean corrosion for 3 quantiles of sea level rise.

5. CONCLUSIONS

Coastal and harbor infrastructures play a capital role in modern societies. Recent infrastructures are at the heart of major stakes: military, energy (including marine renewable energies) and food (fisheries). A large percentage of these infrastructures are constructed of steel, with sheet piling playing a key role. This paper focusses on the probabilistic corrosion of these steel structures modeling in presence of sea level rise. First impacts of sea level rise and corrosion on bending stress limit state are analyzed separately. It is shown that the impact is positive for sea level rise when it is negative for corrosion. Then phenomena are coupled. Finally, a probabilistic model is proposed for the coupling of corrosion and sea rise level. The combined effect is shown to reduce the stress in comparison with corrosion only and results in a large increase of safety for large sear level rise.

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