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Estimation and Impacts of Sea Level Rise in Santos Port and Adjacent Areas (Brazil)

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ABSTRACT: Santos Port is located in Brazilian coast, in an estuarine area inside Santos Bay named Baixada Santista. The currents behavior is forced by tides. The resulting tidal level variability (high tide, mean sea level and low tide) recorded from Santos Dock Company tide gauge (1940 to 2014) shows a consistent increasing trend. The estimation about the magnitude of mean sea level rise (MSLR) in recommendations, guidelines or requirements issued by different countries and agencies from 1990 provide examples of different approaches used around the world in comparison with the local trends obtained for Santos Port. It is concluded that MSLR will have a considerable impact upon the port and adjacent areas, with approximately 1.0 m rise estimated from 1990 to 2100. Baixada Santista is a lowland situated a few meters upper from the sea level and some areas are possible to be submerged in the end of this century. Not only the wetlands of mangroves will be affected, but also the infrastructures, residential zones and the port will face problems. The major SLR impacts upon port operation will be the reduction of freeboard of the quays, flooding of storage yards (and other low storage areas) and of the internal transport tracks or rails. Also the increasing sedimentation in the nautical areas of access channels, turning basins and berths, will induce more maintenance dredging.

1 INTRODUCTION

According to Nicholls *et al.* [1], port cities are a vital component of the global economy and are increasingly becoming important concentrations of population and asset value. Thirteen out of the twenty most populated cities in the world in 2005 are port cities.

Sea level rise (SLR) and the increasing occurrence of stronger storm surge events in metropolitan regions of ports cities with more than one million inhabitants in 2005 were analyzed by Nicholls *et al.* [1] and ranked according to exposed population and assets in 2005 and 2070, including Santos (Brazil).

Santos Port is situated in Santos Estuary, State of São Paulo (Figure 1), is the largest multi-purpose port in South America with over than 13 km of quays. Per year, a throughput of 120 million tons of cargo is made [3] (Figure 1).

The estimation about the magnitude of SLR in recommendations, guidelines or requirements issued by different countries and agencies [3] provide examples of different approaches used around the world in comparison with the local trends obtained for Santos Port.

2 MATERIAL

2.1 *Tides and mean sea level (MSL) variability in Santos Port*

Long term sea level observations are useful for many researches as: tidal analyses, tidal modeling, studies of the ocean dynamics and evaluation of greenhouse impacts. Beside these, works on the estimation of the MSL trends and periodicities were developed in the last years in order to estimate the rates of changes of the sea level [4-6]. These works, considering different long series of sea level, studied the long-term trends of each location.

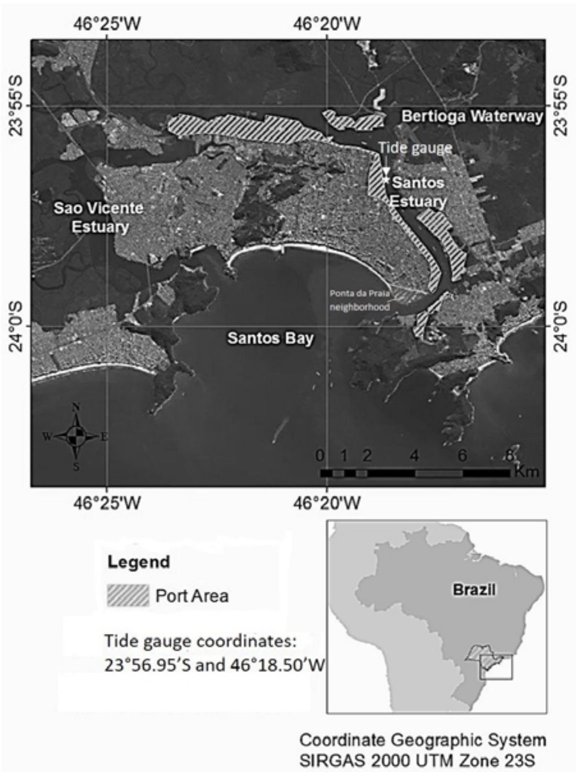

Figure 1. Satellite image of Santos Bay and the estuarine areas of Santos, São Vicente and Bertioga (Southeastern Brazil). Location of the study area, showing Santos Port area and Ponta da Praia neighborhood, example of an urban area which will be inundated when sea level is going to rise with one meter from 1990 to 2100. It is also possible to see the location of the tidal gauge of Santos Port. Adapted from the Source Google Earth/Maps (2015).

2.2 *SLR impacts on port operation and the surrounding neighborhood*

These problems, discussed in [2], are basically consequences of the reduction of quays freeboard, flooding due to insufficient effectiveness of the present drainage system and the increasing sedimentation in the nautical areas. Make available information on the impacts of climate change on the maritime port environment has become an international issue for ports to address global warming impacts [7].

The reduction of quays freeboard is evident as the quay platform height is determined by the level of the terminal area behind the berth apron and the highest observed water level and the tidal level. According to Thoresen [8], the following zones of concrete deterioration will migrate upward with SLR: the permanently submerged zone, below Lowest Astronomical Tide (LAT, Zone 1) will increase in height; the tidal zone, between LAT and Highest Astronomical Tide (HAT), will migrate upward (Zone 2); the splash zone (Zone 3), above HAT, which is periodically exposed to water from waves, will affect the quays aprons; the atmosphere (Zone 4) will affect higher structures of the quay apron (see Figure 2 as an example).

SLR also may contribute for increasing sedimentation in the nautical areas. Considering that mangrove forest in Baixada Santista retains in its roots much sediments, part of the solution for this second problem would lie in measures to preserve these mangrove forests. In a study by Tusinski and Verhagen [9], it was suggested that mangrove forests can serve as an effective coastal defense, including trapping sediment within their roots.

3 METHODS

3.1 *About SLR*

The Projected SLR resulting from simulations of different climate scenarios from the work undertaken by the IPCC [5] increases from 1986 – 2005 to 2081 – 2100 in the range from 0.26 to 0.82 m. However, it is evident that a MSLR in the range of 0.40 to 0.63 m, *i.e.* in the order of 0.50 m in 2081-2100 is expected as an average of all the modeling results reported in IPCC [5].

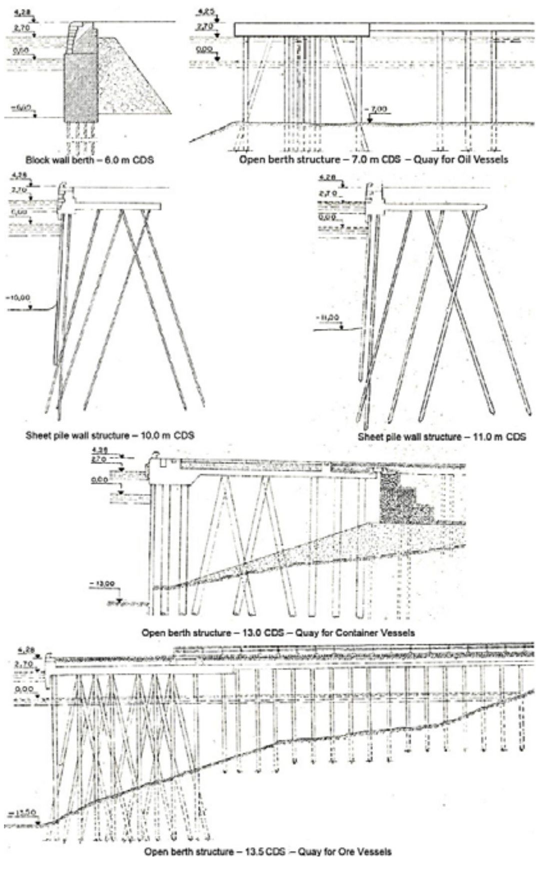

Figure 2. Vertical profiles of some typical quays and piers in the Santos Altimetry Datum. Original project drawings from the Port Authority.

A likely scenario to use as practical recommendation seems to be that the SLR in year 2100 will be in the range of 0.5 m to 1.0 m, however with a risk of being about 50% higher and that the sea level will continue rising also after year 2100, according to Table 1 [3].

There are many approaches for determining an appropriate MSLR scenario, but it is impossible to predict exactly how the future sea level will develop. Consequently, various authorities have developed different estimations [3] as follows.

As example of local practices, the DEFRA – Department for Environment, Food & Rural Affairs of the UK Government [4] in anticipation of increased future SLR, recommend that new engineering projects with a 100-year design life are required to include up to 1 m of SLR from 1990, recognizing that the rate of rise is expected to be larger at the end of this century than at the beginning of the century (Table 2). Other local practices mentioned by PIANC [3] are the projections of the Delta Commission in The Netherlands (projecting up to 1.4 m MSLR from 1990 to 2100 and for USA: California, Oregon and Washington States (Table 3) from 2000.

Considering the period of 1990 to 2014 as an adjustment period for the calibration of the MSLR rate obtained from the tide gauge of Santos Port, this was compared with the rates of UK [4] (moderate rate), States of California, Washington and Oregon [3], The Netherlands Delta Project (equivalent to Rahmstorf [6], higher rate), PIANC [3] higher and lower rate, IPCC [5] higher and lower rate and Rahmstorf [6] lower rate. From these rates, was adopted the best fit to forecast MSLR rate for Santos Port till 2100.

3.2 *The quays in Santos Port*

The quays in Santos Port are named according the depth of the berth (CDS Datum). Figure 2 shows some typical vertical profiles of the quays. The design freeboard observed was 1.58 m, defined in the projects more than 70 years ago (original drawings), considering a Higher High Water (HHW). Nowadays, this freeboard is not the same, due to the SLR occurred.

Table 1. Example of scenario for sea level rise (SLR) as function of type of infrastructure impacted by the design event according to PIANC [3].

Type of infrastructure	Severity of failure	Typical SLR (m) in year 2030	2050	2100	Later than 2100
Farmland and recreational facilities	low	0.1-0.2	0.2-0.4	0.5-1.0	Up to 1.2
Habitation and infrastructure	medium	0.15-0.3	0.3-0.6	1.0-1.2	Up to 1.5
Major habitation, infrastructure and public utilities	high	0.2-0.4	0.4-0.8	1.1-1.5	Up to 2.0 or higher

Table 2. UK recommended net SLR rates and cumulative amounts, relative to 1990 [4].

Time period	Low rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period	Moderate rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period	High rate (mm/yr)/ cumulative SLR since 1990 (m) at end of period
1990-2025	2.5/0.09	3.5/0.12	4.0/0.14
2025-2055	7.0/0.30	8.0/0.36	8.5/0.40
2055-2085	10.0/0.60	11.5/0.71	12/0.75
2085-2115	13.0/0.99	14.5/1.14	15/1.21

Table 3. SLR projections relative to year 2000 for Seattle, Newport, San Francisco and Los Angeles [3].

Cities	2030 Projection (cm)	2050 Projection (cm)	2100 Projection (cm)
Seattle	6.6 ± 5.6	16.6 ± 10.5	61.8 ± 29.3
Newport	6.8 ± 5.6	17.2 ± 10.3	63.3 ± 28.3
San Francisco	14.4 ± 5.0	28.0 ± 9.2	91.9 ± 25.5
Los Angeles	14.7 ± 5.0	28.4 ± 9.0	93.1 ± 24.9

4 RESULTS

4.1 *Assessment of the MSLR*

The tide gauge, which measured water level fluctuations in Santos Port, provided exactly four lunar nodal periods (1940 to 2014) of 18.61 years each one (Figure 3). This is an important astronomical criterion, because take in account complete cycles of repeatability of the Moon influence on the MSL trend, which estimation make possible to evaluate with reliability if the tidal level shows a MSLR after completed each cycle. In the graph of Figure 4 is presented the mobile average of 19 years (approximately the lunar nodal period), showing the consistent increasing of the MSL. From 1940 to 2014, the linear gradient of the MSLR was of 0.33 cm/year with a coefficient of determination.

As it is possible to see in Figure 5, the best fit of the calibration for the linear MSLR trend of 0.33 cm/year was obtained with UK MSLR moderate rate (0.35 cm/year from 1990 to 2014). Hence, the forecasting linear trends for Santos Port were plotted following Table 2 moderate rate from 2014 to 2100.

The resulting MSLR from 1940 to 2100 shows a consistent increasing trend, indeed, compare the following forecasts for 2100 with reference to 1940:

- 174.8 cm: IPCC [5] higher rate.
- 156.5 cm: The Netherlands (Rahmstorf, [6], higher rate).
- 134.8 cm: PIANC [3] lower rate.
- 112.8 cm: California State.
- **108.9 cm**: linear trend of the record of the tide gauge of Santos Port from 1940 to 2014 and adjusted from 2014 with UK [4] moderate rate.
- 108.3 cm: IPCC [5] higher rate.
- 82.8 cm: Oregon and Washington States.
- 54.5 cm: Rahmstorf [6] lower rate.
- 47.0 cm: IPCC [5] lower rate.
- **108.9 cm**: Average value of the mentioned nine MSLR estimations from 1940 to 2100. It is exactly

equal for Santos Port MSLR rate proposed in this paper.

4.2 *The reduction of the freeboard of quays and piers*

The original design freeboard of the majority of Santos Port berths is 1.58 m, referred to 1940's. Hence, with a 1.1 MSLR from 1940 to 2100, results in a freeboard reduction to 0.48 m, value not proper for the quay operation (see Figure 5).

5 DISCUSSION

5.1 *Tidal trend for MSLR in 2100 for Santos Port*

MSLR trend of Santos Port tide gauge from 1990 to 2014 was compared with the recommended rates of UK [6] (moderate rate), States of California, Washington and Oregon [3], The Netherlands Delta Project (equivalent to [6] higher rate), [3] higher and lower rate, [5] higher and lower rate and [6] lower rate. The best adjustment occurred with UK recommended rate [4] (moderate rate), but also California State and [5] higher rate are quite similar. The average MSLR from 1940 to 2100 from all the mentioned methods is identical of Santos Port projection to 2100 using UK [4] (moderate rate). This is an important result, showing the consistence of the suggested rate to be adopted for MSLR rate for Santos Port for the next decades of this century.

5.2 *The case of Santos Port*

The impact on the reinforced concrete maintenance, due to the deterioration of concrete in marine environments can occur in different zones. The usual vertical zonal division of structures in marine environment [8] demonstrate that the SLR will affect all the four zones described. Each zone has different requirements on the composition of the concrete, the placing and covering of the reinforcement, the design load coefficients, the materials coefficients, *etc.* [8]. Considering the six quay and pier types, of Santos Port, it is possible to classify the followings changings about the maintenance procedures for the reinforced concrete:

In this context, it is necessary to be aware that a serious impact in the durability of the reinforced concrete structures will occur, and preventive or corrective maintenances have to prevent the reinforced concrete deterioration with proper repairs.

The average height of quays in the Santos Port were 1.58 m above the sea level in 1940, but with a MSLR of 1.1 m by the year of 2100, this height will be reduced to 0.48 m, quite insufficient.

Other important consequences of SLR in the port area are flooding of storage yards (and other low storage areas) and of the internal transport tracks or rails. Hence, the present drainage system will be insufficient in the rainy seasons.

5.3 *Impact on the mangrove wetlands*

According to the SLR assessment, in 2100 there will be a SLR of 1.0 m from the reference year of 1990 and probably there will be a loss of 26.3% of the riparian zone of existing mangroves, corresponding to 27.4 km^2. Without this retention, a larger amount of sediment will be carried to the inner nautical areas of Santos Port, silting and increasing the dredging volumes of maintenance. Furukawa, Wolanski and Mueller [10] described that up to 80% of the sediment delivered by the tides may be retained in mangrove areas, even though the mechanism of retention of this sediment is unclear.

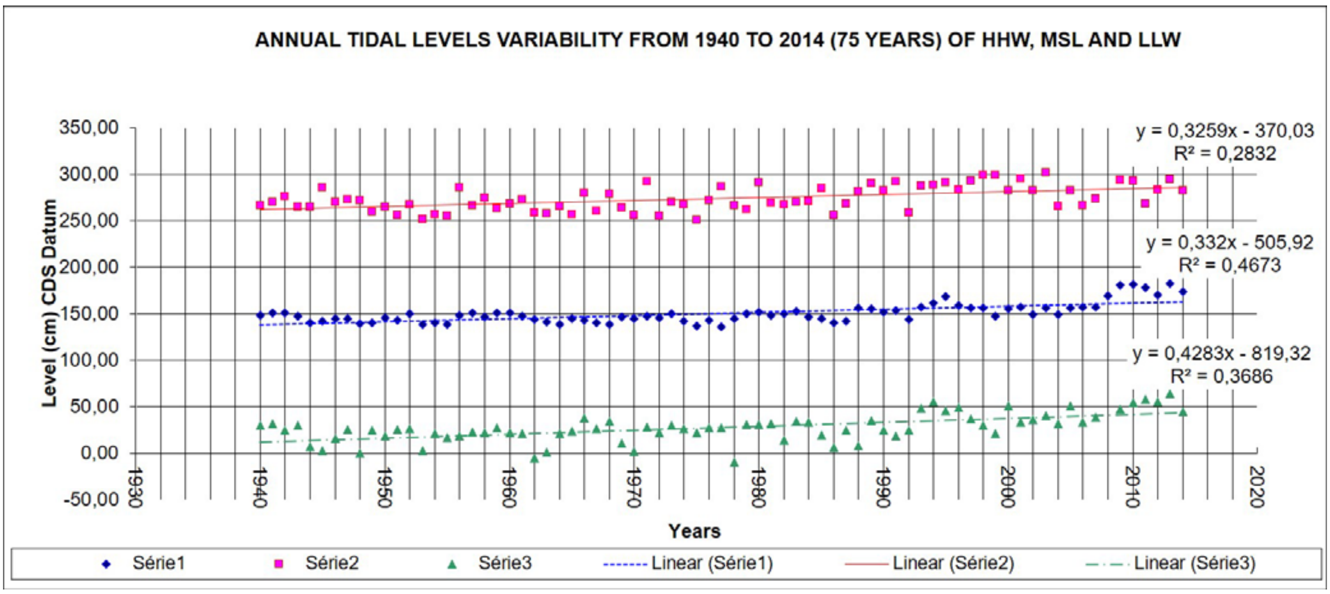

Figure 3. Graph of Santos Port annual tidal level variability from 1940 to 2014. Linear trends of MSL (Mean Sea Level), HHW (Higher High Water) and LLW (Lower Low Water).

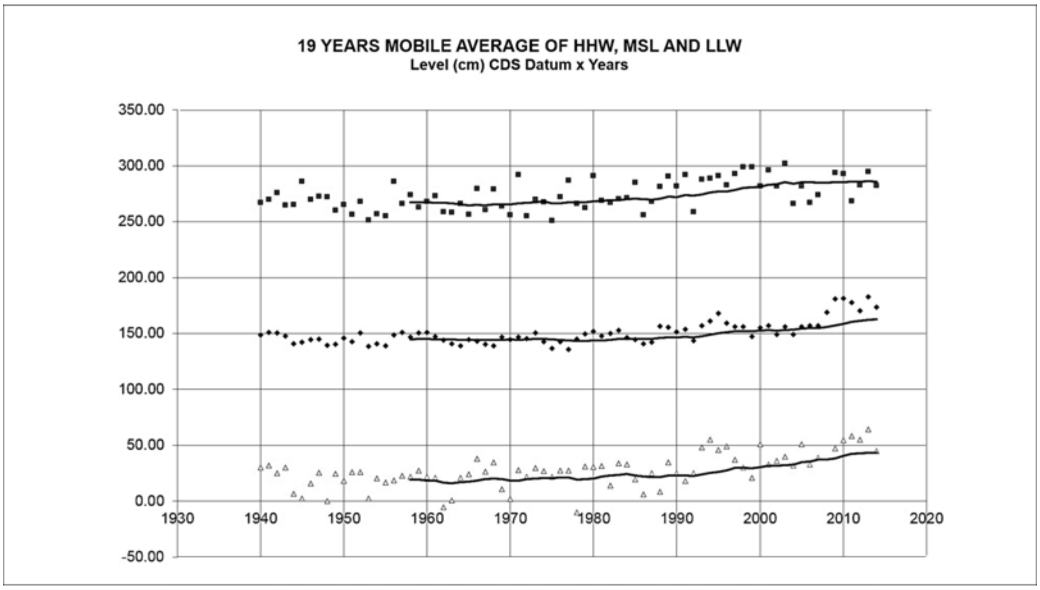

Figure 4. Graph of tide mobile average of 19 years for MSL, HHW and LLW in Santos Port. It is possible to observe a consistent SLR of the levels from 1990.

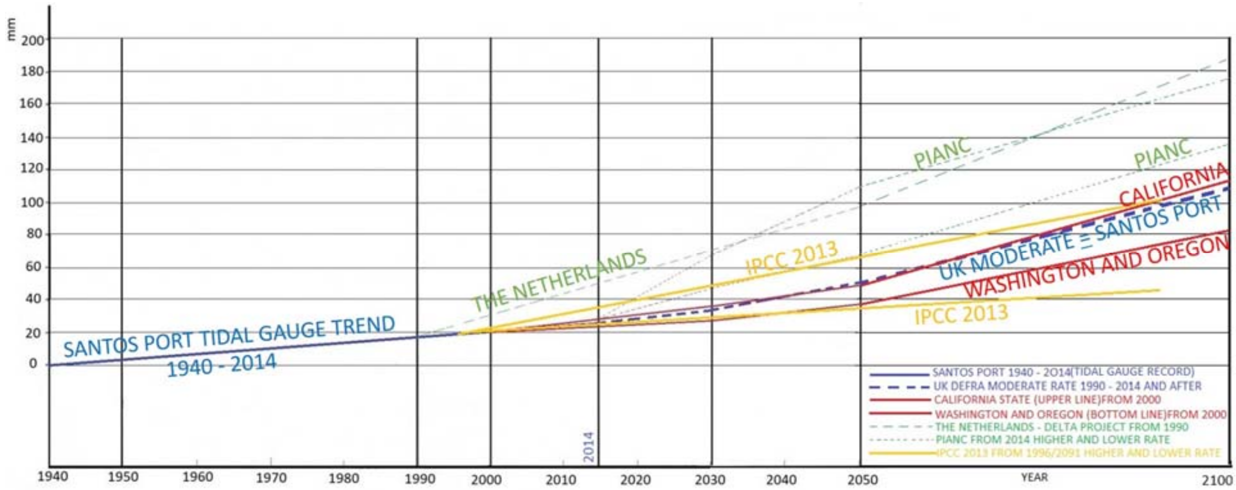

Figure 5. Graph of Santos Port MSL linear trend from 1940 to 2014, with the period of adjustment (1990 to 2014) for the selection of the best fit among some of the most known proposed methods worldwide. Projection from 1990 to 2100 for Santos Port MSL trend adjusted and comparisons with the worldwide recommendations.

6 CONCLUSIONS

The assessment of SLR in Santos Port shows a reliable consistence in comparison with several worldwide recommendations, giving confidence to its use for impacts estimative due to this maritime consequence of climate changings. The estimative of MSLR from 1940 to 2100 is 1.1 m, following from 1940 to 2014 a rate of 0.33 cm/year, which will increase.

The quays freeboard reduction is a direct consequence of SLR, affecting the maintenance procedures, due to the changing of the zones of reinforced concrete deterioration. The present drainage system will be insufficient in the rainy seasons, producing more conditions of flooding.

The increasing in the salinity intrusion upward the estuary due to higher tidal levels will seriously affect the riparian mangroves and will reduce this fine sediment trap.

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