Constructive Solution to Contain Maritime Flood With Minimum Environmental Impact at Ponta Da Praia, In Santos

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Abstract. Significant rises in sea level have caused major disturbances in Santos, on the coast of the State of São Paulo. Initially, this project carried out a survey of storm surges that occurred in Santos, from 1945 to 2013, including the determination of the levels reached. In an initial phase, characteristics of floods were analysed, considering their frequency and intensity. As a solution to the problem of flooding, the purpose of this work was to analyse the feasibility of building a flood containment system, with panels placed in ditches on the line not influenced by geomorphological changes in beach sediments, close to the boardwalk. This panels would be elevated with the activation of pneumatic pistons, in the event of large rises in sea level, having a reduced environmental impact. Numerical simulations were carried out for the years 2016 and 2017, to determine the hydrodynamic behaviour of the coastal region, and thus analyse the major forces acting the containment system. In addition, an outline of the environmental impact analysis for the implementation of the suggested containment system is presented.

1 Introduction

Santos is one city in the State of São Paulo - Brazil, in the central part of the State Coast, comprises an area of 280.3 km², forming part of the Atlantic Plateau. According to [1], the population measured in the 2010 census was 419,400 people. Baixada Santista region (where Santos is located) was one of the first areas occupied in the country, and its economic development is currently linked to activities at the port of Santos and tourism.

This work is based on the master's thesis "Numerical simulation of a constructive solution to contain floods of maritime origin at Ponta da Praia, in Santos, with minimal environmental impact", presented in the Graduate Program in Environmental Science (PROCAM – IEE USP), in 2020 [2]. This research proposes a constructive solution, with low environmental impact, for the Ponta da Praia region, in Santos, which has suffered from severe storm surges in times of high tide and fronts that cause heavy rainfall; due not only to natural effects, but also to the human action.

This research presents a proposal for the construction of trenches in the Ponta da Praia region, on a line not influenced by geomorphological changes in the beach sediments, for the insertion of resistant panels in these trenches, which can be elevated in case of undertows with the activation of pneumatic pistons, in order to protect the metropolitan region from flooding, without influencing the natural dynamics of the coastal area, which is always under the influence of sediment transport and morphological changes due to cyclical natural phenomena [2]. There is currently a boardwalk in this area, which would need one reconfiguration in case of implementation of this flood containment.

1.1. Environmental Panorama

According to [3], in Baixada Santista region, there are some processes that have greater influence in the region of the present study, namely:

- According to [4] some sectors of the region have been presenting intense precipitation episodes. In Cubatão, an industrial valley that is surrounded by unstable hill slopes of Serra do Mar, summer precipitation intensities reached 1021 mm in nine days (February 1929) and 712 mm in two days, (February 1934).
- The region has experienced an increase in tourism activities during the last century. Searching for new opportunities, the working force has occupied unstable slopes in the region. As a result, the city has high deforestation rate and high number of catastrophes triggered by pre soil sealing, due to urban unplanned occupation. [5]
- Deforestation, which has been occurring since colonization and which has increased with economic expansion, but currently occurs mainly in sandbank areas and at the foot of Serra do Mar.
- The drainage system change is a phenomenon that occurs mainly in dense urban occupation areas, where there is drainage channelling; moreover, soil sealing modifies the dynamics of surface runoff, resulting in changes in the flow of rivers in the aforementioned areas.

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- Another impacting phenomenon, mainly in the estuary zone, is the Port of Santos, where the transit of ships leads to silting up of the main channel, modifying the dynamics of sediment deposition in that area.
- According to [6], the emission of domestic effluents, which occurs in areas of recent occupation, areas of hillside occupation and areas of Irregular occupation, where there is a lack of basic infrastructure (sanitation, garbage collection and street layout).
- The accumulation of solid waste.
- Tidal variation is also a determining factor.

1.2. Flood Scenarios

According to [2], one of the concerns of contemporary society regarding climate projections is related to possible changes in the frequency and intensity of short-term extreme weather events. Intense precipitation events have important effects on society, since flooding associated with excessive rainfall, even if short, can be the most destructive among the extreme events in large urban centres, especially when associated with the effects of a sea storm (such as an event of Ponta da Praia, on 08/21/2016). Projections made by the [7] on changes in extreme events due to climate change, for the end of the 21st century, also show an increase in the frequency of intense precipitation events over most regions of the planet, considering all possible carbon emission scenarios in the atmosphere. In fact, strong floods have been more frequent in Santos and their intensity has been increasing in recent years. In view of the exposed problems, it is necessary to propose a containment work that avoids damage of great magnitude in the city. This work uses numerical simulations to support the conception of a sustainable constructive solution, so that the flood problem in the Ponta da Praia region is contained, aiming at the protection of the region's environment, in the short, medium, and long term.

1.3. Coastal Outlook - Time Series Data Analysis

Time series of sea level and meteorological data, in the coastal region of Santos, were analysed by [8], [9], [10] and [11]. Time series analyses allowed obtaining information on sea level variability and the great influence of meteorological conditions, in order to establish the causes of strong storm surges in Santos – especially the intense frontal systems in periods of greater tidal amplitude, in periods of syzygy, which occur when Moon and Sun are in conjunction or opposition, in times of Full Moon or New Moon. Another cause for the severe storm surges that have occurred in Santos is the rise in mean sea level due to climate change. If the projections for future global climate changes are confirmed, the impacts could be potentially irreversible; in this case, island countries and coastal urban regions are the most vulnerable, with real possibilities of flooding in the medium and long term [12][13].

The study by [8] comprised the analysis of the sea level time series obtained from 1945 to 1990 using a tide gauge, and the work by [10] involved the series from 1993 to 2013 measured using of altimetric satellites. It is observed that the sea level rise trend, for the period from 1945 to 1990, was +0.13 ± 0.03 cm/year, while, for the period from 1993 to 2014, it was +0.27 ± 0.06 cm/year. Year.

The rate of sea level rise from 1993 to 2013 [10] was much higher than from 1945 to 1990[8]; it can be inferred that this occurred due to the fact that the rate was very low in the 40's and 50's; from then on, the effects of climatic variations became much more accentuated; it should be noted that the tide gauge series is hourly, and the altimetry series is daily. In any case, these rates of increase in mean sea level indicate that atmospheric pollution, urbanization, and soil sealing have been aggravated in recent decades.

This brief analysis of mean sea level rise can serve as a starting point for further work on the causes of sea level rise. In addition to analysing the effects of global warming, detailed local studies are needed, such as CO2 concentrations in the region, effects of engineering works, among others.

2 Methodology

Due to the rate of sea level rise from 1993 to 2013 [10] was much higher than from 1945 to 1990 [8]; it can be inferred that this occurred due to the fact that the rate was very low in the 40's and 50's; from then on, the effects of climatic variations became much more accentuated; it should be noted that the tide gauge series is hourly, and the altimetry series is daily. These rates of mean sea level rise indicate that atmospheric pollution, urbanization, and soil sealing have been worsened. With advances in computer science and the vulnerability of coastal marine environments, modelling coastal dynamic processes has been developed, providing the use of numerical models for predictions and reproduction of phenomena. It is important to point out that, in order to apply a numerical model, one must take into account the processes that act on the phenomena that one wants to study, in view of the compatibility of the equations used in the model and the errors or uncertainties, so that the result is as close as possible to reality and is useful for the intended application.

For the coastal region of the State of São Paulo, numerical models of the circulation allowed establishing the patterns of coastal currents in periods of storm surges, with strong transport intrusions on the platform coming from the Southwest, these being the main factors responsible for the rise in mean sea level.[13]

In the present work, a model of the coastal region of Santos was implemented, using the Delft 3D software model FLOW[14], which provided sea level values (in meters), current components (in m/s) and current intensity (in m/s). s). The model was processed for a period of 2 years, from January 2016 to December 2017, obtaining sea level and current values at hourly intervals. In this work, the month of August 2016 was chosen to present the results of the simulations. Based on the processing results, 5 “observation points” were chosen for analysis of the time series generated by the model, according to distances gradually removed from the coast from Ponta da Praia, with the objective of following the evolution of the hydrodynamic fields with proximity from the coast. In addition to the 5 observation points, a continuous section of grid points near Ponta da Praia was selected for detailed analysis of the modelling results. The model results were graphically represented using Quickplot in Delft3D.

Initially, 2D processing was carried out to obtain vertically integrated currents, considering only tidal forcing with a time step of one minute, considering as strong: the tides, occurred in the OSU TOPEX/Poseidon Global Inverse Solution (TPXO) models [15].

Next, 3D simulations were performed, in 15 sigma layers, using meteorological data from the Climate Forecast System Reanalysis (CFSR), produced by the National Centre for Atmospheric Research (NCAR)[16], from the National Centre for Environmental Prediction (NCEP), version v2. Mean sea level data and temperature and salinity profiles, at the edges of the grid, were specified from results of the European global ocean model CMEMS – Copernicus Marine Environment Monitoring Service[17].

In addition to hydrodynamic processing, the Delft3D Model was used for surface wave propagation simulations, based on boundary conditions from global CMEMS models and meteorological data from CFSR. These proceedings provided the wave parameters and the induced strength of the surface waves (in N/m²).

From hydrodynamic and wave modelling Delft 3D FLOW[14] and WAVE [18], physical request forces data were obtained, aiming preliminary conception of these structures.

3 Results

From the time series at the chosen observation points, it was possible to choose the best analysis periods of extreme positive and negative levels, in the analysed period. In Figure 3 are the time series of sea level and currents for the point (55,73), the nearer point of Ponta da Praia channel, during August 2016. In that month, the 20th and 21st presented maximum elevations, with mean sea level values above 0.70 m, which caused flooding points and damage to public and private property; values of 0.8m were calculated on 08/21/2016 at 6 pm, and 1.2m at 5 am and 6 am on 8/22/2016 (-3h GMT). Figure 3 also shows the maps of currents and surface waves, on August 21st, at 18:00 -3:00 GMT (21:00 +0:00 GMT).

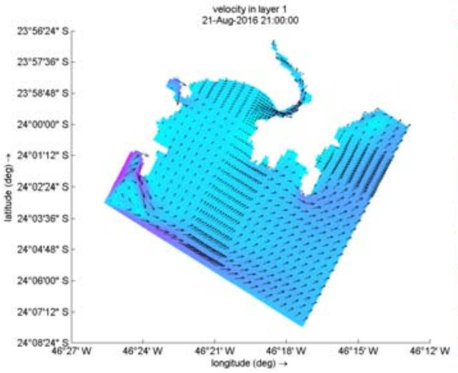

Fig. 1. Map of numerical model current vector results, for the 21st of August 2016 (21:00 +0GMT, 18:00 -3GMT), in the surface layer (in m/s).

In the results section near Ponta da Praia, the vertical profiles of properties calculated by the model were analysed. There was a marked influence of the navigation channel of the Port of Santos; as this area has periodic dredging, the results presented represent the situation found specifically on the analysed day. Among the vertical profiles of variables calculated by the model in the region close to Ponta de Praia, the hydrostatic pressure is of particular importance; values around 20000 kg/m/s², close to the surface.

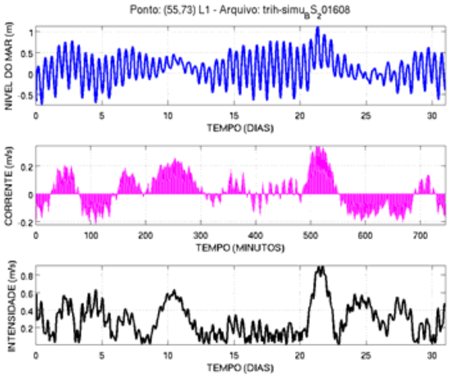

Fig. 2. Time series of model results for sea level (in meters), current vectors (m/s) and current intensity (m/s) at the observation point (55.73), in August 2016.

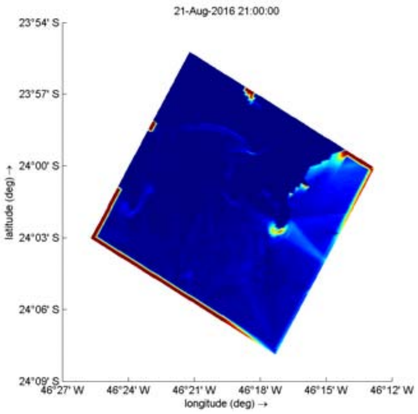

Fig. 3. Map of numerical model results for the induced force of surface waves (in N/m²), for August 21, 2016 (21:00 +0GMT, 18:00 -3GMT). Source: Produced by the author using Delft 3D software.

As for the wave simulation, it can be observed, through the results obtained, that the waves in the outermost part of the grid reached up to 4.5m in significant height; however, close to the region where the intention is to build the flood containment structure, at Ponta da Praia, maximum values of approximately 1.5 m were obtained.

Concluding the modeling analyses, the Delft3D results considered in the design of the flood containment project were: the induced wave force (N/m²), energy transport (W/m), significant wave height (m), dissipation energy (N/m2) and current velocity (m/s).

Wherever possible, modeling results were compared with independent measurements. As an example, the comparison of sea level time series from Delft3D with results from the HYCOM global model, at the point close to Ponta da Praia (55,73), provided a mean difference of 0.041 m and a standard deviation of 0.101 m; the linear correlation coefficient between these series was 0.824, with a significance of 0.023 and Wilmott's comparison skill parameter was 0.936. [19]

3.1. Containment structure request scenarios

In order to carry out the resistance checks of the structure designed in this work (Figure 4), 3 main scenarios were considered, applying the Brazilian Norms for Actions and Safety in Structures (NBR 8681/2004) [20] and Forces Due to Wind in Buildings (NBR 6123/ 1988) [21]. In all scenarios, the GROUND UNDERPRESSURE force on the structure must be considered when calculating the resistance of the piston case, and the weighting coefficients of the standards are used. left, down and clockwise.

3.1.1. Scenario C1

The first scenario C1, when the structure is in flood position, in case of imminent flood, but there is still no flood, so it is forced only by the force of the winds.

Common forces combination

VERTICAL

Positive direction:

$$S_d = 1{,}0.P \tag{1}$$

P = structure weight (N)

Negativedirection:

$$S_d = 1{,}0.\text{sen}\,45\,°.F_{\text{pistão}} \tag{2}$$

$F_{\text{pistão}}$ = Piston resistance (N/m)

HORIZONTAL

Positive direction:

$$S_d = 1{,}25\text{P}+1{,}5.\text{S}+1{,}4.0{,}6.F_{\text{vento}-\text{sobrepressão}}$$

(3)

S = friction (N)

$F_{\text{vento-sobrepressão}}$ = Overpressure wind force (N/m)

Negative direction:

$$S_d = 1{,}0.\cos 45\,°.F_{\text{pistão}} + 1{,}4.F_{\text{vento}-\text{sucção}}$$

(4)

$F_{\text{vento-sucção}}$ = Suction wind force (N/m)

Overturning force

$$M_{ts}=F_a.(-0{,}08H^2+0{,}18H^2)+S.0{,}6H \tag{5}$$

$$FS=M_{Tr}/M_{ts}\geq 1{,}5 \tag{6}$$

$$\text{FS}=\frac{\gamma_{\text{aço}}.B.(-0{,}6\text{H}+0{,}4\,H)}{F_{\text{vento}-\text{sobrepressão}}.(-0{,}08\,H^2+0{,}18\,H^2)+\text{S}.0{,}6\,H}$$

(7)

M_{Tr} = Overturning resistant momentum (N.m)

M_{ts}= Overturning requesting momentum (N.m)

B = thickness of plate (m)

FS = Brazilian Norm security factor

F_a =Wind drag force

3.1.2. Scenario C2

The second scenario C2, when the structure is in a flood position, in case of a flood in transition, there is flooding in part of the structure, so it is forced by the force of the winds in the non-flooded part and by the hydrostatic pressure together with the wave forcing in the flooded part.

Especial forces combination

VERTICAL

Positive direction:

$$S_d = 1{,}0.P \tag{8}$$

Negative direction:

$$S_d = 1{,}0.\text{sen}\,45\,°.F_{\text{pistão}} \quad (9)$$

HORIZONTAL

Positive direction:

$$S_d = 1{,}15\text{P}+1{,}3.\text{S}+1{,}3.F_{\text{wf}}+1{,}3.F_{\text{Ph}}+1{,}2.0{,}6.F_{\text{vento}-\text{sobrepressao}} \quad (10)$$

F_{wf} = Induced waves force (N/m)

F_{ph} = Force produced by hydrostatic pressure on area of structure (N/m)

Negative direction:

$$S_d = 1{,}0.\cos 45\,°.F_{\text{pistão}}+1{,}4.F_{\text{vento}-\text{sucção}} \quad (11)$$

Overturning force

$$M_{ts}=-0{,}08H^2F_{\text{sobrepressao}}+F_{\text{wf}}\,0{,}18H^2+0{,}06P_h.H^2.+S.0{,}6H \quad (12)$$

$$M_{tr}=(P+F_{\text{sucção}})(-0{,}08H^2+0{,}18H^2) \quad (13)$$

$$\text{FS}=\frac{0{,}1\,H\left(\text{P}+\text{F}_{\text{sucção}}\right)}{0{,}16H\,.\left(F_{\text{sobrepressao}}+\text{F}_{wf}+\text{F}_{Ph}\right).+0{,}6.S} \quad (14)$$

3.1.3. Scenario C3

The third scenario C3, when the structure is in flood position, in case of complete flood, in which there is total flooding, then it is forced by the hydrostatic pressure together with the wave forcing in the flooded part.
We will consider positive direction of the vectors from right to left, down and clockwise. Considering that the GROUND UNDERPRESSURE force on the structure must be considered when calculating the resistance of the piston box. And also using the weighting coefficients Oof brazilian standard norms.

Exceptional forces combination

VERTICAL

Positive direction:

$$S_d = 1{,}0.P \quad (15)$$

Negative direction:

$$S_d = 1{,}0.\text{sen}\,45\,°.F_{\text{pistão}} \quad (16)$$

HORIZONTAL

Positive direction:

$$S_d = 1{,}0\text{P}+1{,}0.\text{S}+1{,}0.\,F_{wf}+1{,}0.F_{Ph} \quad (17)$$

Negative direction:

$$S_d = 1{,}0.\cos 45\,°.F_{\text{pistão}}+1{,}0.F_{\text{vento}-\text{sucção}} \quad (18)$$

Overturning force

$$M_{ts}=F_{wf}.(0{,}18H^2-0{,}08H^2)+F_{Ph}(0{,}15H^2)+S.0{,}6H \quad (19)$$

$$M_{tr}=(P+F_{\text{sucção}})(-0{,}08H^2+0{,}18H^2) \quad (20)$$

$$\text{FS}=\frac{0{,}1\,H\left(\text{P}+\text{F}_{\text{sucção}}\right)}{0{,}1\,\text{HF}_{\text{wf}}+0{,}15\,\text{HF}_{\text{Ph}}+0{,}6\,S} \quad (21)$$

In the case of our work, for each meter of containment plate we find the Force caused by hydrostatic pressure:

Fph = 60kN

Force induced waves every meter of:

Fwf = 5kN

Wind drag force on flood day:

Fa=0.253 kN

The uplift force, friction force and the structure's own weight are dependent on the thickness of the plate used, which must be obtained through structural analysis, which is not within the scope of this work.
It should be noted that for the case of implementing the containment structure presented, a detailed Environmental Impact Study must be carried out by qualified professionals for each type of impact, such as biologists, geologists, geographers and environmental engineers.
According to [22], the potential that a given work or human action causes environmental changes is linked to two factors: (1st factor) the requests that will be imposed on the environment by the action or project, represented by the emission of pollutants, suppression or addition of elements in half; and (2nd factor) the degree of vulnerability of the environment, the inverse of resilience, which in turn will depend on the state of conservation of the environment and the demands already imposed on it, whose effects have accumulated, in addition to the importance of the environment or ecosystem.
The solution we propose is illustrated in Figure 4 and its potential impact must be accurately assessed in case of its implementation.

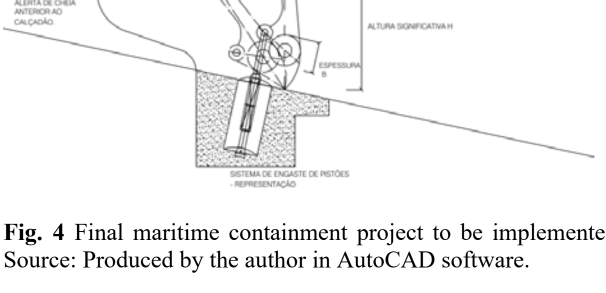

Fig. 4 Final maritime containment project to be implemented. Source: Produced by the author in AutoCAD software.

4 Discussion

With advances in computer science and the vulnerability of coastal marine environments, the modeling of coastal dynamic processes has grown exponentially, providing the use of numerical models for forecasting and reproducing phenomena. This modelling work showed results very close to the global models (in situ data information merged with interpoled information), with good validation rates and proved to be a good tool for the reproduction of phenomena and use for planning containment works.

The events presented are growing and the inhabitants of the place need either to adapt to the new reality of extreme events or to relocate. According to the Santos City Hall Plan 2015-2016 [23], since 2012, with the approval of the Brazilian National Civil Protection and Defense Policy, the cities became obliged to adapt their respective Master Plans to face this problem. In addition, this law defines municipal competence to identify and map areas at risk of disasters, promote inspection and prohibit new occupations in these areas.

This work demonstrates calculation for the conditions found in numerical oceanic simulations, for the considered period and can be applied for this protection barriers planning purpose. However, if this concept of maritime containment is adopted, analogous simulations must be carried out for much longer periods, between one and two decades.

Furthermore, according to [24] , there are no absolute rules, nor absolute solutions in coastal adaptation, given the dynamics and diverse character of each coastline. No single set of regulations or land use management philosophy is appropriate for all situations or all possible coastal scenarios. The presented scenarios have its worses points to be carried out in the structure resistance conception and land use application. As presented in this work, the proposed containment will produce environmental impact, the impact is low, but it exists. However, in one alarming scenario of sea level rise and the socio-environmental and economic threats involved, the application of this constructive solution proves to be plausible and has a lower impact comparing with structures that changes the coastline sediments configration as jetties, breakwaters and moles.

5 Conclusion

As a solution to the problem of flooding in the Ponta da Praia region of Santos, this work analysed the feasibility of building a flood containment system, with panels placed in ditches on the line not influenced by geomorphological changes in the beach sediments, close to the boardwalk, and which would be erected with the activation of pneumatic pistons, in the event of large rises in sea level [2].

From the results of the numerical simulations in the period of 2 years (January 2016 to December 2017), the orders of magnitude of the critical events were obtained for the proposed containment work. They are: the force caused by the hydrostatic pressure of Fph = 60 kN, the force induced by waves at each meter of structure Fwf = 5 kN, the wind drag force on the flood day Fa = 0.253 kN and the significant wave height to be considered in favor of safety and economy H= 2m (for the specific flood scenario). The under pressure and friction forces, and the structure's own weight, depend on the thickness of the plate used, which must be obtained through structural analysis, which is not part of the objective of this work.

It should be noted that more intense positive extremes than those considered may occur if a longer period is analysed; in fact, in case of actual implementation of the project, a longer period of numerical hydrodynamic and wave simulation should be considered, to obtain more accurate extreme data.

Furthermore, this study showed the sea level rise trend in the Ponta da Praia Santos region, based on tide gauge and satellite altimetry data. It is important to use this information in future work, including deeper investigations into the causes of this elevation.

The cost of the containment structure will depend mainly on the scope in extension to be adopted in the Ponta da Praia region, which in turn will depend on the extent of the floods calculated by the specific implementation studies. However, the proposed structure is an investment in protection of the region habitants, infrastructure, and the local economy, it is entirely plausible for a city hall the size of the city of Santos.

Considering socioeconomic and political factors, global climate variations and the rise in mean sea level, and considering the possible impacts, the application of the constructive solution presented is feasible and efficient.

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